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RUBBER

Botany, Production, and Utilization

By

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PREFACE

THIS book represents the culmination of thirty-five years in the United States Department of Agriculture, most of which period was devoted exclusively to the study of rubber-bearing plants for possible cultivation in the United States or Latin America.

The chief credit for the interest of the United States Department of Agriculture in rubber production should be extended to Mr. O. F. Cook, under whose direction I worked from 1920 to 1934. At the beginning of the twentieth century, Mr. Cook foresaw the importance of rubber, and he maintained a lively interest in its cultivation until his death. He was a naturalist with a broad interest in plants and animals, and his contributions to science ranged from tropical botany to detailed studies of cotton production. To him more than to any other individual, I attribute the training and direction that continued to point the way even after his retirement.

The rubber work of the Department was under the direction of Mr. B. Y. Morrison from 1934 to 1940, and received from him much personal effort as well as wholehearted support at all times. In 1940, an expanded programme was placed under the direction of Dr. E. W. Brandes, and blossomed rapidly under his capable, energetic leadership. Later, the leadership passed to Dr. R. D. Rands, who had made many significant contributions to the techniques of rubber production in Latin America. On his retirement, the leadership passed to Dr. M. W. Parker, who is now Director of Crops Research in the Agricultural Research Service of the United States Department of Agriculture. The personal contribution of each of the above individuals to the knowledge of rubber production and to the success of the projects with which I was associated is gratefully acknowledged.

I have received many expressions of confidence and encouragement from many friends who have taken a lively interest in the preparation of this book. In particular, I wish to mention contributions of information, illustrations, and encouragement by Mr. E. G. Holt, Dr. R. D. Rands, and Dr. H. M. Tysdal. Dr. Richard Evans Schultes, of the Botanical Museum, Harvard University, reviewed my chapter on the botany of *Hevea* and made valuable suggestions. Thanks are due especially to my former secretary, Miss Nina K. Shifflette, who has reviewed the manuscript in each stage of its development and has made many valuable suggestions that have greatly influenced its final form.

During the preparation of the manuscript, I have had full access to the records of the United States Department of Agriculture. I want to extend special thanks to that agency and to its fine research organization, the Agricultural Research Service. I am particularly grateful for the constant helpfulness of Dr. L. M. Pultz, who is in charge of the remaining research project of the Agricultural Research Service on natural rubber production.

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1 dram (dr.)	27·343 grains	1·772 grams (grammes)
1 ounce (oz.)	16 drams	28·3 grams
1 pound (lb)	16 ounces	0·454 kilograms
1 stone (st.)	14 pounds	6·350 kilograms
1 quarter (qr.)	2 stones	12·701 kilograms
1 hundredweight (cwt.)	4 quarters	50·802 kilograms
1 (long) ton (2,240 lb)	20 hundredweight	1·016 tonnes

Metric to Avoirdupois

1 milligram (mg.)		0·015 grain
1 gram (gm.)		0·564 dram
1 kilogram (kg.)	1,000 grams	2·205 pounds
1 tonne (metric ton)	1,000 kilograms	0·984 ton

American Weights to Metric

1 pound		453·592 grams
1 cental	100 pounds	45·359 kilograms
1(short) ton(2,000 lb)	20 centals	0·907 tonne

Metric to American Weights

100 kilograms (kg.)	1 quintal	2·205 centals
1 tonne	1,000 kilograms	1·102 (short) tons

Measures of Length—British to Metric

1 inch (in.)		25·400 millimetres
1 foot (ft.)	12 inches	30·480 centimetres
1 yard (yd.)	3 feet	0·914 metres
1 mile	1,760 yards	1·609 kilometres

Metric to British

1 micron (μ)	1/1,000 mm. (1/1,000,000 m.)	1/25,400 inch
1 millimetre (mm.)		0·039 inch
1 centimetre (cm.)	10 mm.	0·394 inch
1 decimetre (dm.)	10 cm.	3·937 inches
1 metre (m.)	10 dm.	1·094 yards
		3·281 feet
		39·370 inches
1 kilometre (km.)	1,000 m.	0·621 mile

Measures of Area (Based on 1 metre = 39·370 inches)

British to Metric

1 square inch (sq. in.)		6·452 sq. centimetres
1 square foot (sq. ft.)	144 sq. in.	0·093 sq. metre
1 square yard (sq. yd.)	9 sq. ft.	0·836 sq. metre
1 acre	10,000 sq.m.	0·405 hectare
1 square mile	640 acres	2·590 kilometres
		258·998 hectares

Metric to British

1 square millimetre (sq. mm.)		0·00155 sq. inch
1 square centimetre (sq. cm.)	100 sq. mm.	0·155 sq. inch
1 square metre (sq. m.)	100 sq. dm.	1·196 sq. yards
1 hectare (ha.)	10,000 sq. m.	2·471 acres
1 square kilometre (sq. km.)	100 ha.	0·386 sq. mile

Measures of Volume—British to Metric

1 cubic inch (cu. in.)		16.387 cu. centimetres
1 cubic foot (cu. ft.)	1,728 cu. in.	28·317 cu. decimetres
1 cubic yard (cu. yd.)	27 cu. ft.	0·765 cu. metre

Metric to British

1 cubic centimetre (cc. = ml.)		0·061 cu. inch
1 cubic decimetre (cu. dm.)	1,000 cu. cm.	0·035 cu. foot
1 cubic metre (cu. m.)	1,000 cu. dm.	1·308 cu. yards

Measures of Capacity —(based on 1 Imperial gallon = 4·546 litres).

1 pint (pt.)—0·568 litre	1 American gallon—3·785 litre
1 gallon (gal.)—4·546 litres	1 litre—1,000 cc.
2 pints—1 quart (qt.)	4 quarts—1 gallon

British to Metric

1 pint	0·568 litre
1 gallon	4·546 litres

Metric to British

1 millilitre (ml. = cc.)—0·061 cu. in.
1 centilitre (cl.)—10 ml.—0·610 cu. in.
1 litre(l.)—100 cl.—1·760 pints

Temperature

0° Centigrade (=Celsius)=32° Fahrenheit

The following formulae connect the two major thermometric scales :

Fahrenheit to Centigrade : $°C = 5/9\ (°F - 32)$

Centigrade to Fahrenheit : $°F = 9/5\ (°C + 32)$

I

INTRODUCTION

WILD rubber was being harvested in the Western Hemisphere before the time of Columbus and was of ever-increasing importance for nearly four-and-a-half centuries thereafter. During that period, rubber was obtained from hundreds of different plants in the tropical regions of the Americas, Africa, and Asia. Rubber cultivation, however, did not become an important farming operation until after the beginning of the twentieth century, and cultivated plants did not become the main source of rubber until after 1912.

First Attempts at Cultivation

Rubber trees were first planted early in the nineteenth century. The desire to cultivate rubber was greatly encouraged by the discovery of vulcanization in 1839 and the subsequent rapid increase in demand for articles of rubber. The first plantings consisted of *Castilla* in Mexico, *Hevea* in Brazil, and *Ficus* in Asia—so that, at this early stage, the local species were merely planted within their respective native ranges. Rubber planting did not get a real start, however, until seeds of the *Hevea* tree were taken from Brazil in 1876 and introduced by the British into their colonies in the Far East. Even then the plantation industry was slow to start, and almost twenty years passed before there was any real impetus in the planting programme; yet, before another twenty years had elapsed, the production of plantation rubber in the Far East had equalled and then eclipsed the production of wild rubber throughout the world.

Search for New Sources of Rubber

The planted rubber that accounted for this astounding development consisted predominantly of *Hevea*. There had, however, been numerous kinds of trees planted: *Castilla* and *Ficus* in addition to *Hevea* in the East; *Funtumia* and *Manihot* in Africa; and *Castilla* in Mexico, Central America, and western South America; also these and other plants in Hawaii, the Philippines, Trinidad, and Madagascar.

French, German, and English officials and botanists searched all tropical areas for plants that might be exploited for rubber, whilst the Intercontinental Rubber Company did a thriving business in the sale of rubber extracted mechanically from wild guayule shrubs in north-central Mexico, and equipped and sent explorers throughout the world to investigate rubber-bearing plants that might be exploited by the use of their mechanical process. This Company furnished a ship with extraction machinery and sent it to Africa to investigate the local root and vine rubbers. They also collected tons of bark from native *Sapium* trees, high in the Andes, and this bark was dried and forwarded to New York for mechanical extraction experiments.

Many factors entered into the final choice of *Hevea* as the chief cultivated rubber tree, and these will be discussed later. By the time the twentieth century reached its half-way mark, *Hevea* had become almost the sole source of natural rubber, its supremacy being challenged by no other botanical source either wild or planted. It faced new competition, however, in the rapid upsurge in the production of synthetic rubber.

Need for Cheap Labour

Throughout the period of wild-rubber production, high profits were gained by the traders in rubber through the exploitation of native peoples —particularly in the Putumayo district of Peru and in the Congo, where the production of wild rubber was marked by human misery and exorbitant profits. These are the regions that came to public attention, but they were not the only areas of inhuman exploitation. The plantation industry received as a legacy from this exploitation the beliefs that rubber production depended on cheap labour and would not be profitable where labour costs were high. It is now recognized, however, that the future of plantation production rests on the development of sound agricultural practices, on the breeding and use of vigorous, high-yielding trees, and on the production of more and better rubber per acre and per worker.

Types of Rubber

Many other plants had been tested for rubber production before *Hevea* rubber became established as practically the sole source of planted rubber. Rubber had been collected from hundreds of wild plants and the products of all of these plants had been used in rubber manufacture; some of these rubbers contained large quantities of dirt, trash, and similar impurities, whilst others contained such a high proportion of resins (acetone-soluble constituents) that they were soft and sticky or hard and brittle.

Dirt, trash, and water-soluble constituents were removed by washing the rubber, and some of the resins were removed by solvents. General differences in the composition of the wild rubbers were compensated for by blending the rubbers in manufacture. Compounders in the period of wild-rubber exploitation were highly skilled artists, expert in the blending of numerous types of rubber and other ingredients to attain a particular quality desired in the finished article. Although performing on a rule-of-thumb basis, they were able to accomplish wonders with the available materials.

Neither the development of a plantation industry, nor the concentration within that industry on *Hevea* as the sole source of rubber, has resulted in the production of a uniform type of rubber; for, in the same way that there were a multitude of different types and grades of rubber from wild plants, there are also a multiplicity of grades of rubber from plantations.

WHAT IS RUBBER?

It scarcely seems necessary to define rubber, a product that is familiar to everybody. From earliest infancy throughout life, all civilized people make use to some degree, or in some way, of this resilient material. Even before Columbus first acquainted Europe with this strange new substance, natives of the Americas had made extensive use of rubber, and this use extended from the Amazon to as far north as what is now New Mexico. Rubber as a useful material has been, and is, familiar to most of the people of the world, for civilized man makes use of it in work, in play, and while at rest. Sections of old tyres provide sandals for plodding millions in Asia and Africa.

As long as it was solely the product of plants, there was a minimum of confusion as to the material being referred to as 'rubber'. Rubber could exist either as a raw material for the fabrication of useful articles—such as in crêpe shoe-soles—or as the manufactured article in the vulcanized form.

Raw natural rubber is not a pure material but contains a complex of chemical substances of considerable diversity. The non-rubber constituents of some rubbers may exceed the rubber itself in weight, and, although these constituents are minor in amount (but not unimportant) in *Hevea* rubber, they include sugars, inorganic compounds, resins, and 'trace' quantities of many other organic compounds. Rubber obtained by mechanical maceration may contain material from many portions of the plant in addition to that from cells where rubber is found. The proportion and kind of these non-rubber constituents of rubbers from various plant sources are characteristic, and represent the basic differences between rubbers from these sources.

The Rubber Hydrocarbon

The major constituent of the rubber from the *Hevea* rubber tree is a hydrocarbon with a chemical composition designated by the formula $(C_5H_8)_n$, where n represents a large but indefinite number of replications of the basic unit. The basic unit is generally considered to be isoprene, C_5H_8, and thus the rubber hydrocarbon is a polyisoprene. This hydrocarbon is found in all natural rubbers and is responsible for their resilience and elasticity. Polyisoprene occurs in greatly varying proportions in different crude rubbers—over 90 per cent in *Hevea* rubber and less than

5 per cent in the so-called potato gum obtained from species of *Euphorbia* in Africa. A similar hydrocarbon, with an identical chemical composition to that of rubber but having dissimilar chemical structure, is also found in the latex of many plants; this material is known as 'gutta' or 'gutta-percha'. The *chemical* difference between the rubber and gutta hydrocarbons will be discussed later. The chief *observable* difference is that rubber is elastic and must be broken down mechanically before it can be formed into desirable shapes, whereas gutta is thermoplastic and can be heated and moulded without the necessity for mechanical or chemical breakdown.

Gutta

Gutta-percha is a fairly pure grade of gutta obtained from *Palaquium* trees in Indonesia. The gutta tree, *Palaquium oblongifolium*,* has been brought into cultivation, and there has been a small-scale production of gutta from cultivated trees by crushing the leaves mechanically. A more resinous gutta known as 'balata' is produced from wild trees of *Mimusops balata* in northern South America, whilst an even more resinous gutta known as 'chicle' is produced from *Achras sapota* in Central America. Whereas thousands of species of plants contain rubber and these plants are classified in numerous families, most of the relatively few species of plants that are known to form gutta belong to the family Sapotaceae.

Lupeol

As will be discussed later, Hendricks & Wildman (1946) have shown that in the latex of *Cryptostegia madagascariensis* there is a triterpene ester, lupeol, that apparently acts as a competitor with rubber for the precursors in the latex. In breeding experiments, this ester has been studied in hybrids of *C. madagascariensis* and *C. grandiflora*. Whether it or the rubber hydrocarbon is formed appears to be determined by relatively simple genetic factors. In *Hevea brasiliensis* (Teas & Bandurski, 1956) and *Parthenium argentatum* (Bonner & Arreguin, 1949), it has been shown that rubber can be derived exclusively from acetate and that the branched-chain acids, beta-methyl crotonic acid and beta-methyl-beta-hydroxy-glutaric acid, are probably intermediate. Neither lupeol nor any other material has been demonstrated as competing for the substrate. More than a single enzyme must be involved in the control of the formation of ester or rubber in *Cryptostegia*; but the formation of rubber in *Hevea* and *Parthenium* is controlled by a single enzyme. There are no genetic studies

* The addition of the publishing authority for Latin names of plants mentioned in this book will be dispensed with except in those chapters devoted to the botanical treatment and classification of the plants most concerned. This will simplify matters where there is no question as to the identity of the particular plant referred to, as is usually the case, every reasonable effort having been made to keep plant names properly up to date in accordance with the latest available edition of the *International Code of Botanical Nomenclature*. Authorities for the rubber-bearing plants treated can be found in the Subject Index, where all plants mentioned in the text are listed.—Ed.

to explain the reported formation of rubber in a species of *Achras* that normally produces only gutta.

Other Constituents of Crude Rubber

The major non-aqueous ingredient of the latex of *Hevea brasiliensis* is the hydrocarbon known chemically as *cis*-polyisoprene but more usually referred to as 'rubber'. The associated substances in the latex are considered as impurities, although some of these impurities in *Hevea* and other rubbers contribute significantly to the coagulation, preservation, and vulcanization of the rubber, as well as to the usefulness of the finished article. They serve as antioxidants, accelerators, softeners, etc., while a powerful antioxidant has been extracted from *Hevea* rubber by acetone. Prior to the development of chemical accelerators, it was found that some of the constitutents of *Hevea* latex were effective accelerators of vulcanization but that they were often lost in the serum in coagulation. *Funtumia* latex contains a substance that makes the latex extremely stable. African rubbers were used as softeners of *Hevea* rubber for many years. The acetone-soluble materials extracted in deresination from guayule rubber were later used by one manufacturer as softeners of *Hevea* rubber. However, these non-rubber constituents of rubber do not contribute directly to elasticity. More than the hydrocarbon itself, which appears to be identical, or almost identical, in all natural rubbers, the non-rubber constituents characterize the rubbers from different botanical sources and are responsible for the differences in grade in various lots of rubber prepared from the latex of any given species.

Crude Rubber v. *Pure Rubber*

Rubber in one terminology is a raw product, a crude material for use in manufacturing; but by extension of the term it is also the manufactured article. In another context, it is a pure hydrocarbon basic to the raw material or the manufactured article. In the past, this plural usage led to little confusion as the context of any reference was usually sufficient to indicate the particular usage. For instance, any reference to the rubber content of a plant referred to the proportion of the pure hydrocarbon; a reference to the rubber content of a tyre or other manufactured article referred usually, unless otherwise indicated, to the proportion of crude rubber added to the compound. In any case, the same hydrocarbon was responsible for the resilience and elasticity both of the crude product and of the finished article.

Synthetic Rubber

The development of synthetic materials with the same characteristics of resilience and elasticity as natural rubber, caused some confusion in terminology. Rubber as a pure chemical was considered to be the hydrocarbon $(C_5H_8)_n$, found in the gum from the latex of various tropical trees or other plants. As a commercial product, it was the gum itself or a manufactured article made from the gum; under such a definition, any synthetic product, to be a true synthetic rubber, would need to have the same chemical composition as natural rubber. Until very recently, all synthetic materials that approached the chemical structure of the natural rubber hydrocarbon, lacked the physical properties characteristic of natural rubber. In the synthetic rubbers that have been produced commercially, the basic unit contributing elasticity bears little relationship to the (C_5H_8) unit of natural rubber either in composition or in structure. The monomer unit with the nearest structure to this is butadiene which, as will be shown later, has a chemical structure closely approximating that of isoprene, which is the monomer unit of the natural rubber molecule. Butadiene is basic to the synthesis of many of the artificial rubbers but, to give qualities similar to those of natural rubber, requires the use of a co-polymer; consequently the structure of the resulting polymer is quite dissimilar to that of natural rubber.

These synthetic rubbers are highly elastic, and the articles manufactured from them are elastic and indistinguishable by visual observation from similar articles made from natural rubber. Because of this similarity, the raw materials are known as synthetic rubbers, although both the manufacturer of synthetic rubber and the rubber farmer have had cause to dislike this terminology. Those interested in the development of the new synthetic products have been dissatisfied with the terms 'synthetic' and 'artificial' as applied to the new products, because such terms still imply the imperfection of *ersatz* materials made as substitutes for unobtainable or costly natural products. Producers of plantation rubber, on the other hand, disliked the use of the term 'rubber' at all, even with the modifiers 'synthetic' or 'artificial'. The new materials did not have the chemical structure of the natural rubber hydrocarbon and therefore were not rubber: they were rubber substitutes, not synthetic rubber.

Dictionary Definitions of Rubber

The term 'rubber' antedates the christening of the elastic product and, even in modern usage, refers to a multitude of dissimilar things or operations.

Thus the *New Century Dictionary* (1938) gives the following definition:

One who rubs; one who practices rubbing, as in order to smooth or polish something; one who makes rubbings; one who practices massage, or who rubs persons down, as at a bath; one who rubs horses down, as those used in racing; also, an instrument, implement, etc., used for rubbing something; a coarse file; a towel or piece of cloth for rubbing the body after bathing or for rubbing horses down; a kind of brush consisting of wool, felt, or the like, fastened to a back, for erasing chalk from a blackboard or slate; a piece of caoutchouc, or india-rubber, for erasing pencil marks, etc.; also, caoutchouc or india-rubber; also something made of india-rubber; an india-rubber band, or elastic, as for holding things together; an overshoe (usually in pl.); in baseball, the home base or plate, or the slab marking the pitcher's position, both made (properly) of whitened rubber.

India-rubber is defined as 'A highly elastic substance obtained from the milky juice of numerous tropical plants, used for rubbing out pencil marks, and variously in the arts and manufactures; caoutchouc; gum elastic; rubber'.

Caoutchouc is defined as 'The gummy coagulated juice of certain tropical plants; india-rubber'.

Webster's Collegiate Dictionary (1923) defined rubber as:

1. One who, or that which, rubs; as: *a* An instrument used in rubbing. *b* An eraser, esp. of caoutchouc. 2. In various games, a set of (usually) three games, of which the odd game is played to decide the contest when each side has won one game; also the odd game so played; also, a contest determined by the winning of (usually) two out of three games. 3. Caoutchouc, or india rubber, esp. in commercial form. Pure rubber is soft and elastic, becoming sticky when heated, and melting at about 300°F. It is usually mixed with vulcanizing agents, fillers, etc., and then molded and vulcanized. 4. Something made of india rubber; as: *a* An overshoe. *Colloq.* *b* A band of rubber.

India rubber is defined as follows:

India rubber *or often* india-rubber, *n.* 1. A tough, elastic substance got from the milky juice of various tropical plants. See CAOUTCHOUC and RUBBER. 2. A piece of this substance or an article made from it; a rubber.

Caoutchouc is defined as:

A tenacious elastic substance got from the milky juice of many tropical plants; india rubber; gum elastic.

Webster's New Collegiate Dictionary (1951) defined rubber as:

1. One who rubs, as a polisher, masseur, etc. 2. An instrument or thing used in rubbing, as an eraser, whetstone, etc. 3. [From its earliest European use, the making of erasers.] *a* A substance obtained from the milky juice (rubber latex: *cf.* latex) of many tropical plants, and usually characterized by elasticity;—called also *caoutchouc* and *india rubber*. Perfectly pure rubber is a white unsaturated hydrocarbon having the composition $(C_5H_8)_x$ or $(C_{10}H_{16})_x$. To increase its useful properties, crude rubber is worked on rolls to make it more plastic, then compounded with other materials, molded and vulcanized. *b* Any of certain synthetic products resembling natural rubber in its properties. 4. Something made of rubber, as an overshoe.

Popular v. Technical Concept

As may be seen from the above, it is extremely difficult to find a definition for rubber that expresses the popular concept as formulated in the dictionary definitions and reconciles it with the various concepts in technical literature, or, in fact, even to reconcile the concepts in technical literature alone. Dictionary definitions are based largely on the origin of natural rubber in the latex of tropical plants such as the Para rubber tree, *Hevea brasiliensis*. In this usage, synthetic rubber is a synthetic product that merely resembles natural rubber in its properties.

The Term Rubber in Technical Literature

There is much in technical literature that might justify restricting the technical use of the term rubber to the pertinent hydrocarbon isolated from plants. The technical term rubber and the chemical term *cis*-polyisoprene would then be synonymous; this would require that a modifying adjective be used in expressing any other concept. Yet such usage would be confusing even in technical literature, as rubber is such a well-known general term that restricting its technical use to a single concept within its general meaning would invite difficulties in the field of natural rubber and create obstacles in the synthetic field.

Some writers have used the French word *caoutchouc* to designate pure rubber and the English word *rubber* to designate the crude or manufactured product. Such usage is not justified on two counts: (1) Caoutchouc, in French, has just as broad a meaning as rubber has in English. (2) The word caoutchouc, like many other foreign words, has been taken over without change into English and is now completely synonymous with rubber.

Rubber as a Physical Concept

Schidrowitz (1955), in discussing whether certain synthetic materials should be called rubber, stated:

> . . . there may be something to be said for restricting the term 'rubber' to natural rubber and maybe to certain synthetic rubbers. The language has already been enriched by adding the cellular silicones to the list of rubbers, where the physical properties are similar to or have some resemblance to natural rubber. The point, therefore, as I see it, is whether the description 'rubber' should refer to the origin of the material, or simply to its physical and/or chemical properties.

Popular usage of the term rubber has become so generalized and inclusive that it would be difficult to restrict its use within the general field of rubber-like materials. It is no longer possible to restrict the word to a particular compound or to any particular source of material; nor does there seem to be any chemical concept that would be useful or informative in defining rubber. From both the popular and technical aspects, rubber has come to be a physical concept; it is not a specific material but, rather, any material that will perform certain tasks or react in certain ways to outside force. Rubber must bounce; it must stretch; it must yield to deformation and then snap back when the deforming force is removed. Technically, rubber must first exist in a raw state in which it may be made plastic in order that it can be moulded, extruded, or otherwise shaped into a useful form, and it must then be capable of being set into a permanent form—vulcanized—so that it will resist further deformation and resume its given shape after deformation. Such a material would meet the popular concept of rubber, irrespective of its origin or chemical structure.

Acceptance of a physical concept for rubber justifies the normal acceptance of the usual modifying adjectives—natural, synthetic, etc. It is incongruous to accept a definition of rubber as, necessarily, the gum from the latex of a tropical tree and then to accept, let alone define, a term such as synthetic rubber. Under the dictionary definition of rubber, there could be no synthetic rubber. If the physical concept is accepted as the sole definition of rubber, the restricting modifiers become useful and meaningful; thus natural rubber designates an elastic material obtained from botanical sources, whereas synthetic rubber denotes an elastic material made in a factory.

Technical Definition of Rubber

The American Society for Testing Materials has proposed a very useful definition of rubber that will be used in this book. ASTM designation D883-55T defines rubber as 'a natural or synthetic material that can be or is already vulcanized to a state in which it has high extensibility and forcible quick retraction'. In some cases, it may be necessary to modify the term in order to be explicit as to the material being discussed: raw or crude will designate the commercial grade of uncompounded and unvulcanized natural rubber. The modifiers, natural and synthetic, will be used only in discussing or comparing the production, use, and/or qualities of the rubber produced on plantations with that produced in factories, and the context will usually indicate what type of rubber is referred to—without the necessity of explicit differentiation.

SYNTHETIC *v.* NATURAL RUBBER

To many people, the term 'synthetic' denotes inferiority. Synthetic is taken to mean not real, but a substitute. There was some excuse for such connotations in the days before chemical synthesis had reached the precision possible with modern technology, but synthetic materials today can have a greater degree of purity and greater uniformity than competing natural substances. Synthetic materials can be high in quality or they can compete merely on the basis of cost.

Some of the desirable qualities of natural rubber have not been duplicated or equalled by any synthetic material; but for many uses there are synthetic materials that are superior to natural rubber. Natural rubber is pre-eminent in its resistance to heat accumulation (hysteresis), resistance to crack growth, and for products that must come into contact with the body. Synthetic materials are available that resist the passage of gases far better than natural rubber, whilst others resist cracking due to sunlight, and some are much more resistant to solvents.

The term 'artificial' has been used to replace 'synthetic', but the popular connotation of inferiority remains. E. G. Holt of the United

States Department of Commerce suggested that the synthetic rubbers be known as chemical rubbers. John C. Collyer, American Rubber Director during World War II, suggested the term man-made rubbers. Both of these terms received some acceptance but not extensive use.

In these days of laboratory miracles, there is an ever-decreasing need for terms to hide the fact that products come from factories. Laboratory wonders have become commonplace, and the scientific creation of new materials, or improvement on the old materials, is no longer considered only as the substitution of a cheaper product for a more costly natural product. This is particularly apparent in the field of fibres and fabrics. Many synthetic fibres now find general acceptance, with no need for such appellations as artificial silk or synthetic wool; nor is there any feeling of inferiority when such designations are used.

The Value of Rubber to the Plant

The value of natural rubber to the plant that produces it bears no relationship to its value to man. Rubber is found in thousands of species of plants in all parts of the world—in the latex of giant trees, in shrubs, herbs, climbers, creeping plants, and even in fungi. No one has demonstrated why a plant makes rubber, and it does not appear to be a food reserve. Strong evidence indicates that rubber is an end-product that is not re-used in the metabolism of the plant. There is also evidence that rubber may be active in chemical processes in the plant; that rubber of high molecular weight is produced before the synthesis of rubber of lower molecular weight; and that, conceivably, the smaller molecule is derived from the larger—rather than the reverse.

Type of Information Available

Discussion of the formation and accumulation of rubber in plants is complicated by the fact that rubber is harvested from different plants in different ways. In general, plants of the tropics are tapped to get the rubber, and plants of temperate zones are harvested mechanically. Data regarding yields are based on the method of harvest of the rubber. Yield data for *Hevea*, *Funtumia*, *Castilla*, *Manihot*, and other tree crops, are based on the amount of latex and rubber that can be obtained by tapping at a single time or over some period of time. Only a minor portion of the rubber in the plant is obtained at any one tapping, but a very satisfactory index is thus acquired as to the rate of rubber renewal under given conditions. With plants such as guayule, goldenrod, and the Russian rubber-bearing dandelions, the plants are macerated and all of the rubber is extracted at one time. Periodic tests of temperate-zone plants have shown the rate of accumulation of rubber and the conditions under which the highest accumulations occur. Information can also be obtained from plants, such as *Cryptostegia*, for which no satistactory method of exploitation has been found but which have been studied extensively: their rubber has been harvested both by tapping and by mechanical and chemical extraction.

Seasonal Variation in 'Hevea'

There is considerable seasonal variation in the rate of flow of the latex of *Hevea brasiliensis* when the tree is tapped. The greatest flow, and thus the highest yield, is, generally, during the wet months, while the least flow and lowest yield of rubber is during the dry season. This simple relationship is complicated by the fact that the annual leaf-change also occurs during the dry season and that physiological factors involved in the leaf change affect the flow of latex. Since the greatest flow of latex occurs during the rainy period, it is simultaneous with the time of maximum growth. Likewise, the period of least yield, the dry season, is a period of retarded growth, and normally the dry period is also the period of lowest temperatures, though the seasonal fluctuation in temperature in the tropics is small.

Wintering of 'Hevea'

The leaf-fall period (wintering) in *Hevea* is not identical for all clones or for all trees; and even a single tree may, at one time, have portions of its canopy in different stages of wintering. To the degree that the dry season and the wintering coincide, their end marks a spring period in the seasonal life of the tree. There is then rapid growth of the terminals and flowering precedes the production of new foliage. As some clones winter early in the dry season and some late, the irregularity of wintering makes it impossible to make specific designation of a spring in the seasonal change. The refoliation of the trees after wintering is marked by a rapid increase in the flow of latex.

Seasonal Variations in Guayule

In temperate-zone plants such as guayule, harvest may be either annual or after several years, when rubber accumulation has reached its highest level. Rubber formation and rubber accumulation are synonymous to the degree that rubber is an end-product not re-used in the economy of the plant. Traub (1946) showed that the amount of rubber in a guayule plant was not decreased during periods of stress, and he concluded that rubber was not a food reserve in guayule—in spite of previous work by Spence & McCallum (1935) who had found a loss of rubber during stress periods. Traub's work was designed not to show that there was no turnover in the rubber formed in the guayule plant, but to demonstrate that under stress conditions the hydrocarbon level remained constant or even increased while the carbohydrate was being depleted.

Under normal growth conditions, the lowest rate of gain in rubber content in guayule occurs during periods of rapid growth. The highest rate of accumulation occurs when the growth-rate of the plant is arrested, although this period of arrested growth normally occurs at the end of the growing-season and is brought about by the onset of lowered temperatures. It can also be induced by drought, whether occurring naturally or by withholding irrigation needed for normal growth.

Flowering and Growth of Guayule

Flowering in *Hevea* is seasonal and more or less coincident with resumption of growth at the end of the wintering period. Off-season flowering is not uncommon, however, and, at some distance from the Equator, may extend for up to six months. Flowering of guayule occurs when growth is most rapid, and successive flowering can be forced throughout the summer by successive irrigations. The facts that rubber accumulation is at a minimum during periods of rapid growth, and that the accumulation can be increased by slowing growth, may be used to advantage in guayule cultivation. Growth can be forced without regard to rubber formation. Periodical controls can be provided in the form of suspended irrigation, deficient fertilization, or other cultural controls to check the growth of the guayule and permit the accumulation of rubber. Growth can be forced continuously for eighteen months to two years, and the formation of rubber can then be encouraged by inducing stress conditions. The accumulation of rubber under these conditions is equal to that obtained by providing stress conditions at more frequent intervals.

Seasonal Variation in Kok-saghyz

The Russian rubber-bearing dandelion, kok-saghyz, accumulates rubber throughout the growing-season. Rubber accumulation does not cease in the autumn but continues throughout the winter, the highest content being found in the spring just before new growth starts. After growth is resumed in the spring, the old bark tissue containing most of the rubber formed the previous year is discarded. However, as the spring resumption of growth takes place early, there is insufficient time between the thawing of the ground and the initiation of growth for harvest of the crop and replanting, so the optimum time for harvest of this root-crop is late in the autumn before the ground freezes.

Rubber Formation and Accumulation

There is little accumulation of rubber in an untapped *Hevea* tree or in a vigorously growing guayule plant. If rubber formation occurs, it must be counterbalanced by the destruction or re-utilization of that formed previously. A guayule shrub that is not harvested continues to accumulate rubber for several years. As was mentioned above, kok-saghyz discards a major portion of its accumulated rubber annually before resuming new growth but does not cease the formation of rubber at any time, even during the winter resting period. The amount of rubber in dried tissue of *Hevea* seldom exceeds 1·5 per cent, and such a high percentage is found only in the bark where the latex vessels are located. In kok-sagyhz, the content of rubber in the dried roots may be as high as 6 to 8 per cent. Percentages as high as 25 have been reported in guayule, and even higher percentages have been reported in the roots of another Russian rubber-bearing plant, *Scorzonera tau-saghyz*.

The precursors of rubber must be constantly or quickly available in *Hevea* and guayule. Speedy formation of rubber is started in *Hevea* by the initiation of tapping, and in guayule by natural or artificial stress.

Leaf Rubber in 'Cryptostegia'

Rubber is found in the roots, stems, and leaves of *Cryptostegia*, being present in both the bark and pith of the stem. Whittenberger *et al.* (1945) investigated the rubber in the leaves of *Cryptostegia*. Latex vessels that contain appreciable amounts of rubber follow the midrib and veins of the leaf and penetrate some distance into the adjacent tissues of the lamina. Rubber is also found as globules associated with the chloroplasts in all types of green cells (palisade parenchyma, spongy parenchyma, guard-cells) of the mature leaf. Such globules are most numerous in the palisade layer where there may be from one to eight per cell. Within the cells, the largest globules are entirely distinct from the chloroplasts although some of the smallest ones are not. The globules may attain a diameter of 10 to 12 microns (·01–·012 mm.), although smaller ones (3 to 7 microns in diameter) are more common.

These authors suggested that rubber might be formed in the leaves and then transferred by appropriate means into the latex vessels. Having no specific proof, they stated cautiously: 'Their general correlation with the presence of chlorophyll may be physiologically significant; the existence, in some cases at least, of very small globules in non-chlorophyllous parenchyma adjacent to the laticiferous ducts associated with the larger veins suggests a possible interchange of globular and duct material. Furthermore, in the dorsal half of the leaf (spongy parenchyma), the globule-bearing cells are more numerous adjoining the ducts than in non-duct areas.'

Goldenrod also has rubber associated with the chloroplasts in the leaves; but, in goldenrod, there are no latex vessels in leaves or stems, and only traces of rubber are found in any portion of the plant other than the leaves. Among known rubber-bearing plants, *Cryptostegia* occupies a unique position in being rich in rubber in the green cells of the leaves, and also in the latex vessels in the leaves, bark, and pith. *Hevea* has no latex vessels comparable with those in the pith of *Cryptostegia*, while guayule and kok-saghyz have negligible amounts of rubber in the leaves.

The Value of Rubber to Man

Rubber was one of the last of the major plant products to be produced domestically, and to a remarkable degree typifies modern civilization. The discovery of rubber, and the development of rubber-like materials, have come during the development of modern conveniences that make the life of the average man of today easier than that of even the most pampered of those who lived but a few decades ago. Rubber has been an important ingredient of many of these conveniences. In its resilience and elasticity, rubber has served to cushion man from his environment and has added to the comforts of his life.

The Uses of Rubber

Many kinds of articles can be fabricated from rubber—hard, strong, structural materials; soft, yielding, comfortable materials; resilient, elastic materials; conductors and non-conductors of electricity; shock absorbers; mountings for motors and other machinery; transmission belts; gaskets; hoses for transporting gases and liquids; transparent materials; translucent materials; articles of clothing to keep out rain or to control the figure; sports goods; cements; paints; plastics; pharmaceuticals; drug sundries; and, above all, tyres, the chief outlet for rubber.

The Sociological Value of Rubber Production

The cultivation of rubber is the chief means of livelihood in many of the countries of the Far East. Indonesia, Malaya, Burma, Ceylon, Viet-Nam, Cambodia, Thailand, Brunei, Sarawak, and British North Borneo, all depend largely on exports of rubber for the prosperity of their peoples and the stability of their economy. Millions of people in these countries are dependent directly or indirectly on wages or profits received from the production of plantation rubber. In India, Pakistan, Liberia, Nigeria, and the Congo, rubber production makes a substantial though not a preponderant contribution to the national income.

The production of plantation rubber is thus a major factor in the national economy of tropical countries of the Far East and is rapidly assuming importance in Africa, whilst the production of synthetic rubber contributes significantly to the national income of the United States and Canada, is important in Germany, and is of prospective importance in France and Italy. Russia does not always contribute to international statistical information but is understood to be making progress in the manufacture of synthetic rubber. In 1957, the United States led all countries for which statistical information is available in the production of rubber, and Canada, the second major source of synthetic rubber, was fifth of all rubber producers, being exceeded in production only by Indonesia, Malaya, and Thailand in addition to the United States. The production of natural and synthetic rubber in the leading countries (those producing more than 30,000 long tons [1 ton = 2,240 lb.]) in 1957 is shown in Table I.

TABLE I

PRODUCTION OF NATURAL AND SYNTHETIC RUBBER IN 1957 BY PRINCIPAL PRODUCING COUNTRIES *

Country	Type	Production (long tons)
United States	Synthetic	1,118,173
Indonesia	Natural	684,515
Malaya	Natural	638,706
Thailand	Natural	132,964
Canada	Synthetic	132,141
Ceylon	Natural	98,164
Viet-Nam	Natural	68,556
Sarawak	Natural	40,982
Nigeria †	Natural	39,946
Liberia †	Natural	38,161
Congo †	Natural	33,763
Cambodia	Natural	31,183

* Compiled from data in *Rubber Statistical Bulletin*, August 1958.

† Net exports rather than production.

II

HISTORY

Pre-Columbian

The literature on rubber dates only from the first visit of Columbus to America, when the use of rubber was already well established in the Western Hemisphere. Protective garments, balls for playing games, and syringes, have been recorded by the earliest visitors to the new continent. The unrecorded history of rubber usage preceded its literature by many generations or, possibly, centuries.

Schurer (1957) has traced the use of rubber in Peru, in the Mayan civilization in Yucatan, and in the ancient Mexican civilization: in all of these ancient civilizations rubber, and demonstrably *Castilla* rubber, was an important element of religious rites. In Yucatan and Mexico City, the rubber was preserved and used in the liquid form and was related in ceremonial use to the blood of living sacrifices. It was spread symbolically on banners or used to make statuettes of the gods, and even the handball games took on the aspect of religious rites.

The First Rubber Tree

The chief, now almost sole, source of vegetable rubber, *Hevea brasiliensis*,* is native only in South America. The natural range of *Hevea* extends but slightly beyond the limits of the Amazon basin, members of the genus being thus found only in a restricted though sizeable area.

Castilla, on the other hand, occurs throughout the Amazonian basin, in parts of Ecuador and Colombia where no *Hevea* is native, and throughout Central America and southern Mexico. Early usages of rubber in Mexico undoubtedly were based on rubber from the local species of *Castilla*; and the presumptive evidence is strong that, even in South America, the first trees to be bled extensively for rubber were *Castilla*. Even the name *Hevea* was adopted from the native name for the *Castilla* rubber tree in Ecuador. La Condamine (1745) reported a rubber tree at Esmeraldas, Ecuador, known locally as 'hheve'. Aublet (1775) used the native name reported by La Condamine in describing a species of rubber tree as *Hevea peruviana* (later changed to *H. guianensis*). Aublet did not have botanical material from Esmeraldas and merely assumed that the tree reported by La Condamine was the same as the one being described.

* *See* footnote on p. 4.

No *Hevea* tree was ever found at Esmeraldas and there can be little doubt that the tree seen there by La Condamine was *Castilla*. It was not until some time later that La Condamine had his first opportunity to see *Hevea*.

There are dozens of latex-bearing species of plants in the Amazon basin, and *Castilla ulei* bleeds most freely and copiously of them all. Yields of over 100 lb. of rubber at a single tapping of a felled tree have been reported though not fully substantiated. The yield of a *Hevea* tree is comparatively small at any one tapping and cannot be increased materially by felling. The fast-bleeding *Castilla* was the first rubber tree, and native tappers only turned to the slow-responding *Hevea* after the supply of *Castilla* had been depleted.

Early Use of Guayule

Even guayule, the desert rubber-bearing shrub of northern Mexico and the Big Bend district of Texas, entered into the early history of rubber in the Western Hemisphere. This shrub, *Parthenium argentatum*, does not yield a latex when tapped, because its rubber is held in isolated cells and it has no latex-vessel system to transport the latex to a cut. Lloyd (1911) stated that extracting the rubber from wild guayule by chewing the bark was common in the northern part of Mexico in the eighteenth century, and adduced that the use of guayule for making balls for play must have antedated Columbus.

Rubber Usage Developed Only in the West

It is astounding that the use of rubber prior to the time of Columbus was confined to the Western Hemisphere. Rubber-bearing plants are found throughout the world—*Ficus* in India, *Funtumia* in Africa, and shrubs and vines such as *Cryptostegia* in India and Madagascar, *Landolphia* in Africa, and hundreds of latex-bearing Apocynaceous vines and shrubs in southern China and the Malayan Peninsula. Plants of at least one, and presumably more, species of *Hevea*, at least two species of *Castilla*, and guayule, had been used for rubber production in the Western Hemisphere before the time of Columbus. The only usage for latex in the East was as a bird-lime.

Rubber as a Symbol of Advanced Civilization in the West

The use of rubber is an illustration of the advanced civilization that European explorers encountered in the West. The uses of rubber had evidently been well established before the time of Columbus, as methods of tapping the trees and processes for making crude articles from the latex had already been developed. This primitive technology persisted as the guiding force in the usage of rubber for nearly three-and-a-half centuries after the discovery of rubber in the West. Technical progress was made and the use of rubber increased; but the over-all conception of rubber as a usable material was not greatly changed during that time. The merged civilizations of the East and the West made their first big joint contribution to rubber technology when vulcanization was accomplished in 1839.

Rubber was brought to the European market in crude bottles until after the middle of the nineteenth century, nearly four centuries after the official discovery of America. These bottles were made by putting successive layers of rubber latex on the outside of suitable forms that could be removed, forcibly if of wood or by washing if of clay, after a sufficient thickness of rubber had been built up and dried. They were shipped empty though on occasion they were used as containers. The development of the art of making bottles, the making of crude footwear, even the impregnation of fabrics to make waterproof raincoats and other coverings, were natural results of working with and making use of the latex obtained chiefly from the *Castilla* trees that abounded from Bolivia to Mexico. The manufacture of syringes consisted merely in putting a straw or hollow spout in a bottle. Even the evolution and use of the rubber balls for playing games were natural developments once this bouncy stuff was available in Mexico and in South and Central America long before the time of Columbus. However, the development of handball as a spectator sport, with rules and specially-constructed arenas, showed that long before the Europeans knew of rubber its use had become an important factor in the Western civilization.

Rubber in the Sixteenth and Seventeenth Centuries

De Las Casas in 1409, in a memorandum not published until 1909, noted that Columbus showed him one of the astonishing American rubber balls. Yet the knowledge of this strange new product spread slowly. Schurer (1956) refers to Hernandez (1651) as the only European—two-and-a-half centuries after the discovery of America—who was then on record as having seen a rubber-yielding tree. Hernandez devoted a page to the Mexican rubber tree, now called *Castilla elastica*, and illustrated his account with a good drawing. The sixteenth and seventeenth centuries constituted a period of incubation in the history of rubber, a period when the curious were familiarizing themselves with the nature of rubber but throughout which it remained essentially a curiosity without any particular use in Europe.

Rubber in the Eighteenth Century

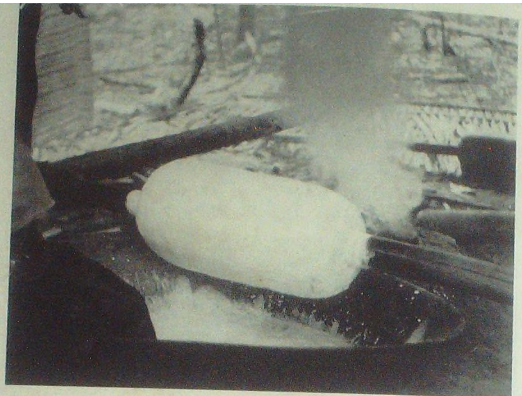
Sources of Rubber in the Eighteenth Century

The rubber balls brought back to Europe by Columbus and other early explorers, the crude bottles and syringes, and other articles found in use among the native peoples of the Americas, continued as curiosities in Europe while the first knowledge of the botanical sources was being

(a) A wild tree of *Hevea brasiliensis* badly scarred by numerous tappings with

Photographs by permission of ARS. U.S. Dept. Agric.

(b) Smooth bark renewal on a tree of *Hevea brasiliensis* that has been tapped



Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) A rubber ball being held over a pan of latex for convenience in adding fresh latex. It is then rotated slowly over the smoky fire in the background, to coagulate the latex and partially dry the rubber.

(*b*) A fruiting branch of *Funtumia elastica*.

PLATE 3

accumulated. Knowledge of the new material and of the plants that produce it was slow in development, but by the end of the eighteenth century four species of rubber-bearing plants had been identified and described. These were two species of *Hevea*, *H. brasiliensis* and *H. guianensis*; one species of *Castilla*, *C. elastica*; and an Indian vine, *Urceola elastica*.

In addition, an unidentified Apocynaceous vine had been reported as a possible source of rubber in French Guiana, as had an Apocynaceous vine tentatively named *Vahea* that had been discovered in Mauritius, while a mistletoe had been suggested as a possible source in Germany, and a milkweed had been studied in this connection in Russia.

'*Castilla ulei*', *the First Brazilian Source of Rubber*

There can be little doubt that many more plants were exploited for rubber by 1800 than had been described, for although by then only the first beginnings of European usage had developed, native usage in the Americas was centuries old. The assumption that of all species of *Castilla* only *C. elastica* was tapped is manifestly untrue, as other species of *Castilla* are found in Central America and tropical South America that are equal to *C. elastica* in yield and quality of rubber. The Amazonian species, *C. ulei*, is one of the highest yielding of all rubber trees, and presumably furnished a predominant share of the prehistoric rubber in South America.

Switch to '*Hevea*'

As *Castilla* trees were felled and the stands along the rivers became depleted, the native tappers turned to other sources of latex. *Hevea* was found to be a suitable alternative, with a latex that was comparatively easy to coagulate. Unlike those of *Castilla*, yields of *Hevea* increased with successive tappings and no advantage was gained from felling the trees. The trees continued to bleed when tapped repeatedly, until the trunk was covered with burrs resulting from the constant wounding. The increased yield from successive tappings encouraged daily tappings during the dry season in the annually flooded valleys of the Amazon Basin. In clearing for home gardens, the existing *Hevea* trees were preserved and more were planted. Thus, with the disappearance of the primeval stands of *Castilla*, *Hevea* became the first choice of the rubber gatherers—particularly near the streams that constituted the only pathways through the jungle.

Other Species of '*Castilla*'

Even in Central America and Mexico, where *Castilla ulei* is not found, there are several species of *Castilla* that might rival *C. elastica* in rubber production. No comparative tapping tests have ever been made that would serve to differentiate the species of *Castilla* on the basis of comparative yield, and no selection within any species has been made on the basis of growth in cultivation and ability to yield latex in a significant amount at an early age. Nor have any breeding tests been conducted. Good yields of high-quality rubber were obtained from other species in Mexico, Guatemala, Costa Rica, and Panama. Only *C. fallax* has been reliably reported as a non-rubber species with an excessively high proportion of resinous materials in the latex. There can be little doubt that in the early days of rubber tapping, several other species of *Castilla* in addition to *C. elastica* and *C. ulei* were tapped for rubber, and that all were considered to be *C. elastica*.

Eighteenth-century use of Guayule

The prehistoric use of guayule has already been pointed out. A Jesuit, Negrete, is credited by Endlich (1905) with having observed the country boys in Mexico using rubber balls made by the mastication of the bark of guayule. Altamirano (1906) records such balls as having been found as late as 1906, and that the balls were made by chewing the bark of 'tatanini'—a name applied, in Queretaro, to *Parthenium incanum* and *P. lyratum*. Thus the record is clear that some use was made of rubber from species of *Parthenium* in the eighteenth century; but the family, Compositae, to which *Parthenium* belongs, did not find a place in rubber literature until the middle of the nineteenth century (1859), when the identity of guayule was first established botanically.

The Usage of Rubber in the Eighteenth Century

The Eighteenth century was more than half over before there was any significant interest in the commercial use of rubber; before, indeed, the material became known as rubber. The English chemist J. Priestly is quite generally given credit for the observation that this new material would erase pencil marks. The fact that rubber would serve as an eraser would have to be considered a rather minor finding if that discovery had not led to its christening in the English language. The French 'caoutchouc' and the German 'kautschuk' come from native names for the gum or the trees that produce it, whilst the Portuguese 'borracha' comes from the bottles, the form in which the gum originally appeared on the market. Only in English did the adopted name refer to a use.

Schurer (1956) states, 'The year 1770 is memorable in the history of rubber. It was in this year that the maker of "philosophical instruments", Edward Nairne, owner of a shop opposite the Royal Exchange at 20 Cornhill, started selling small cubes of a new nameless substance which he claimed would make excellent erasers.' Schurer shows that by 1778 the new material was known popularly as rubber, and that by 1780 a great number of the erasers were on sale in London shops.

According to Schurer, the French were ahead of the English in the theoretical field, but the only practical application anybody in France had been able to think of was for the manufacture of catheters, and even these had only been produced on an experimental scale as laboratory specimens.

The use of rubber for surgical purposes had made little progress in France as late as 1791. In that year the Scottish economist James Anderson expressed a feeling that it was deplorable that such a marvellous substance should find scarcely any other use than for effacing marks or mildly amusing children who stretched it out and observed how perfectly it again recovered its shape.

Rubber in the Nineteenth Century

Sources of Rubber in the Nineteenth Century

Progress in finding and developing new sources of rubber was much more rapid in the nineteenth century than it had been previously. Clouth (1903) stated that there were then more than 400 known rubber-bearing plants. Clouth classified the rubber-bearing plants into four main groups:

Euphorbiaceae—typified by *Hevea*, *Manihot*, *Sapium*, *Euphorbia*, etc.

Moraceae—typified by *Ficus* and *Castilla*.

Apocynaceae—typified by *Funtumia*.

Asclepiadaceae—typified by *Cryptostegia*.

During the nineteenth century, a differentiation was made between the elastic gums, *gummi elasticum* (rubber), and the plastic gums, *gummi plasticum* (gutta). Also, a fifth large family of plants, the Sapotaceae, yielding primarily gutta, was added to the classification of plants yielding rubber and allied gums (including gutta-percha, balata, and chicle).

Brazilian Rubber Production

By far the most important geographical source of rubber in the nineteenth century was the Amazonian forests of Brazil. For the Rubber Development Corporation of the United States Government, Holt (1943*a*) made an invaluable summary covering the history of rubber production in the Amazon Valley. Holt's account was in the form of a mimeographed information bulletin and is not generally available for consultation; yet it is of sufficient historical value to justify a somewhat lengthy quotation:

> The Frenchman, La Condamine, first scientist to journey down the Amazon, found Omagua indians near Iquitos using rubber bottles or syringes (seringues) made with a hollow reed fixed in the mouth through which to squirt water. That was in 1735. The Brazilian words, 'seringa' for the Hevea tree, 'seringalista' for the owner of a rubber property, and 'seringuero' for the tapper, derive from this origin.
>
> When Hancock began manufacturing unvulcanized rubber goods in England 85 years later, the Hevea rubber he imported from Para was still usually in the form of bottles.
>
> After another 30 years when Lt. Wm. L. Herndon explored the Amazon from the headwaters of the Huallaga to the delta, in 1851–52, under the direction of our Navy Department, he found: 'the most common form of the India-rubber of commerce is that of a thick bottle; though it is also frequently

made in thick sheets, by pouring the milk over a wooden mould, shaped like a spade, and when it has a coating sufficiently thick, passing a knife around three sides of it, and taking out the mould. I should think this the least troublesome form, and the most convenient for transportation.' His 'Valley of the Amazon', published as a House Document in 1854, is a classic reference.

Holt states,

Although Para rubber was used in commercial quantities in England, Continental Europe, and the United States for nearly 20 years prior to the discovery of vulcanization in 1839, a greater volume was used during that period in Brazilian production of finished goods by rubber tappers and their families. Exports of unvulcanized rubber until about 1850 consisted more of articles in the shape of shoes, bottles, small balls and toy figures, than in the form of sheets, or large balls which came later. These articles were 'smoked' in the process of manufacture from latex.

Holt shows that at the time of Herndon's visit to the Amazon, the volume of production in the Amazon had just reached 1,500 tons annually. Thereafter production increased steadily—except for a short period of speculative control during 1880 to 1883. A maximum was reached in 1914, but the output of wild *Hevea* rubber never surpassed 34,000 long tons in any year.

During the period covered by Holt, there was wide fluctuation in the price of rubber. A low of 30 cents per lb. on the New York market was registered in 1858, and highs of $1.20 per lb. in 1853 and 1854 during the American Civil War, $1.18 in 1883 due to speculative influences, and $2.92 in 1910 due to a Brazilian valorization scheme.

The price booms had the effect of increasing the production of *Castilla* rubber, motivating the expansion of African production of rubber, and pushing the production of *Hevea* rubber farther up the Amazon.

Holt noted that *Hevea* trees in the neighbourhood of Para had been continuously exploited for a century, and quite fully exploited since 1870. The upper Amazon regions had been exploited to some extent since 1880, and the Acre Territory of Brazil, and Bolivia, since 1890. Peru did not become a significant producer of Para rubber until 1900.

Holt (1943) stated that production of rubber from 'castilloa' in Ecuador and Colombia first assumed importance in the eighteen-seventies. Exploitation spread north and also south into the interior of Colombia. Meanwhile *Hevea* tapping extended up the Amazon and the two met below Iquitos around 1885. By 1890, production of rubber reached 1,000 tons of caucho from *Castilla* in Brazil. In Peru, a production of about 500 tons of caucho yearly was reached by 1900. Holt stated that caucho represented 16 per cent of the total rubber exports from the Amazon in the decade ending with 1909, and 22 per cent for the decade ending in 1919.

The Discovery of Vulcanization

The first great contribution of European civilization to the development of the uses of rubber was the discovery of vulcanization. Prior to the advent of Charles Goodyear, the technology of rubber manufacture was largely an extension of the native uses developed by ancient Indian customs in the West. The chief contribution of European culture hitherto had been the use of solvents such as turpentine, and the manufacture of raincoats by the application of the dissolved rubber to fabrics.

All articles of rubber were observed to become sticky in hot weather and brittle in cold weather; for example, crude overshoes made in the tropics and imported into commercial channels in America and Europe soon became sticky and lost their shape. The same thing happened to rubber articles fabricated in the small rubber factories of the time, while rubber-proofed garments also became sticky after being exposed to the sun.

Charles Goodyear, an American rubber manufacturer and inventor, worked on the problem of making rubber more stable and less subject to heat and cold and light. He accomplished this, after many failures, by the discovery that a mixture of rubber and sulphur can be induced to react under the influence of heat and that the resulting product was superior to raw rubber in its resistance to temperature and light. In view of the heat required to activate the reaction, this process became known as 'vulcanization', in reference to the Roman god of fire. Modern theories of vulcanization will be discussed later; but historically the process can best be understood as the stabilization of rubber by combining with it small quantities of sulphur.

As with many basic discoveries, there has been some dispute as to who was the real discoverer of vulcanization and as to how much credit is deserved by the discoverer. In the case of Charles Goodyear, the reluctance to give full credit has been particularly outstanding. Many chemists were concerned with the stabilization of rubber to avoid the changes due to light and temperature, whilst others had blended sulphur with rubber. It has been stated that vulcanization was discovered by accident, although such was true only to the degree that 'carelessly' (Goodyear's own word) overheating a mixture of rubber and sulphur on a hot stove resulted in the chemical reaction. If Goodyear had not prepared a mixture of rubber and sulphur, the accident could not have occurred; and if he had not perceived the change brought about by the application of heat, the so-called accident would have continued to be an accident, pure and simple, unnoted and unrecorded.

The Importance of the Discovery of Vulcanization

The discovery of the principle of vulcanization opened up the entire field of 'compounding', involving the mixing of raw rubber with active and inert ingredients that would affect the subsequent behaviour of the rubber. These materials, and sulphur as the active vulcanizing agent, were added to the rubber in its raw, unvulcanized state. In that condition, the rubber could be worked and manipulated to incorporate the mixing ingredients and could then be formed into useful shapes. Submission of the shaped material to controlled, elevated temperature resulted in the stabilization (vulcanization) of the mixture. Thereafter, the rubber could no longer be manipulated and its shape could be altered only by cutting or abrading.

Rubber Quality in the Nineteenth Century

As the art of compounding developed, there was a growing recognition of the differences in the rubbers from various botanical and geographical sources. Real uniformity in natural rubber has never been attained, but it was not even approached until the day of planted rubber. The nineteenth century was the time of wild rubber, and all thought of uniformity was centred on a few of the Amazonian grades. All rubbers were classified in comparison with up-river-fine, a superior type of *Hevea* rubber from the southwestern portion of the Amazon basin.

The most obvious impurities in wild rubber were stones and trash, put in deliberately by the rubber gatherers to give greater weight, and dirt and trash that got into the rubber more or less unintentionally in the processes of tapping, coagulation, storage, or shipment. A less obvious defect of rubbers was the fact that non-rubber substances associated with the rubber in the latex of the plant were incorporated with the rubber. These non-rubber constituents of the latex varied with the botanical source, and those most commonly found in the rubber were soluble in acetone and were known as resins. The resin content of native rubbers became the chief index of quality after making allowance for dirt and observable trash or added 'foreign' materials.

By the end of the century, fine-hard-Para from the upper Amazon had become the standard for comparison, because of its excellent quality. It had a resin content of only 4 to 6 per cent and, in comparison with other types of rubber, was remarkably clean and uniform. Other rubbers might have up to 25 or even 50 per cent of resins and high contents of dirt and trash. They were soft and sticky and hard to work in compounding. Many types of rubber were difficult to store because of their impurities, and tended to oxidize and flow even under the best of storage conditions.

Of the hundreds of plants used or tested as possible sources of rubber by 1900, less than a score ever produced rubber in significant quantities. Yet, at the end of the nineteenth century, no pattern of rubber production had been set and no single rubber plant had been established as the principal source of rubber.

First Interest in Planting

The nineteenth century saw the first vulcanization of rubber, the first development of specialized machinery and techniques for manufacturing rubber goods, the rise of commercial trade in rubber, and the first efforts to cultivate rubber. Even before the discovery of vulcanization, individuals throughout the world, impressed by the growing importance of the new product, were giving thought to its production on plantations.

The first plantings succeeded but were not directly motivated by the discovery of vulcanization. Plantations of *Castilla* were started in Mexico, where *C. elastica* is native. *Hevea* was planted in Brazil, and towards the end of the century *Funtumia elastica* (formerly known as *Kicksia elastica*) was planted in Africa, whilst *Ficus elastica* was planted in India. The earliest plantations of significant size were started in Brazil and Mexico. Many thousands of trees were planted; but lack of technical knowledge, together with governmental instability, caused the failure of the Brazilian plantings. The same causes, plus the rise of speculation, brought about the failure of the Mexican ventures—even those that were honestly designed to produce rubber.

Introduction of 'Hevea' into the East

The first significant contribution to rubber cultivation was made when English officials first succeeded in transporting *Hevea brasiliensis* from Brazil to the East, with an intermediate stop at Kew Gardens in England for the germination of the seed. Henry Wickham played the immediate role in gathering the seed and arranging for its transportation to Kew. Thus his name has been associated in an important manner with the event, and he was later knighted and finally granted a special pension in recognition of his services.

The frequently told story of how Wickham gathered 70,000 seeds and smuggled them out of Brazil need not be repeated here. The implication that Wickham exported the seeds in violation of Brazilian laws has been denied on the basis that there was no Brazilian law that would have prohibited the export of the seed. Such laws came into effect later, when Wickham's seeds had already been exported; and the fact that Wickham labelled the seed as valuable botanical specimens was instrumental in avoiding delays in sailing that might have proved fatal to the seed.

It is interesting to note, and important, that some of the trees from which Wickham obtained seeds are still living in the Amazonian jungle on the Tapajos river. One Brazilian native was still alive in 1957 who, as a child, assisted in the collection of the seeds. Thus the life of a single person spans the entire course of the successful rubber-planting industry up to the present. Two decades followed the importation of *Hevea* into the East before there was any significant planting of rubber. Many persons now living were associated with the first efforts to establish rubber-growing as a new plantation enterprise.

Development of Specialized Plantation Techniques

The nineteenth century saw three important contributions to the new rubber plantation industry. The first of these was that described above, the transfer of *Hevea* from the West to the East. The other two contributions were the discovery of an adequate tapping system, and the discovery of a suitable method of coagulating the latex. Both of these processes (tapping and coagulation) had been accomplished by native methods in the forests of Brazil; but although such native systems were ingenious and effective, they were not suited to use on plantations.

The Native System of Tapping in Brazil

The native method of tapping in the Amazon jungle was to use a long-handled, narrow-bladed hatchet (machadinho) to cut out small segments of bark. These cuts were made near to those of the previous day, and several incisions would be made on each tree each day, the number depending on the size of the tree. Receptacles fashioned originally from leaves or clay, and later made from ceramics or tin, were attached to the tree under the cuts, to catch the latex that oozed from them. The flow from a tree would be very small when tapping was first started, but increased on subsequent tappings.

The cuts were made through the bark into the wood of the tree and resulted in ugly wounds and the formation of large burrs, such as those shown in Plate 2(*a*). These excrescences eventually made it difficult to tap the trees, though tapping with the machadinho could be continued until the tree surface was completely covered with these burrs. Such tapping would ruin cultivated trees and force re-planting; however, in the jungle, the tapper could merely abandon the maltreated trees. To the relatively small band of tappers in the immense Amazon Basin, the jungle seemed inexhaustible: the need for conservation did not occur to them.

Ridley's Tapping System

Some 2,700 seeds from Wickham's collections are said to have germinated and been sent to the East in Wardian cases,* but the most important to the resultant seedlings were the twenty-two that were received at the Singapore Botanic Garden on 11 June 1877. Progeny of these trees later played an important part in the development of the rubber plantation industry in Malaya, and it is probable that the twenty-two trees themselves played a more important part in the development of the rubber-planting industry than any other group of trees then or since. A fortunate factor in this early importation was that H. N. Ridley became Director of Gardens and Forests in the Straits Settlements, stationed at Singapore, in 1888, after the trees had reached maturity. He was possessed of a natural curiosity that impelled him to experiment with this new tree to find the best means of making it useful.

Ridley was honoured on his hundredth birthday in 1955 for his great contributions to the rubber plantation industry. The honours were richly deserved, as progeny of his original twenty-two trees furnished a large

* Covered packing cases for transporting living plants. Designed to allow control of moisture, humidity, and ventilation.

share of the foundation for the millions of acres of planted rubber in the East. We are interested here in one of Ridley's minor accomplishments, though one that has had profound influence on rubber plantation practices. He, it was, who demonstrated that it was possible to reopen a tapping cut and gradually pare away all the bark rather then leave numerous strips and small, isolated sections of untapped bark as was the custom in Brazil. This was the first complete departure from the rubber-production techniques of the native tappers in the Amazon. It allowed rubber farmers to take greater advantage of the increased flow resulting from repeated tapping; allowed for conservation of the bark resources of the tree; permitted the development of controlled depth of tapping to avoid wounding the cambium layer; and provided a basis for tapping and retapping the same surface, thus allowing fresh, smooth bark to grow to appropriate thickness on one panel while a panel on the opposite side of the tree was being tapped (Plate 2(*b*)). Not all of this was the direct contribution of Ridley; but he (1910) demonstrated the method and made the subsequent development possible.

The Native Method of Coagulation in Brazil

The third great contribution to rubber production made in the East was the use of acetic acid to coagulate the latex. The Amazonian method of coagulating the latex at the time of Wickham's seed-gathering exploit was to drip the latex onto sticks that were then revolved slowly over smoky fires (Plate 3(*a*)). The heat and smoke served to coagulate and partially dry the rubber. This method of coagulation was effective under jungle conditions, and had the advantage that it required no materials that were not present in the jungle.

Coagulation with Acetic Acid

Coagulation of rubber by this smoking process was effective in the jungle where transportation was a problem, where permanent installations, such as coagulating sheds, were not available, and where sheeting equipment was unknown to nineteenth-century tappers. But such a process was not suitable for use on plantations. While many investigators sought to improve the smoking process for plantation use, others sought alternative methods of handling the latex. A significant development was the use of acetic acid to coagulate the latex. Formic acid has since replaced acetic acid on many plantations, but for many years acetic acid was the standard coagulant.

Summary of Rubber in the Nineteenth Century

The nineteenth century saw rubber transformed from a curiosity, used chiefly as an eraser, into an important commercial and industrial product. Annual consumption expanded from a negligible amount to thousands of tons. That century saw tremendous advancement in scientific knowledge and technical development. Its primary contributions to rubber development were: (1) the discovery of vulcanization, (2) the importation of the *Hevea* rubber tree into the East, and (3) the introduction of new methods of tapping and latex coagulation. The nineteenth century also contributed the beginnings of the automobile industry that since then has been responsible for the ever-growing demand for more and more rubber. As will be discussed later, the nineteenth century also contributed knowledge of the chemical structure of the rubber molecule. The first rubber-like material was synthesized artificially in the nineteenth century, though more than a half-century more was to elapse before such synthesis would first rival plantation production.

Rubber in the Twentieth Century

In the twentieth century, rubber suddenly assumed an expanded importance because of the development of the automobile and its need for tyres. This affected compounding techniques; caused the all-out exploitation of every known source of wild rubber and intensified search for new sources; encouraged efforts to cultivate rubber-bearing plants; and motivated chemical research into the phenomenon of elasticity and into methods of synthesizing new materials with the elasticity of natural rubber. In the two world wars of the twentieth century, rubber has been found to be a necessity to national survival. In peace, it has become essential to the enjoyment of the conveniences and amenities of modern life.

Cultivated v. *Wild Rubber*

The first half of the twentieth century saw a complete revolution in rubber production. Wild rubber, that had reigned alone at the turn of the century, was equalled by cultivated rubber in 1912. Thereafter, the production of cultivated rubber doubled and redoubled. The production of wild rubber did not stop. It failed to expand and, by standing still, lost the race to the rapidly expanding agricultural production. The low cost of the farm-produced rubber and its higher quality led first to the disappearance of the wild African rubbers from the market and then to a diminution in demand for Amazon rubber except for cable manufacture, where its use had become standard practice and there was a preference for it because of its superior extrusion qualities. At the beginning of World War II, the production of wild rubber was at a low ebb, being continued only by stranded populations with no other recourse for a cash crop, and still under the domination of 'rubber barons' who survived by exploiting the lives of disease- and debt-ridden natives.

The End of Wild Rubber

World War II marked the last effort of the wild-rubber industry. Not the least engrossing of the many tales of rubber production was the effort of the Rubber Development Corporation of the United States Government and agencies of the governments of Great Britain and France to find new sources of this strategic commodity outside of the areas overrun by the Japanese. Every wild plant of any rubber-bearing species that could be located was tested and, if possible, exploited. So skilful was the organization of the modern exploitation, that the best production of wild sources was surpassed. Never had the wild plants of *Hevea*, *Mascarenhasia*, *Manihot*, *Castilla*, *Parthenium*, *Landolphia*, *Ficus*, etc., yielded so abundantly. Cost was not the controlling factor; yet the over-all cost of all of these projects was remarkably low.

When the shooting stopped and the world again resumed some semblance of normal international relationships, it was found that wild-rubber gathering could no longer compete with plantation production. Synthetic rubber also had entered the scene to enlarge the field of competition. Some countries where the production of wild rubbers was an essential portion of the livelihood of resident populations, were forced to support the price of wild rubber as a temporary measure to give employment to the rubber gatherers. Bolivia, Peru, and particularly Brazil, were forced to subsidize the production of wild rubber even after it was possible to import Eastern rubber for much less than the production cost of the native rubber. From a monopoly position at the beginning of the century, wild rubber gathering had slipped to a negligible production by mid-century, and had been unable to hold its own even while the needs for rubber increased far beyond what could have been imagined in 1900.

The Plantation Industry

The rubber plantation industry discarded its swaddling clothes when it first equalled the wild rubber production in 1912. From that time, it grew at a rate equalled only by the giants of the industrial age. Restriction programmes by the British in the nineteen-twenties, and by international agreement of the British, Dutch, and associated independent countries in the nineteen-thirties, were adopted in order to restrain the uncontrolled expansion of planted rubber. Japanese invasion of the rubber-plantation areas of the Far East cut off even the meagre expansion allowable under the international restrictions.

The increase in the need for rubber, however, did not cease. The recent world war itself, with its immense problems of movement of men and materials, increased the need for rubber. At that time, more than a half-century of research came into fruition. Acceptable types of synthetic rubbers became available to supplement the natural product in meeting the demand.

Development of Synthetic Rubber

The spectacular and almost unbelievable development of the atom bomb during World War II overshadowed many technical developments that contributed to the survival of the allied world. The development of a successful synthetic rubber industry in war-time in the face of critical shortages of materials, measured against any other standard than the atomic bomb, would be recognized as one of the outstanding scientific and engineering accomplishments of all time. From a negligible production (in terms of tonnage) at the beginning of the war, the production of synthetic rubber was expanded to a total of 866,069 tons in 1945 and, of this total production, 87 per cent, or some 756,040 tons, was general-purpose synthetic co-polymers of butadiene and styrene, known as GR-S.

Continuing Need for Natural Rubber

The trickle of natural rubber that reached the allied nations during the war, made it necessary to make full use of the expanding production of synthetic rubber. Meanwhile, Liberia and Ceylon contributed fresh supplies of natural rubber. Wild and cultivated rubbers from the Americas and Africa made it possible to use much greater amounts of the synthetic rubbers than would have been possible without the natural product. Synthetic rubbers helped to stretch the supplies of the natural product to the maximum. Nevertheless, before the stockpile of natural rubber in the United States could be replenished from recaptured sources of supply in the East, it dipped far below the minimum level of 70,000 tons established by the Baruch Report.

Natural and Synthetic—Not Natural v. *Synthetic*

The first half of the twentieth century has seen the death of the wild rubber industry, spectacular growth of the plantation industry, and the birth of the giant synthetic-rubber industry that, in a few years, is already supplying a third of the world's needs for rubber and is nearing a half. This has resulted from a tremendous increase in the needs for rubber, improved techniques of manufacture, and increased knowledge of the structure and reactions of rubber and allied substances. As the plantation and manufacturing industries are now joined in supplying raw materials for the rubber industry, they already must make way for the fast-growing plastics industry that is using many of the same techniques of synthesis and manufacture that are used in the rubber industry.

There is bound to be a continuing competition between natural and synthetic rubber. It is inevitable that there will also be competition between rubber and plastics for borderline uses. The main effect is to provide a wide range of industrial raw materials, closely allied in processing requirements and chemical structure but with an infinite variety of industrial characteristics—hard, soft, elastic, resilient, transparent, translucent, opaque, strong, water-resistant, heat-resistant, acid-resistant, and on and on in an almost endless list of qualities to meet needs that in many cases did not even exist until these new materials were available to fill them.

III

ORIGIN

Introduction

Plantation and Factory

NEARLY all of the natural rubber that is produced in the world comes from the Para rubber tree. Only a trickle of natural rubber from other botanical sources continues to reach the market, and even the wild Para rubber from Brazil constitutes less than 1 per cent of the world's total rubber output. Today rubber is almost entirely the product of human industries—plantations in the tropical regions of the world and factories elsewhere.

The important role of factories in the production of rubber will be detailed elsewhere. Here we are concerned with plants, the living factories of nature, rather than with the artifices of man.

Sources of Natural Rubber

Though natural rubber is essentially the product of only a single species of plant, there are thousands of species that contain rubber. However, many of these contain only traces of the substance. The *Hevea*, or Para, rubber tree contains less than 1 per cent of rubber. The guayule rubber plant, *Parthenium argentatum* Gray,* has been reported to have a rubber content as high as 25 per cent of dry-weight, and the tau-saghyz of Russia, *Scorzonera tau-saghyz* Lipschitz & Bosse,* may be even richer in rubber.

Cultivated Sources of Rubber

Hevea

Hevea is a genus of South American trees belonging to the dicotyledonous family Euphorbiaceae (spurges, etc.) and native to the Amazonian drainage basin. The chief rubber tree of this genus is *Hevea brasiliensis* (Willd. ex A. Juss.) Muell.-Arg., that is now under cultivation on some 11,210,000 acres of land, of which 10,508,000 acres are concentrated in a comparatively small area within 15 degrees latitudinally and longitudinally of Singapore. There are small plantings in Tropical America and sizeable

* *See* footnote on p. 4

plantings in Africa. The acreages of *Hevea* plantation rubber in the various countries, as compiled by the International Rubber Study Group (1958), are shown in Table II.

TABLE II

ACREAGE OF PLANTED *Hevea* BY GEOGRAPHICAL AREA AND COUNTRY *

Country	Acres	Country	Acres
	Asia		
Malaya	*3,517,000*	India	207,240
Indonesia	4,429,283	British North Borneo	128,477
Ceylon	659,247	Burma	115,138
Thailand	839,600	Brunei	30,575
Viet-Nam and Cambodia	*307,937*	Philippines	8,352
Sarawak	*265,000*	Portuguese Timor	*500*
Total in Asia			*10,508,000*
	America		
Brazil	*37,125*	Other American countries	*12,875*
Total in America			*50,000*
	Africa		
Nigeria	*257,000*	French Cameroons	*21,000*
Belgian Congo	197,375	Other African countries	*13,625*
Liberia	155,000		
Total in Africa			*622,000*
	Oceania		
Papua	26,197	Other Oceanian countries	*3,803*
Total in Oceania			*30,000*
Total in World			11,210,000

* Data taken from *Rubber Statistical Bulletin*, April 1958 (*International Rubber Study Group, 1958*). Italic figures are partly estimated.

Castilla

Castilla is a genus of trees belonging to the dicotyledonous family Moraceae (mulberries, figs, etc.). The species are found in southern Mexico and Central America, on the west coast of tropical South America, and in the Amazon Valley. Reports of cultivation have been limited to *Castilla elastica* Cerv., but many plantings have consisted of other species. The large plantings made in Mexico in the early days of rubber cultivation were primarily of *C. elastica*; but early plantings in Haiti consisted of at least three species.

Ficus

Ficus is a large genus of plants belonging to the same family Moraceae and widely distributed in the tropical and subtropical portions of the world. Only one species, *Ficus elastica* Roxb., has been cultivated extensively for rubber, though rubber has been obtained from wild plants of several other species. In the early days of rubber planting, a considerable acreage of *Ficus* was planted, but in most areas it soon gave way to *Hevea*. The International Rubber Study Group (1956) reported 1,950 acres (789 hectares) of *Ficus* rubber trees in 1956 in the Mandated Territory of New Guinea.

Manihot

Manihot is a small genus of South American trees belonging to the family Euphorbiaceae. These trees are mostly native to the arid sections of Brazil, and cultivation was attempted mostly in areas that were too dry for *Hevea*. The most extensive plantings were in the former German East Africa, where some 112,000 acres were reported in 1912. The chief species was the Ceara rubber tree, *Manihot glaziovii* Muell.-Arg., but plantings were also made of *M. dichotoma* Ule, *M. heptaphylla* Ule, and *M. piauhyensis* Ule. Little difficulty was experienced in the domestication of *M. glaziovii*, but the tree was more difficult to tap than *Hevea*, and the yields were low.

Funtumia

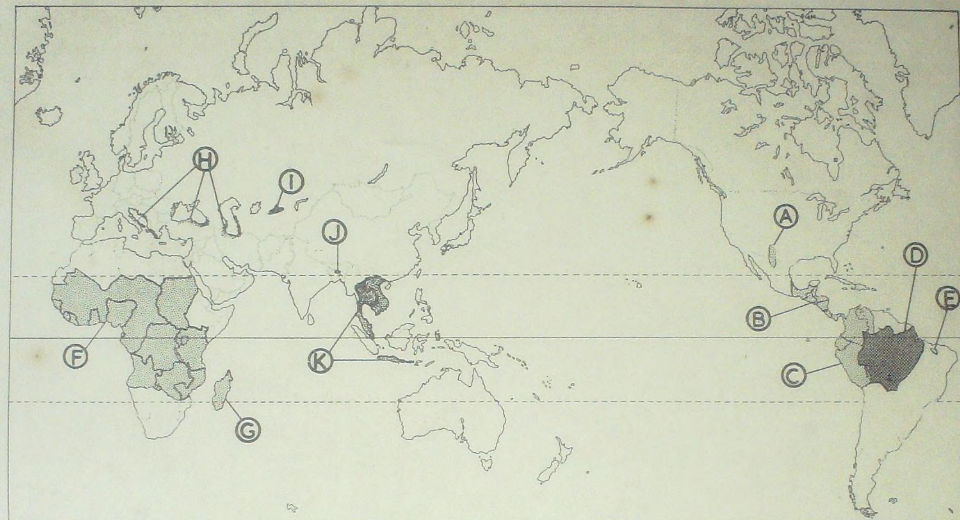
Funtumia is a genus of African trees belonging to the family Apocynaceae. *Funtumia elastica* Stapf is the only species that has been exploited as a source of rubber. *Funtumia* was planted extensively throughout the tropical portions of Africa, and some 14,000 acres were reported in 1912.

The advantages claimed for *Funtumia* were that it could survive and flourish where the climate was too dry for *Hevea*; that it was less subject to damage from insects than *Hevea*; that it needed to be tapped only once or twice a year; and that the latex could be coagulated easily by boiling. Its obvious defects were that up to twenty years were required to bring a planting into full tap, and that even then the yields of a few ounces of rubber per tree per year were too low to justify tapping except when prices were high.

Parthenium

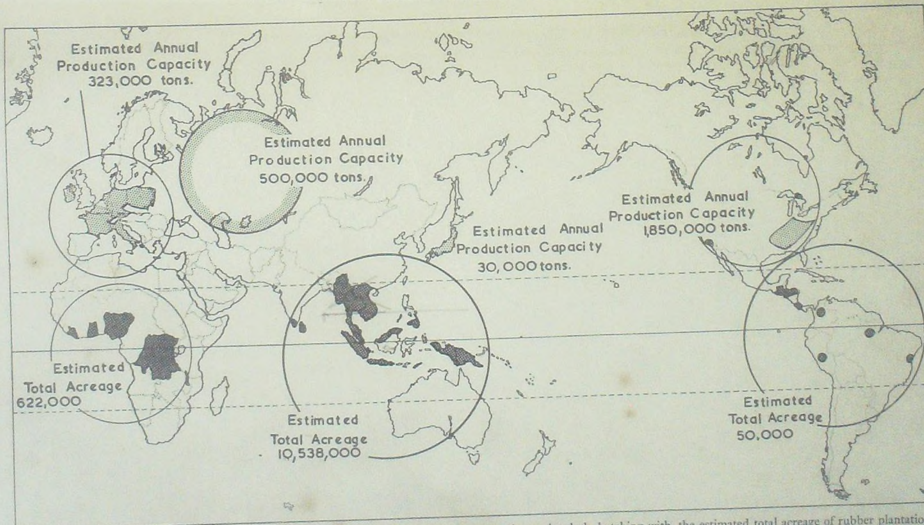
Parthenium is a genus of herbaceous and woody plants belonging to the family Compositae (daisies, dandelions, sunflowers, etc.). Members of the genus are found widely distributed in North America and the West Indies. The only important species from the standpoint of rubber production is guayule, *Parthenium argentatum* Gray, a desert shrub native to parts of northern Mexico and southern Texas.

Guayule was planted by the Intercontinental Rubber Company in Mexico in the early part of the present century, but revolution forced the transfer of the plantings to the United States. By 1931, a total of some 8,000 acres of guayule, which was harvested for rubber but not replanted because of the prevailing low prices of rubber, had been planted. During World War II, the United States planted 32,000 acres of guayule. After



Native habitat of plants that have been exploited for rubber. A, Parthenium; B, Castilla; C, Castilla and Sapium; D, Hevea, Castilla, and Sapium; E, Manihot; F, Apocynaceous climbers, shrubs, and trees; G, Cryptostegia; H, Taraxacum; I, Taraxacum and Scorzonera; J, Ficus; K, Apocynaceous climbers and trees.

FIG. 1.—World map showing native areas of main rubber-producing plants.



Rubber-producing areas of the world. Localities that produce natural rubber are shown in dark hatching with the estimated total acreage of rubber plantations shown for each indicated area. Localities where synthetic rubber is produced are shown in light stippling with the estimated annual production capacity in tons shown for each indicated area. The invaluable assistance of Mr. S. E. Overley of the United States Department of Commerce in assembling the data on rubber production capacity is gratefully acknowledged.

FIG. 2.—World map showing main areas of natural and synthetic rubber production in the nineteen-fifties.

the war, cheaper rubber became available and the guayule was ploughed up without harvesting the rubber. Research on guayule cultivation has been discontinued in the United States, but field plantings are being made in Spain and Turkey.

Russian Rubber-Bearing Root Crops

The Russian rubber-bearing dandelions, kok-saghyz (*Taraxacum kok-saghyz* Rodin) and krim-saghyz (*T. megalorhizon* Hand.-Mzt.), and the Russian rubber-bearing salsify, tau-saghyz (*Scorzonera tau-saghyz* Lipschitz & Bosse), are all members of the same family Compositae. They were supposedly planted on a large scale in Russia before and during World War II. However, no reliable information is available as to the acreages planted or the rubber produced. After the outbreak of war, the Government of the U.S.S.R. furnished the United States with several thousands of pounds of seed of kok-saghyz, and with experimental quantities of seed of krim- and tau-saghyz. Plantings were made in forty-one of the then forty-eight states of the United States, and commercial-size plantings were made in a few selected areas. The plantings were discontinued at the end of the war.

Rubber-Bearing Plants Native to Africa

The forests of Africa are rich in rubber-bearing trees, climbers, and shrubs. Many of the rubber-bearing climbers that grow in the humid forests as true lianes, climbing to the tops of even the tallest trees, become shrubby climbers in the open forests and mere shrubs in the savanna grasslands. The most important rubber-bearing tree here is *Funtumia elastica* Stapf, and the Landolphias are the most important rubber-bearing climbers. Whitford & Anthony (1926) reported on rubber production in Africa.

Funtumia

Funtumia elastica Stapf (Plate 3(*b*)) belongs to the family Apocynaceae. It is native to portions of the Congo, the Cameroons, Ghana, the Ivory Coast, Liberia, Nigeria, Sierra Leone, and Uganda. A second species of *Funtumia*, *F. latifolia* Stapf, occurs in the forests of Uganda but is not an important source of rubber. The *Funtumia* trees were tapped usually by a double herringbone system consisting of a central vertical channel with lateral oblique channels draining from both sides into the main channel. Tapping cuts were continued high up the tree, often to 50 feet above the ground. In Sierra Leone, the custom was to fell the tree and ring it at frequent intervals to get the maximum amount of rubber possible. A rolling pricker was often used to increase the depth of the tapping cuts and so increase the flow of latex.

Several methods of coagulating the latex were used by the native gatherers of wild *Funtumia* rubber. In the Gold Coast (now Ghana), a shallow, oblong trench was dug in the ground and lined with moist clay to make it partially waterproof. The latex was poured into this trench and allowed to coagulate naturally. After coagulation, the rubber was taken from the trench and allowed to dry. It contained a high percentage of serum, and on fermentation developed offensive odours. Some natives added latex from other plants to the *Funtumia* latex, to increase their yield without regard to quality.

The juice of limes and other fruits were also used as coagulants in the Gold Coast, and tannic acid or mercuric chloride were so used in Uganda. In the Congo, the latex was diluted and left to coagulate naturally, and when the rubber rose to the surface, it was skimmed off, washed, drained, and kneaded until dry. In Sierra Leone, the coagulation was brought about by heating the latex in a pot, after which the freshly coagulated rubber was placed between leaves and stamped with the feet into rough sheets. These sheets were cut into strips and hung to dry in the native huts, where they also got the advantage of the wood fires. Government encouragement was offered to the natives in the Gold Coast to keep the latex pure, to strain it, and to obtain coagulation by boiling.

Mascarenhasia

The genus *Mascarenhasia* also belongs to the family Apocynaceae. *Mascarenhasia elastica* K.Schum. is a rubber-bearing tree native to Kenya, Madagascar, and Mozambique. In Kenya, it is known as the 'mgoa' rubber tree and is found in the forests of Shimba Hills. It is not abundant but the rubber is of good quality. In Mozambique, *M. elastica* was said to be the source of about half of all the rubber produced north of the Zambesi river.

Several species of *Mascarenhasia* were exploited for rubber in Madagascar. *M. arborescens* A.DC. was reported as the source of most of the rubber from the west coast. It was known under the native names of 'barabanja', 'guidora', or 'guidorandano'. The India Rubber Journal (1904) stated that in Madagascar the black rubber came from Mascarenhasias, the pink rubber from Landolphias, and the white rubber from *Euphorbia intisy*. Particular mention is made of three Mascarenhasias, *M. lisianthifolia* A.DC., growing in dry soil, *M. anceps* Boiv., growing in damp soil, and *M. longifolia* Jum., inhabiting wet soil.

The latex of the Mascarenhasias was coagulated with a decoction of tamarind, the latex being poured into the extract to ensure complete coagulation. A 3 per cent solution of sulphuric acid was said to be capable of coagulating ten times its volume of latex.

Jumelle & Perrier (1918) list *Mascarenhasia angustifolia* A.DC., *M. arborescens* A.DC., and *M. lanceolata* A.DC., as occurring north of Vohemar in Madagascar. They reported that *M. velutina* Jum. was the source of most of the rubber collected in the eastern portions of

Madagascar, where it was known as 'guidroa', and described 'guidroa' as a small tree 5 to 6 yd. high with a trunk 6 to 8 in. in diameter. After tapping, the latex coagulated on the tree and the rubber was stripped off and wound into balls. The rubber was of good quality.

Costatin & Poisson (1907) reported on the collection of rubber from 'kokomba' (*M. geayi* Costatin) and 'kidroa' (*M. kidroa* Costatin). The rubber was obtained from the roots, which were gathered and exposed to the sun to coagulate the latex. The roots were next beaten with a piece of hard wood to separate the bark which contained the rubber, and the bark was then pounded to a mass and afterwards boiled in water to eliminate the free bark. The boiling and beating were repeated once or twice, and the strands of extracted rubber were then made up into balls.

Ficus

The genus *Ficus* belongs to the family Moraceae. *Ficus vogelii* Miq. was the chief source of *Ficus* rubber in Africa. Other species were exploited but the product from them was inferior. The low-quality rubber from *F. vogelii* was known as 'kobo' in Gambia and 'memluka' in Ghana. That from Nigeria was shipped as 'balata', and that from Togoland was known as 'sayi' or 'Togo lump'. According to Agronomie Tropicale (1912), *F. platyphylla* Delile was the source of a hard, resinous material resembling gutta that was known as 'red kano' and came from the Kano district of the Northern Provinces of Nigeria.

Landolphia

The Landolphias, chiefly vines and climbing shrubs, belong to the family Apocynaceae and were important sources of rubber in all parts of tropical Africa. The methods of obtaining the rubber and coagulating the latex varied greatly, as did the quality of the rubber. Thus some of the *Landolphia* rubbers were well prepared and clean, whereas others were dirty and contaminated. That from French Guinea, in particular, was reported by Whitford & Anthony (1926) to be poorly prepared and adulterated by the addition of extraneous substances such as inferior gums, oranges, stones, and water, which were secreted in the balls during preparation for the market. Because of the resulting notoriety, the rubber from French Guinea became almost unsaleable when prices were down.

More than twenty species of *Landolphia* were exploited in Africa and Madagascar in the hey-day of wild rubber. Some produced root rubber that entailed digging the plant and using both roots and stems for extraction of rubber by maceration rather than by bleeding.

Landolphia owariensis Beauv. is the most widespread of the Landolphias and, next to *Funtumia elastica*, was the most important rubber-bearing plant of Africa. It occurs in Angola, the Congo, Dahomey, Ghana, the Ivory Coast, Liberia, Nigeria, Northern Rhodesia, Sierra Leone, Southern Rhodesia, and Togoland. It was the chief rubber-bearing climber in all of these areas except in the Congo where it was exceeded by *L. kirkii* Dyer and in the Ivory Coast where it was equalled by *L. heudelotii* A.DC.

Landolphia kirkii was the foremost rubber-producing climber of Angola, the Congo, Kenya, Mozambique, and Nyasaland. *L. heudelotii*, in addition to ranking with *L. owariensis* in the Ivory Coast, was the foremost rubber vine in Gambia, Senegal, Upper Senegal, and Niger. *L. perrieri* Jum. was the foremost *Landolphia* in Madagascar. *L. stolzii* Busse and *L. dondeensis* Busse were important for rubber production in Tanganyika, as was *L. dawei* Stapf in Uganda. *L. klainii* Pierre was the foremost source of 'vine' rubber in the Cameroons and was a supplemental source in the Congo, Ghana, and Mozambique. *L. thollonii* Dew. and *L. parvifolia* K. Schum. were important sources of root rubber in Nyasaland, and the former was also a source of root rubber in Angola and the Congo. *L. florida* Benth. was widespread, but the rubber obtained from it was of poor quality. However, Chevalier (1906) held that this climber was identical with *L. dawei*, which is an important source of good rubber in Uganda.

The species of *Landolphia* mentioned above are the source of the major portion of the vine rubber produced in Africa. Moyle (1942) listed a total of fifty-one species of *Landolphia* that have been described as sources of rubber.

Rubber was obtained from the *Landolphia* plants by several means. In the rainy season, or in moist locations, the climbers could be tapped by slashing them at random without any particular tapping pattern. The latex flowed out and was caught in suitable receptacles and coagulated by means of acids or fruit juices. In dry weather, or in the more arid locations, the latex coagulated too quickly to run off into a receptacle. In such circumstances, the latex was allowed to dry on the vine and then was stripped off and wound into balls. In some areas, where the latex was not too fluid, a small quantity of it was smeared on the arms or body of the tapper. As soon as it was dry, it was stripped off and rolled into a ball, which was then used as a nucleus for collecting more rubber from the climber. For such collection the ball was held against the gummy latex in the cut and, by using a circular motion, was used to collect the latex into a larger and larger ball. Both the roots and stems were used to produce the so-called root rubber. The plant was cut down and the roots were dug up. Stem and roots were then cut into small pieces, which were later soaked in water for several weeks. The bark was subsequently removed by pounding, and the rubber was separated from the bark by alternate pounding and washing. Finally, the strands of rubber so obtained were rolled into balls.

Hamet & Josse (1912) made a study of the latex of various species of *Landolphia* occurring in Madagascar and made comparisons with that of *Cryptostegia madagascariensis* Boj. and *Marsdenia verrucosa* Decne. They found, in the latex of *Landolphia madagascariensis* K.Schum., from

6 to 25 per cent of rubber, based on the wet-weight of the latex, in that of *L. perrieri* Jum. from 4 to 17 per cent of rubber, and in that of *L. sphaerocarpa* Jum. from 18 to 26 per cent of rubber. The latex of *Cryptostegia madagascariensis* contained 15 to 20 per cent of rubber, while that of *Marsdenia verrucosa* contained from 10 to 12 per cent of rubber.

Hamet (1900) also made a study of the latex of *Landolphia heudelotii* A.DC. in the Sudan. This plant was known as 'gohine' and was the only important source of rubber growing in the Sudan. Its latex was white or faintly pink. The rubber obtained by coagulating the latex had a specific gravity of 0·92 to 0·93. Sodium fluoride was used to separate the rubber from the serum as completely as possible and so to prevent further fermentation. The 'gohine' flourished in the most arid parts of the Sudan and an adult plant yielded from 10 to 12 litres of 'milk' annually, amounting to an annual yield of from 6 to 7 lb. of rubber.

A sample of the rubber obtained from *Landolphia ugandensis* Stapf in Uganda, studied at the Imperial Institute (1905*a*), was somewhat soft but exhibited good elasticity and tenacity and was free from stickiness. It contained: rubber, 78·3 per cent; resin, 9·1 per cent; moisture, 6·2 per cent; dirt and insoluble matter, 6·4 per cent; and ash (included in dirt), 2·4 per cent.

Clitandra

Several species of *Clitandra*, belonging to the family Apocynaceae, have been exploited for rubber in the Congo (where the product was known as Kasai black), in Sierra Leone (where the local species is known as 'jawe'), and in Angola, the Ivory Coast, Liberia, Nigeria, Southern Rhodesia, and Uganda. Moyle (1942) listed nine species of *Clitandra* that have been reported as sources of rubber.

The more important species are *Clitandra elastica* A. Chevalier, *C. orientalis* K.Schum., and *C. arnoldiana* Wildem. The latex of these climbers is obtained by making incisions a few inches apart all over the stem, and is usually collected in a cup formed from a banana leaf. The latex is transferred to an earthenware container and, at the end of the day, is coagulated by immersing the container in boiling water. Siedler (1914) reported that a sample of latex obtained from *C. elastica* in Togoland was excellent for the manufacture of rubber articles. It contained 1·95 per cent of moisture, 11·59 per cent of resins, and 1·46 per cent of ash.

Carpodinus

Carpodinus also belongs to the family Apocynaceae. The rubber-bearing plants of *Carpodinus* in Africa are 'vines' or shrubby climbers. *Carpodinus chylorrhiza* K.Schum. is widely distributed. *C. gracilis* Stapf is somewhat more restricted. In Angola, *Carpodinus* has much the same range as *Landolphia*. The rainfall in the natural range of *C. chylorrhiza* and *C. gracilis* is said to average 35 in. per year, spread over about seven months. Temperatures range from 26°F. to 97°F., and the altitude ranges from 3,900 to 4,900 ft.

In Angola and the Congo, where the genus is represented by two species, *C. gentillii* Wildem. and *C. ligustrifolia* Stapf, the rubber marketed is mainly root rubber, which is obtained by pulling up the rhizomes and exposing them to the sun for some time to coagulate the latex. They are then cut up and beaten with wooden mallets to remove the bark that contains the rubber, and the bark is then alternately pounded and washed until only strands of rubber are left.

Carpodinus hirsuta Hua. is a common climber, found in the dry zone of Nigeria and along the Niger River, with an inferior latex that is coagulated into a flake rubber by boiling. It was shipped as a sticky mass with the consistency of dough. Both *C. hirsuta* and *C. fulva* Pierre are found in Northern and Southern Rhodesia. Moyle (1942) also lists *C. lanceolata* K.Schum., *C. landolphiodes* Stapf, and *C. uniflorous* Stapf as being sources of rubber in Africa.

Cryptostegia

Cryptostegia belongs to the family Asclepiadaceae. Excellent rubber has been produced from wild plants of *Cryptostegia grandiflora* R.Br. and *C. madagascariensis* Boj. in Madagascar.

Marsdenia

Marsdenia also belongs to the family Asclepiadaceae. *Marsdenia verrucosa* Decne., a native of Madagascar, is a large climber with a large, rough fruit (somewhat resembling a cucumber) that yields latex profusely when cut or injured. The rubber is of good quality.

Euphorbia

Euphorbia is a large genus belonging to the family Euphorbiaceae. The Euphorbias are scattered over most of the earth and range from small creeping plants and annual weeds to large trees, and include shrubby plants as well as succulents, some of which resemble large cacti. Some forty-four species have been listed as sources of rubber. An attempt was made to produce rubber commercially in West Africa from *Euphorbia tirucalli* L., the idea being to bleed the trees and then separate the rubber from the predominating resins. The latter were to be sold for use in the paint and varnish industry. The project was not successful.

Audy (1942), Compagnon & Ziller (1942), Le Bras (1942), and Colombat & Compagnon (1943), made detailed field studies of the possibility of exploiting *E. resinifera* Berg., and Le Bras (1943) and Compagnon (1948) made similar studies of *E. balsamifera* Ait. These cactus-like Euphorbias occur in dense stands and yield large quantities of latex. The latex contained less than 20 per cent of rubber but deresination gave rubber of good quality.

Three Euphorbias have been reported as sources of rubber in Madagascar. The most important of these was *E. intisy* Drake. This is a shrub or small tree that produces rubber both in its stems and in swollen underground tubers that Swingle (1930) described as specialized organs for the storage of water. The rubber from *E. intisy* is of high quality and is the best produced by any species of *Euphorbia*. After the discovery of *E. intisy* in 1891, the annual exportation of rubber from Madagascar rose from less than 50,000 lb. to almost a million lb. The wild stands of *E. intisy* in Madagascar were greatly depleted by ruthless exploitation, and even before it had been studied and given a botanical name the shrub was hard to find in areas where it had previously been abundant.

Euphorbia elastica Jum. and *E. pirahazo* Jum., which are trees 65 to 85 ft. high found in restricted districts of north-west Madagascar at the foot of the plateau regions, have been reported as sources of rubber of good average quality. Scassellati-Sforzolini (1915) reported a number of Euphorbias as of industrial importance in Somaliland. Among these he listed *E. tirucalli* L. and *E. cuneata* Vahl. Rebuffat (1907) reported that *E. candelabra* (*E. candelabrum* Tremont) grows abundantly in Eritrea, and that the latex contains 50 per cent of dry rubber, based on the weight of the latex.

Raphionacme

Raphionacme utilis N.E.Br. & Stapf is the only rubber-producing species out of the twenty or more comprising this genus which belongs to the family Asclepiadaceae. *R. utilis* was known in Angola as 'bitinga', and the rubber from it was generally known as 'ecanda'. The plant was exploited as a source of rubber in Angola and was also tested under cultivation. No particular difficulty was experienced in domesticating the plant, but the growth was slow and the yield disappointing. The rubber of *R. utilis* is produced from the root, which resembles a yam in colour and is of the shape and general size of a turnip. It gives a good yield of latex with a fair quality of rubber. The plant is not common and the total amount of rubber obtained from this source was not great.

Rubber-Bearing Plants Native to Asia

The tropical portions of south-east Asia are rich in rubber-bearing plants, most of which are members of the family Apocynaceae. A great number are climbers, and several have been reported as having rubber of from good to excellent quality. *Ficus elastica* Roxb. has been the foremost contribution of tropical Asia to the known rubber-yielding plants: there are also some twenty-seven other species of *Ficus* that have been exploited for rubber. The arid, subtropical, and temperate zones of Asia also have rubber-bearing plants, the chief of which are the Russian root crops belonging to the Compositae.

Photograph by permission of ARS, U.S. Dept. Agric.

Crude Ceara rubber from Brazil.

PLATE 4

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Coagulating the latex of *Hancornia speciosa* by heating.

(*b*) Crude 'mangabeira' rubber.

PLATE 5

Ficus

Ficus belongs to the family Moraceae and some twenty-eight species have been reported as sources of rubber in Asia. *Ficus elastica* Roxb. was one of the first of the plants of tropical Asia to be exploited for rubber. The earliest plantings in the East were of this tree, and it was also planted elsewhere in the tropics. It is now more popular as an ornamental in Mediterranean areas and suitable parts of the United States and tropical America than as a source of rubber. The names for *F. elastica* were 'rambong' (or 'ramboeng') and 'Assam', the latter for the Indian province from which the species was originally described. These names were also applied to the rubber, that was also known as India rubber (or India-rubber), which became the 'generic' name for all rubber in the nineteenth century.

Heyne (1927) lists *Ficus alba* Reinw. as a tree that has been tapped for latex in Indonesia. The rubber content of the latex is low, however, and the gum finds use in the differential dyeing of fabrics in the batik industry rather than as a rubber.

Dussert (1910) reported that *Ficus albinervia* Miq. on Réunion Island was a promising source of rubber. It was not exacting as to soil, and yielded a latex with from 40 to 45 per cent of excellent rubber. He reported annual yields of about 1 kilogram of rubber per tree, and stated that the tree could be tapped at the age of eight to ten years. Maranon & Carato (1932) made a study of twenty-four species of *Ficus* in the Philippine Islands and found rubber in *Ficus calophylloides* Elm., *F. elastica* Roxb., and *F. minahassae* Miq. Gummi-Zeitung (1903) reported rubber as having been produced in New Caledonia from a tree thought to be *F. prolixa* Forst. Many seeds of it were shipped to the Berlin Botanic Garden where a large number of plants were grown and shipped to Togoland for cultivation. A sample of Papua rubber from *F. rigo* F. M. Bailey was examined at the Imperial Institute (1912) and reported to be good. The washed rubber (3·6 per cent was lost in washing) contained: resin, 4·9 per cent; protein, 3·1 per cent; ash, 0·9 per cent; and rubber, 91·1 per cent. The rubber varied from light to dark brown and was tacky. Sengoku & Ikeda (1940) reported that the rubber from *F. retusa* L. was promising.

Bleekrodea

Bleekrodea tonkinensis Dub. & Eber. is a member of the family Moraceae and was discovered around 1907 in Tonkin, where it is known as 'teo-nong', and in North Annam. It is a large, rapidly growing tree 12 to 20 metres high with whitish bark, highly ramified branching, and soft white wood. Its roots are characterized by the presence of swollen nodules that serve as water reserves, allowing the tree to resist long periods of drought. The latex has a yellowish tint described as 'café-au-lait', and contains up to 42 per cent of rubber. Spontaneous coagulation is rapid and gives a brown-grey rubber. A 1 per cent solution of sulphuric acid coagulates about six times its own volume of latex. The latex must be stirred during the addition of the acid, to avoid local coagulation. Such rubber coagulated with sulphuric acid has excellent quality; on the other hand, acetic acid hinders the cohesion of the particles of rubber and the coagulum lacks homogeneity. Hydrochloric acid gives a rubber with less elasticity than that produced either by spontaneous coagulation or by the use of sulphuric acid.

Bleekrodea tonkinensis is found in comparatively heavy stands in Tonkin, North Annam, and Upper Laos. The most important areas for exploitation in Tonkin were reported to be in the Province of Bac-Kan (at Kai-Kinh and in the region of That-Khe) and in the Province of Ninh-Binh. Control measures were urged to avoid the prompt destruction of these native stands by over-tapping.

This species is very hardy. It prefers calcareous soils, and its best growth and richest stands in nature are found on slopes where the run-off is rapid and where there is never standing water. Dubard & Eberhardt (1907) reported that *B. tonkinensis* was a large tree that was found in dense stands in some of the Provinces of Tonkin, and that it produced a high percentage of rubber that could not be distinguished commercially from the better sorts of Para rubber. Eberhardt (1907) made a study of this rubber and reported its pure rubber content to be 67·6 per cent. He stated his belief that the species might become very important under modern methods of exploitation.

Apocynaceous Climbers

The forests of what was formerly Indo-China are rich in rubber-bearing climbers. Prior to 1890, only small quantities of rubber were collected from these wild 'vines', and all were marketed through Thailand or Singapore. Beginning in 1890, the collection of rubber was organized by the formation of exploitation companies and associations. Botanical explorations were made to identify and classify the wild climbers, almost all of which were found to belong to the family Apocynaceae, numerous genera being represented.

Paris (1911), Cayla (1914), Carton (1924), and Crevost (1926) reported on the various rubber-bearing species of Indo-China, and the more important of the genera were: *Aganomerion*, *Aganosma*, *Amalocalyx*, *Bousigonia*, *Chonemorpha*, *Ecdysanthera*, *Ervatamia*, *Holarrhena*, *Ichnocarpus*, *Kopsia*, *Melodinus*, *Micrechites*, *Nouetta*, *Parabarium*, *Parameria*, *Pottsia*, *Rhynchodia*, *Vallaris*, and *Xylinabaria*.

In addition to the reports of these climbers in Indo-China, several species were reported from elsewhere in tropical Asia. *Chonemorpha macrophylla* G.Don was reported by the Imperial Institute (1905) as the source of an inferior rubber from Burma. The *Chonemorpha* rubber was reported to be rather sticky but of good elasticity and tenacity. The specimen examined was too small for commercial evaluation but the analytical results, indicating a rubber of inferior quality, were reported as: moisture, 8·0 per cent; caoutchouc, 55·2 per cent; resin, 34·6 per cent; dirt, 2·2 per cent; and ash (included in dirt), 0·97 per cent. The same report included rubber from *Rhynchodia wallichii* Hook. coming from Burma. This rubber was reported to be quite free from stickiness, with good elasticity and tenacity. The analysis showed: moisture, 2·8 per cent; caoutchouc, 86·5 per cent; resin, 6·5 per cent; dirt, 4·2 per cent; and ash (included in dirt), 0·48 per cent.

Carton (1924) stated that, of all the species studied or listed by him, *Ecdysanthera rosea* Hook. & Arn. is the most widespread in Indochina, being found at all altitudes from the valley lowlands to the high mountain slopes. After it, species of *Parabarium* are most abundant and have the widest distribution. *Parameria glandulifera* Benth. grows well in the wet, humid lowlands and is the best rubber plant of the level forests of Cambodia. The various species of *Xylinabaria* are distributed throughout all of Indo-China. The highest producer is *Xylinabaria raynaudi* Jum., which is common in Tonkin. The number of climbers encountered in the forests varies widely, but stands with as many as 250 individuals per hectare have been reported. Cultivation tests were considered early in the twentieth century, and Vernet (1904) stated (transl.): 'We have in Indo-China at least two species rich in latex of good quality that have been suggested for some time as suitable for cultivation: *Parameria glandulifera* of Cochin China and Cambodia and *Xylinabaria raynaudi* of Tonkin.'

When the price of rubber was high, in 1899 and 1900, the collection of latex from the rubber-bearing vines of Indo-China was continued throughout the year. But, in general, collection was made only during the dry season when agricultural work decreased, when the forest was less infested with mosquitoes and leeches, and when the conditions of heat, humidity, and absence of rain were favourable for collection and for the spontaneous coagulation of the latex. The methods of tapping were very crude, and they varied from place to place; one was to make numerous incisions in the standing climbers. The tapping was done by preference in the morning—when the latex was most liquid and before the sun was high enough to induce spontaneous coagulation of the latex. After clearing around the 'vine', the natives made incisions along it, up to as high as they could climb. The latex was caught in horn-like cups made of leaves, in sections of bamboo, or in leaves on the ground, being then carried back to camp in a length of bamboo and coagulated over a wood fire. The rubber that coagulated on the climber was collected in the form of small pellets.

A second method, practiced only by certain natives of Cammon, was to cut off a large piece of bark from a climber. As the latex oozed out, it was collected with the finger and transferred to a bamboo tube. A third method, followed by the Annamites of Hatinh and of the coastal range, was to cut down the climbers and collect latex from their entire length.

The rubber obtained by spontaneous coagulation was considered to be the best, as it was dry, flesh-coloured, and showed little loss on further drying or when cut. It was marketed in the form of small balls 6 to 8 cm. in diameter, in small bobbins of corresponding size, or in flat blocks 18 to 25 cm. in diameter and 2 to 8 cm. thick.

The rubber obtained by coagulation of the latex was marketed in three forms. The first and poorest was that coagulated in a kettle. It was in the form of a cake 25 to 30 cm. in diameter and about 6 or 8 cm. thick. It turned brown immediately and blackened rapidly in the air. The exterior surface of this cake was fairly smooth; but, when it was cut, a great number of cavities filled with water could be seen. The second form was that obtained by coagulating the latex in a short length of bamboo. It had a diameter of 6 to 10 cm., a dense consistency, a brown colour, and less tendency to become sticky than that made as a cake. It was in the form of a cylinder and was known to rubber dealers in Indo-China as rubber pudding. The final method was similar to the latter except that the bamboos used were smaller, with diameters of only 3 to 4 cm. In this case, the bamboo had to be cut to obtain the rubber. When freshly removed from the bamboo, the rubber had a brownish surface colour, the inside being flesh-coloured and without impurities or vacuoles. The rubber was elastic and showed good response to physical manipulation.

In addition to the species of rubber-bearing plants that have been reported from Indo-China, two important genera from elsewhere in tropical Asia are *Willughbeia* and *Urceola*.

Willughbeia. Heyne (1927) describes *Willughbeia firma* Bl. as a climber with a stem up to 10 cm. in diameter and distributed throughout Malaya. Tapping the stems gives a rapid flow of latex that coagulates easily and can be collected after one day. This is the only way that cultivated plants can be handled, whereas wild plants are torn from the supporting trees and laid on the ground, the stem being then ringed at intervals of 30 to 40 cm. and the latex collected. Coagulation is by heat or by the addition of a solution of table salt, or both. A fourteen-year-old vine yielded 2 kg. of rubber, and plants about six years of age yielded up to 100 gm. of rubber each. The rubber was known as 'getah soesoe' in Singapore; elsewhere, it was known usually as Borneo rubber. It was shipped in round or pear-like shapes, occasionally as more or less flat cakes, and sometimes in big blocks. In the pure state, it had a light or dark grey appearance and was elastic. One sample from a twelve-year-old plant had a resin content of 13·18 per cent.

Moyle (1942) lists *Willughbeia apiculata* Miq. (Sumatra, Borneo), *W. ceylanica* Thw. (Ceylon), *W. coriacea* Wall. (Malaya), *W. flavescens* Dyer (Singapore), and *W. javanica* Blume (Java). Dunstan *et al.* (1903) mention *W. edulis* Roxb. (Burma, Assam, Malaya). Romburgh (1900) listed *W. firma* Bl. and *W. tenuiflora* Dyer (East Indies).

Urceola

Urceola elastica Roxb. was found late in the eighteenth century on the Island of Penang by James Howison and described by the famous botanist William Roxburgh who at that time was Keeper of the Calcutta Botanical Garden. Several other species of *Urceola* have been described since, including, as rubber-bearing plants, principally *U. brachysepala* Hook., *U. esculenta* Benth. & Hook., *U. javanica* Boerl., and *U. maingayi* Hook. Romburgh (1900) states that species of *Urceola* produced rubber of good quality but in small amounts. He reported *U. brachysepala* as growing in eight or nine years to a height of 13 metres, with a girth of 30 cm. From two average plants, he obtained 50 gm. of rubber. *U. javanica*, he said, was characterized by its large horn-shaped fruits that are so heavy that they sometimes break down the supporting tree on which the climber is growing. A report by the Imperial Institute (1903) on the rubber from *Urceola* gave the following analysis: moisture, 6·9 per cent; resin, 7·0 per cent; rubber, 76·2 per cent; and dirt, 9·9 per cent. The rubber showed good elasticity and tenacity and was valued as equal to the rubber obtained from climbers in Tonkin.

Apocynaceous Trees

The most important of the Asian rubber-bearing trees of the Apocynaceae belong to the two closely related genera, *Alstonia* and *Dyera*. These trees furnish a low-grade rubber that is marketed generally as 'jelutong'. This material requires deresination for use in rubber compounding, but has found some use in the manufacture of chewing gum for which its high resin content is not a disadvantage. It has a consistency comparable with that of chicle, and has the additional advantage that its rubber-content makes it valuable in the manufacture of bubble gums that require the admixture of small proportions of rubber to provide extensibility.

Alstonia scholaris R.Br. is a very tall, thick tree. It is said to be the largest of the Javanese trees belonging to the Apocynaceae, and is usually 20 to 25 metres high and 40 to 60 cm. in diameter. It is common throughout the Malayan Archipelago and in Java below an elevation of about 900 metres. Heyne (1927) states that *A. pneumatophora* Backer and *A. polyphylla* Miq. are also sources of gums sold as 'jelutong'. Moyle (1942) lists *A. angustifolia* Wall. (Malaya), *A. duerckheimiana* Schlecter (New Caledonia), and *A. plumosa* Labill. (New Caledonia) as sources of rubber.

Dyera costulata Hook. f., *D. laxiflora* Hook. f., and *D. lowii* Hook. f., have all been reported as sources of 'jelutong'. The Dyeras are large, spreading trees. One described by Romburgh (1899) had a girth of 7·5 metres and an estimated height of over 45 metres. Wechel (1911) stated that, with the largest trees, it might be as much as 30 to 50 metres to the first main branch.

According to Wechel, a tapper taps some fifty trees a day and so arranges his total number of trees under tap that he can return to the first group on the eighth day. He starts tapping at a height of about a metre-and-a-half from the ground. He first makes four, five, or six cuts of about a hand's-width each—through the bark into the wood of the tree. At each subsequent tapping, each wound is increased by about three fingers' width, the increase being alternately to the left and then to the right of the old cut. The cut is abandoned when it approaches the margin of the next cut, and new cuts are opened higher and higher on the tree.

The first latex that emerges is watery, but after some five minutes a thick milk begins to ooze out. After finishing with the tapping of the fifty trees, the tapper returns along the same route and uses a wooden spatula to scrape the thick mass from the tap-wounds into a wooden or tin vessel. The collected latex is poured into a vessel made of bark, and three parts of water to 1 part ($\frac{1}{8}$ litre) of petroleum are added. In some areas, alum is used to replace the petroleum. The next morning, the coagulum is separated from the serum and washed in warm water.

'Jelutong', also known as 'pontianak' (formerly 'dead Borneo'), has a high resin content which Eaton & Dennett (1923) reported as from 75·9 to 80·9 per cent in samples examined by them. They reported the rubber-content to be 19·1 to 24·1 per cent, while the ash-content of all of the samples they tested was low. They examined a sample of 'jelutong' latex which they described as resembling *Hevea* latex, and which could be coagulated by acetic acid or alum and also anaerobically by placing it in sealed bottles. Anaerobic coagulation yields a coagulum that has no unpleasant odour, even after standing for several days, which indicates a low content of organic nitrogenous matter. The total solids in 100 cc. of latex amounted to 18·2 per cent and contained 79 per cent of resins.

Russian Rubber-bearing Plants

It is expedient to treat all of the Russian rubber-bearing plants as a group rather than to try to separate them into Asiatic and European species, for several are found both in Asia and Europe. Moreover, species of krim-saghyz are found widely distributed in the Mediterranean region, while some of the genera, such as *Apocynum* and *Euonymus*, have an even wider distribution in the temperate zone of Europe, Asia, and North America.

Generally speaking, the rubber-bearing plants of tropical countries are distinguished by having a latex that is the source of the rubber. Most of the plants were tapped by some means to obtain the latex, but in a few cases in Africa it was the custom to coagulate the latex in the plant and then obtain the rubber by mechanical maceration. With temperate-zone plants, mechanical maceration is the sole method of obtaining the rubber.

A few of the northern plants in Russia have, on occasion, been gathered in the wild for rubber extraction but, in general, they are small and must be grown in cultivation to provide sufficient plant material for the mechanical devices developed to extract the rubber. Cultivation by horticultural or forestry methods, such as is practised in the tropical regions, must give way to field-crop methods, when the whole concept of rubber cultivation is completely changed.

Taraxacum. This genus belongs to the family Compositae and its member species are the dandelions. *Taraxacum kok-saghyz* Rodin is a Russian rubber-bearing dandelion discovered by L. E. Rodin on a high plateau of the Tien Shan Mountains in the Kazakh S.S.R. just east of Alma Ata. The first botanical collection of the plant was made in 1910 by A. I. Michelson and deposited in the Herbarium of the Botanical Institute of the Academy of Science, Leningrad. However, the expedition headed by Rodin had been organized by N. I. Vavilov specifically for finding rubber-bearing plants.

As an herbarium specimen or set of specimens, Michelson's collection remained unstudied for more than twenty years; but as a potential industrial crop, Rodin's collection received immediate study and christening.

Taraxacum megalorhizon Hand.-Mzt. (*T. hybernum* Stev.) is known as krim- (or krym-)saghyz. Ulmann (1951) states that the original description of krim-saghyz was made in 1856 by Ch. Stevens who described it as *T. hybernum*. However, this dandelion had been included within the concept of *T. gymnanthum* DC. by A. De Candolle in 1838. Handel-Mazzetti made a detailed study of the available botanical material and renamed the concept now recognized as krim-saghyz, using the name *T. megalorhizon*. This species has been found to be widely distributed in the Mediterranean region.

Scorzonera. This is a second genus of the Compositae that is the source of important rubber-bearing plants in Russia. The most important are tau-saghyz (*Scorzonera tau-saghyz* Lipschitz & Bosse) and teke-saghyz (*S. acanthoclada* Franch.). These plants, like kok- and krim-saghyz, are sources of root rubber, the aerial portions of the plants being unimportant for our purpose.

Tau-saghyz was discovered by Ss.Ss.Saretzki in the mountains of Kara-tau in the Tian Shan range in southern Kazakhstan. It is a very slow-growing plant and requires up to five years to reach its maximum rubber concentration. At maturity, the rubber-content of the root is reported to be higher than that of any other known plant. Ulmann (1951) states that the rubber-content of the root can be 30 per cent or higher (of dry-weight). The highest on record for guayule is 25 per cent and the normal percentages are much lower.

Unlike krim-saghyz, tau-saghyz is extremely variable in all characters. Ulmann (1951) described four variants representing characteristics associated with the geographical distribution of tau-saghyz in nature. The seedling populations studied in the United States exhibited considerable differences in seed and root characters.

Teke-saghyz (*S. acanthoclada*), occurring in the high mountains of Middle Asia at elevations of 2,200 to 3,900 metres but chiefly around 2,500 to 3,200 metres, was first described in 1883. The climate in the native range of teke-saghyz is very severe, the mean yearly temperature being about 3°C. and the mean summer temperature about 15°C. The annual rainfall is around 400 mm., with 85 per cent falling in winter and early spring and the rest at the end of the summer and in the autumn. The period from June to September is normally without rain. The plants attain an age of ten years or more and, in nature, there may be as many as 2,000 plants per 100 square metres in good stands. The plant flowers first in its second or third year. In general, however, teke-saghyz that is harvested in the wild for rubber has reproduced vegetatively rather than by seed. After the roots are torn from the ground for rubber collection, those left regenerate new plants, and considerable amounts of wild plants have been gathered without seriously depleting the wild stands. The growth of the plants is very slow and teke-saghyz has not responded satisfactorily to domestication.

Chondrilla. This genus also belongs to the Compositae. It includes two species that have been studied as promising sources of rubber. These are *Chondrilla ambigua* Fisch. and *C. pauciflora* Lbd., and, in contrast to the species of *Taraxacum* and *Scorzonera*, they contain significant amounts of rubber in the bark of the stems and twigs as well as in the roots. They are unique in being subject to underground bleeding owing to the attacks of certain insect larvae, and this bleeding results in the accumulation of rubber in the soil around the root.

In *Chondrilla*, rubber is only found in the parenchyma cells of the bark and roots. The twigs contain an average of 1 to 1·5 per cent of rubber and 9·5 to 10 per cent of resins. Bark constitutes a third to a half of the twigs and stems and contains 3.0 to 3.5 per cent of rubber and 15 to 20 per cent of resins. Thus the extraction of the rubber is facilitated by first separating the bark from the wood.

The rubber is contained in *Chondrilla* in the form of latex. When the insect larvae attack the roots of the plants the latex flows out into the surrounding sandy soil, where it coagulates and forms a mass consisting of rubber, resin, and sand, that is known either as 'naplywy' or 'tschechliki'—according to the size, shape, and composition of the individual masses. The differences are due to the fact that the larvae of two insects are involved. Thus the 'naplywy' are caused by the larvae of *Sphenoptera foveola* Gebl.: they attain a weight of 15 to 50 gm. and consist of sand, 80 to 90 per cent; rubber, about 1·4 per cent; and, for the rest, resin. The 'tschechliki', on the other hand, result from attacks by the larvae of *Bradyrrhoa gilveolella* Fr. They reach a length of 3 to 5 cm. and a thickness of 0·5 to 0·8 cm., with a weight of 1 to 3 gm. The 'tschechliki' are richer in rubber than the 'naplywy', and attain a rubber content of 5 to 18 per cent.

RUBBER PLANTS NATIVE TO TROPICAL AMERICA

Tropical America gave the world its chief rubber-bearing plants, the most important being *Hevea brasiliensis* of the family Euphorbiaceae. That family also contributed other important rubber-bearing plants, as did the Moraceae and Apocynaceae.

Euphorbiaceae

The Euphorbiaceae are common throughout the world. In addition to *Hevea*, species of *Manihot*, *Sapium*, *Micrandra*, *Jatropha*, and *Euphorbia* have been important sources of rubber in tropical America.

Hevea. *Hevea brasiliensis* (Willd. ex A.Juss.) Muell.-Arg. is the outstanding rubber tree of the world. The genus is distributed throughout the Amazon Valley in South America. Schultes (1956) lists seven species in addition to *H. brasiliensis*. The species and genus will be discussed in greater detail in Chapter IV.

Micrandra. Micrandra is, according to Schultes (1956), 'rather closely allied to *Hevea*, but it has a much wider range. Known from the entire Amazon basin and from southeastern Brazil, the Orinoco drainage-area and all of Venezuela, the Guianas, as well as from the Magdalena Valley in Colombia, *Micrandra* would appear to be an old genus. Only one species —*Micrandra minor*—has been of any commercial importance as a rubber producer.' Schultes says of *Micrandra minor* Benth.:

> Widespread and abundant in the Amazon Valley and the upper Orinoco basin, *Micrandra minor* is a gigantic tree, often attaining a height of one hundred and ten feet. The crown is very heavy, and the corpulent trunk is unbuttressed. This species prefers the high river-banks which are inundated only at the height of the annual flood, and is never found in low-lying swampy areas. The very abundant, thick, pure white latex yields a rubber of high quality and has been tapped in the past for 'Caura rubber'; but, as the tree cannot be subjected to repeated and frequent tapping, it is not promising for planting.

Manihot

Manihot. The Ceara rubber tree, *Manihot glaziovii* Muell.-Arg., is the most important species of this genus for rubber production. In the early days of rubber gathering, *M. glaziovii* furnished large quantities of high-quality rubber that appeared on the market as Ceara or Manicoba rubber (Plate 4). The Ceara rubber tree was one of the first species to be planted, and the seeds were shipped to many parts of the world. It is native to the States of Rio Grande do Norte, Paradyba, and Ceara, all in Brazil, and is found growing along mountains that are sparingly covered with shrubs and low trees. Its native habitat is strongly characterized by long periods of drought; indeed, because of its resistance to drought, the Ceara rubber tree was originally favoured over *Hevea* for planting in Hawaii and parts of Africa.

Considerable difficulty was experienced in gathering *Manihot* latex because of spontaneous coagulation on the tree. It was often necessary to allow the latex to coagulate in the cuts and then strip off the rubber and wind it into balls.

Manihot dichotoma Ule, *M. heptaphylla* Ule, and *M. piauhyensis* Ule have also been exploited for rubber. The central area for the collection of rubber from *M. dichotoma* was the town of Jequie, and the rubber was known as 'Jequie rubber' or 'manicoba de Jequie'. It was claimed that, from this species, one man could gather from 3 to 4 lb. of latex daily and that from this he could obtain from 1 to 1·53 lb. of rubber. Rubber was collected from *M. heptaphylla* along the São Francisco river and the rubber was known as São Francisco rubber.

Much of the rubber of *M. piauhyensis* was shipped through the port of Piauhy and the rubber was known as Piauhy rubber, whilst the same name was applied to rubber shipped from Pernambuco and Bahia. One workman was said to be able to collect from 2 to 3 kg. of rubber daily from this species, and some trees were reputed to produce up to 5 kg. of rubber annually. Under cultivation, it was claimed that 200 three-year-old trees produced 35·83 kg. of rubber at one tapping.

Sapium. *Sapium* is one of the least known of the important rubber-bearing genera. Some species of *Sapium* produce rubber that is equal to the best *Hevea* rubber. Plants of this genus are native to the tropical portions of both the Eastern and Western Hemispheres, although the rubber-bearing species occur only in the Western Hemisphere (and there principally in the Andean regions of Colombia, Peru, Ecuador, and Venezuela, and throughout the Amazon Valley as far east as Belem). Manifold (1944) says, 'The Sapiums have never held major importance as rubber producers, for although the quality of the rubber is high, yields are low and distribution limited. The quality is similar to *Hevea*, while flow of latex and tapping methods are generally comparable to *Castilloa*.'

The Rubber Development Corporation of the United States Government made intensive studies of the possibilities of obtaining rubber from native stands of *Sapium* during World War II. Uphof (1942) and White (1942) made preliminary surveys of the botanical literature, basing their comments chiefly on the monograph of Pax (1912). L. Williams (1944) summarized the field-work of the Corporation in 1944. The following information is abstracted from these reports:

Sapium jenmani Hemsl. is a tall tree sometimes exceeding 90 ft. in height with a diameter at the base of 30 or more in. It grows in the alluvial forests of British Guiana, especially in the Pomeroon District, and is said to have been planted early this century in County Berbice, on the Essequibo River, and in the north-west district. The presence of *Sapium* in

British Guiana was authenticated as early as 1884, and the aboriginal Indians were reputed to have used the rubber to form balls for their games. *S. jenmani* or a closely similar species grows in abundance in the western plains of Venezuela. Three variants are recognized by the natives, 'caucho rosado', 'caucho negro', and 'caucho blanco'. 'Caucho rosado' grows in the dense forest that is periodically flooded. It has a thick, slightly fissured bark, is fairly easy to tap, and gives the best yield. 'Caucho negro' is also found in the dense forest. It has a thick, tough, much fissured, dark-brown bark, and is more difficult to tap. 'Caucho blanco' is found in open or second-growth areas; it is of smaller stature than the other two, has a light-grey, flinty bark, and is considered a poor yielder.

Sapium verum Hemsl. is a fast-growing tree up to 75 ft. in height, with an open crown, an erect trunk, and a greyish to brown bark. It grows in virgin forests in mountain areas at altitudes of between 3,600 and 9,500 ft., and is recorded in Colombia from the Departments of Tolima, Huila, and Cauca, and from the vicinity of Chimborazo, Ecuador. This species yields a large quantity of latex and is considered a valuable source of rubber, which is known as 'Colombia virgin' or 'Colombia scrap', 'caucho virgin', or 'caucho blanco'.

Sapium peloto Pax & Hoffm., a tall tree known in Bolivia as 'peloto', grows in rain forests along the Mamore River and its affluents. Crist (1944) states that there are at least four types of 'peloto' in the Trinidad-Eviato area: two of these, 'peloto blanco' and 'peloto rosado', yield rubber of good quality, while the other two, 'peloto ligoso' and 'peloto morado' or 'barcino', are considered of no commercial value.

Sapium taburu Ule, a medium-sized or tall tree, at times attaining a height of 120 ft., with stout branches, is widely distributed in the Amazon basin, as well as at high elevations, especially in central and upper Madeira, along the Jurua and Javary rivers, and in northeastern Peru and in Ecuador. The latex is said to be used often as an adulterant with *Hevea*. The local names for the tree are 'tapuru' or 'seringuerana', while in commerce the rubber is known as 'tapuru', 'cameta sernamby', or 'roll-gummi sernamby'.

Sapium hippomane G. F. W. Mey, is a small or medium-sized tree, up to 60 ft. in height. It has a wide distribution in Barbados, Trinidad, Tobago, Surinam, British Guiana, the temperate zone of Venezuela, upper Brazilian Amazon, and, in Peru, Jurua and the Andean regions of Junin, Tarma, and La Merced. The vernacular names are 'milk tree', 'poison tree', 'gum tree', and 'lechero'.

Sapium pavonianum (Muell.-Arg.) Huber is a small tree 30 to 45 ft. in height, having the twigs densely covered with leaves. It grows in dense forests along the Noya, Micaya, Sayja, and Timbequi Rivers in Colombia, at altitudes of up to 650 ft., as well as between Katchari and La Clementina, Ecuador, and at Imana de Oro, Peru. The rubber is considered of good quality and is known as 'caucho blanco', 'caucho andullo blanco', and 'cauchillo'.

Sapium stylare Muell.-Arg. is a tall tree having the twigs densely covered with oval or elliptic leaves. It grows in virgin forests in subtropical and temperate regions of Venezuela, and is reputed to be the principal species on the slopes of the Andes in Ecuador, at elevations of from 3,000 to 6,000 ft. No attempt is made to exploit the rubber in Venezuela; but the tree is tapped in the Province of Oriente in Ecuador, where the trees are said to be most productive at elevations of between 3,900 and 4,200 ft.

Other species of *Sapium* that have been reliably reported as sources of rubber include: *S. aubletianum* (Muell.-Arg.) Huber, from the vicinity of San Gabriel do Cachoeira on the Rio Negro, Brazil. Its vernacular names are 'mapa', 'mapam', and 'strapo'. *S. ciliatum* Hemsl. is a tree 12 to 15 ft. high reported from Para, Santarem, and Cararauca. *S. hamatum* (Muell.-Arg.) Pax & Hoffm. is reported from the Brazilian Amazon and from subtropical regions of Peru. *S. eglandulosum* Ule is a tree up to 45 ft. high growing along the Jurua River and in Peru. *S. marmieri* Huber grows in the alluvial forests along the Ucayali and Huallaga Rivers in northeastern Peru, and along the Napo River in Ecuador. Its juice is reputed to be poisonous, and its local names are 'seringarana' and 'seringueira'. *S. bogotense* Huber is reported from Ubala, near Bogota, Colombia, at elevations of from 5,700 to 6,000 ft. *S. aucuparium* Jacq. is a small tree growing in the savannas of the Venezuelan Guiana, in the vicinity of Caracas, and along the northern Colombian coast around Santa Marta.

Sapium trees are more difficult to tap than are those of *Hevea*. Field technicians of the Rubber Development Corporation carried out many tests to determine the best manner of tapping them, but did not establish a general uniform method because of varying conditions and differences in bark characteristics. In almost every instance it was found that tapping with a tapping knife, such as is used with *Hevea*, was impossible because of the hardness of the bark. In general, the best tapping instrument was a machete used in conjunction with a wooden mallet. In some areas, a herringbone cut consisting of a central vertical channel with side cuts at a 40° angle was suitable, whilst in other cases, full spiral cuts were made. On larger trees, or where the trees were scattered, a second full spiral would be made above the first. This, however, involved the use of ladders, which slowed down the tapping; so if the stand of trees was adequate, it was preferable to make only one full spiral cut on each tree.

Sapium does not show any wound response, as does *Hevea*, and does not recover rapidly from being tapped; it was necessary, therefore, to rest the trees for a considerable period between successive tappings. Usually it was found that a period of at least two months, and sometimes up to four months, must be allowed between tappings, although in some areas the rest period needed was only fifteen days. It was necessary to tap early in the morning, from 5 to 10 a.m., and even then some technicians advised tapping on the west side of the tree, to avoid heating of the cut surface by the sun. The latex tends to coagulate in the cut and to stop flowing after only a few minutes if tapping is continued after 10 o'clock in the morning, whereas earlier in the day the flow will continue for up to three hours.

The latex of *Sapium* coagulates spontaneously. Some of the latex coagulates in the cut and is allowed to dry for some four days and is then stripped off. The latex that flows from the cut into the tapping cup coagulates overnight without the addition of any coagulants, and is washed and sheeted the next day.

Jatropha. McVaugh (1942) states:

> The genus *Jatropha* consists of more than 100 species which are particularly abundant in the American and African tropics; a few species are found in tropical regions elsewhere. . . . The genus *Jatropha* is divided into two principal groups, which are considered distinct genera by many botanists. *Jatropha* proper has no stinging hairs, and the flowers are provided with both calyx and corolla. The second group, subgenus *Cnidoscolus* . . . has an abundant supply of painfully stinging hairs and the showy white flowers consist of a calyx only, the corolla being absent. . . . The subgenus includes perhaps 40 species, all native to the American tropics, with a few extending their ranges into temperate and sub-tropical regions. Some of the species are small, strictly herbaceous plants; others become shrubs or even large trees. All the plants that have been mentioned as sources of 'chilte' belong to this group.

'Chilte' has been known and used in Mexico for many years, mostly for its local application in the making of toy balloons and figurines. When broken, the toy balloons were used as a chewing gum. The gum contained a high proportion of resin and around 50 per cent of rubber. The Rubber Development Corporation made intensive studies of the native stands in Mexico during the war, but found that they were much less plentiful than had been reported. Yields were too low for commercial exploitation.

It was not possible to determine any one species as the source of 'chilte': *Jatropha aconitifolia* Mill. was the principal source in some areas, whereas *J. tepiquensis* Cost. & Gall. was probably the principal source of 'chilte' from a narrow zone along the west coast of Mexico. Other species undoubtedly were also tapped for 'chilte'.

Various methods of tapping 'chilte' were reported, although generally these consisted in making a series of oblique cuts from ground-level up to as high as the tapper could reach from the ground or by climbing the tree. The cuts were made alternately to the left and right, with the lower ends of successive cuts overlapping. No vertical groove was made, and the latex was allowed to flow over the smooth uncut bark from one cut to the next below. The cuts were made through the bark but not into the cambium layer, and they healed quickly. The tree could be tapped at eight-to thirty-day intervals throughout the year. The flow of latex was best in clear, sunny weather: in the rainy season when the bark was wet, the latex tended to coagulate and stop flowing.

The latex was coagulated by the addition of water. Coagulation was immediate and the rubber could then be washed, dried, and sold in blocks. The rubber was of inferior quality, even after being deresinated by treatment with acetone to remove most of the acetone-soluble constituents; but it could be used in the manufacture of rubber articles either with or without deresination.

The latex is occasionally drunk by natives without any ill-effects. It can be used directly as chewing gum, as it coagulates in the mouth. The milk is palatable and sweeter than cow's milk. Unless dried carefully, the rubber develops an extremely disagreeable odour.

Euphorbia. The Euphorbias are well represented in the Western Hemisphere but none of them has been an important source of rubber. One that has received some attention is *Euphorbia fulva* Stapf, which is known locally in Mexico as 'palo amarillo' or 'palo colorado'. It is found in the dry, semi-tropical zone on the slopes of the Sierra Madre at elevations of from 900 to 4,800 ft., and extends southwards along the Pacific Coast of Mexico from Durango to southern Oaxaco. The tree is from 20 to 34 ft. high, with a trunk diameter of from 7 to 12 in. The yield is low and the latex contains only from 7 to 16 per cent of rubber but about twice that amount of resins.

Moraceae

Castilla. The most important genus of American rubber plants assigned to the family Moraceae is *Castilla*. In many references this genus has been corrupted to '*Castilloa*', because a careless or presumptuous translator of V. Cervantes's original description first published it in English as such. Both Cook (1903) and Pittier (1910) give the correct spelling as *Castilla*.

Species of *Castilla* are abundant from southern Mexico to Bolivia, and will be discussed later.

Ficus. Species of *Ficus* have been reported from tropical America and some of them have been described as rubber-bearing plants. Moyle (1942) lists these as *Ficus anthelminthica* Mart., *F. doliaria* Mart., *F. elliptica* H.B., *F. nymphaeafolia* Mill., and *F. prinoides* Humb. & Bonpl.

Apocynaceae

Hancornia. The 'mangabeira' or 'mangaba' rubber tree, *Hancornia speciosa* Gomez, occurs along the northern and eastern coasts of Brazil, and in Paraguay. It is the foremost rubber of tropical America belonging to the family Apocynaceae. Ackerman (1901) stated that a rubber similar to Para rubber was being produced on the Tocantin River, that the juice was easily collected, that the solid product was obtained by heating the juice (Plate 5(*a*)), but that the rubber was little known and had not yet found a market. Rusenheim (1898) reported that 'mangabeira' rubber was being exported from São Paulo.

H. speciosa is a small tree and the yields are low. It was exploited as a source of rubber more or less continuously during the first part of the twentieth century while wild sources of rubber were being tapped aggressively in Brazil. During World War II, particular attention was given to the production of rubber from 'mangabeira' (Plate 5(*b*)). Under this stimulation, there was a total production during the war period of some 2,000 to 2,500 short tons of rubber from this source.

Native methods of tapping 'mangabeira' and coagulating the latex were very crude, although fortunately the latex was quite stable and could be kept for several days without deterioration. Coagulation was brought about by heating or by the use of table salt or alum. Bekkedahl & Saffioti (1947) made a study of the latex and rubber of 'mangabeira' and reported a mean dry rubber-content in the latex of about 33 per cent, with values ranging from 25 to 40 per cent. They found that the native coagulants, alum and sodium chloride, had a degrading influence on the quality of the rubber, the best coagulants being hydrochloric acid (about 0·5 per cent) and the latex (about 5 per cent) of the caxinguba tree, *Ficus anthelminthica* Mart. They stated, 'Mangabeira rubber is softer and weaker than *Hevea* rubber, but with the improved methods of processing, the physical and ageing properties of the mangabeira rubber have been greatly improved, and this rubber may find commercial application in the future, especially as a special-purpose rubber'.

Plumeria. Olsson-Seffer (1911) states that the rubber plants of Mexico known commonly by the Indian name, of 'cacaloxuchitl' include chiefly *Plumeria rubra L.* but also *P. acutifolia* Poir. and *P. lambertiana* Lindl. (listed by Olsson-Seffer as *P. mexicana*). These species occur over considerable areas in central and southern Mexico and Central America at elevations of from 500 to 7,000 ft. The trees average about 12 ft. in height and the trunks are from 6 to 18 in. in circumference at 3 ft. from the ground. The latex may be collected from November to February and averages from 14 to 16 per cent of rubber; although a single tree has yielded 1 lb. and 3 oz. of rubber, the yield is usually much less. The young branches are rich in rubber, and periodic clipping followed by maceration to obtain the rubber was suggested by Olsson-Seffer. The rubber contains from 12 to 20 per cent of resins and is soft. Kaye (1911) described cacaloxuchitl rubber as clean and light-coloured, but lacking in strength and elasticity.

Couma. Several species of *Couma* have been reported as sources of rubber in Brazil. Moyle (1942) lists among these *Couma macrocarpa* (Barb.) Rodr., *C. rigida* Muell., and *C. utilis* Muell. Karling (1935) made a detailed study of the production of latex by *Couma guatemalensis* Standl.

Karling was interested in this tree as a possible source of chicle and made no study of the gum from the latex, but it is to be assumed that the hydrocarbon in *C. guatemalensis* is rubber (rather than gutta, which is found in chicle).

Rubber-Bearing Plants of North America

Parthenium argentatum Gray, the guayule plant of northern Mexico and southwestern Texas, is the only plant native to the United States that has been a source of commercial supplies of rubber. Nevertheless, rubber has been found in over 800 species of plants native to the United States. There have been surges of interest in other plants than guayule, such as the milkweeds, rabbit brush, Indian hemp, and the Osage orange; but none of these has assumed any importance for rubber production. The first cultivation of rubber plants in the United States was of the Colorado rubber plant (*Hymenoxys floribunda* Cock.). The desert milkweeds were studied extensively by the United States Department of Agriculture. Following Thomas A. Edison's work, attention was given to the goldenrods, and several hundred acres of goldenrod were planted during World War II to try to work out a successful production procedure.

The investigation of native rubber-bearing plants in the United States started with the studies of Cockerell (1903), of the University of Colorado, who investigated the rubber content of native species of *Hymenoxis*. The first effort to cultivate rubber in the United States was made in the southwestern part of Colorado early in the twentieth century.

A decade after the work of Cockerell, Fox (1912, 1912*a*, 1912*b*, 1913) investigated the rubber content of several plants, including the common milkweed (*Asclepias syriaca* L.), Indian hemp (*Apocynum androsaemifolium* L.), wild lettuces (*Lactuca canadensis* L. and *L. scariola* L.), and a species of Osage orange (*Maclura aurantica* Nutt.).

Surveys of Rubber-bearing Plants of the Western States

Several years later, Hall & Goodspeed (1919) made a survey of the rubber-bearing plants of the western parts of the United States. Outstanding among the plants studied was the rabbit brush, *Chrysothamnus nauseosus* Britton & Brown, which was reported as containing relatively high proportions of rubber and as occurring in almost pure stands. Hall & Goodspeed made surveys of the amount of rabbit brush and of the rubber content of the major stands, and estimated the yield of rubber that might be obtained from the existing wild stands.

Hall & Long (1921) reported studies of other rubber-bearing plants, including species of milkweed and Indian hemp. They analyzed samples of some 250 species of plants and found rubber in a larger proportion of them than had been expected. *Asclepias subulata* Decne. and *A. sullivanti* Engelm. were found to be of particular interest.

Other Surveys of Native Rubber-bearing Plants

Following the first World War, Thomas A. Edison became concerned about sources of natural rubber and organized surveys of the native plants of the United States and Mexico. The results of his work were never published, but during it thousands of plants, many of which were found to contain from a trace to several per cent of rubber, were collected and analyzed.

Polhamus (1933) made a survey of the native species of goldenrod occurring near Washington, D.C., and later (1957) published a summary of tests made by the United States Department of Agriculture. Mitchell *et al.* (1942) studied the rubber content of plants native to South Carolina. Moxon & Whitehead (1943) searched for rubber-bearing species among the native plants of South Dakota, and Buehrer & Benson (1945) reported on those in Arizona. Minshall (1957) reported on the rubber content of native and introduced plants in Canada. An important contribution to the summarization of knowledge of plants other than *Hevea* that have been reported as containing or producing rubber was made by Moyle (1942) during World War II.

Rubber in Fungi, etc.

Hitherto, rubber has been reported only in flowering plants, but recently W. D. Stewart *et al.* (1955) isolated rubber from benzol extracts of sporophores of species of the fungus genera *Lactarius* and *Peziza*. Samples from a mixed collection of *Lactarius* species, several saprophytic species of *Peziza*, and a separate collection of *Lactarius deceptiva*, were tested. All contained rubber, though it was of low molecular weight, but the infra-red absorption pattern was almost identical with that of *Hevea* rubber. Analysis for carbon and hydrogen showed 87·90 and 11·69 per cent, respectively, compared with theoretical values of 88·15 and 11·85.

Die (1954) reported rubber of low molecular weight in species of *Balanophora* found parasitizing roots of *Vaccinium* and *Schima*.

Rubber in the Plant Kingdom

Table III lists the families, and the number of genera and species in each family, of plants in which rubber has been reported. The greatest diversity of plants studied and reported to contain rubber was by investigators in North America, and these are shown separately with respect to plants reported since 1900. A minor portion of the plants listed under the work performed in North America were not natives there but had been introduced from other countries, and some of these plants are also included in the tabulations from elsewhere. Surveys made in Russia were comparable with those made in the United States, and the work of many Russian investigators is included in the final column of the table.

TABLE III

SHOWING, BY FAMILY, THE NUMBERS OF GENERA AND SPECIES OF PLANTS THAT HAVE BEEN REPORTED EITHER AS SOURCES OF RUBBER OR AS HAVING A MEASURABLE RUBBER CONTENT

	Before 1900		Since 1900			
			North America		Elsewhere	
Family	Genera	Species	Genera	Species	Genera	Species
Acanthaceae			2	2		
Aceraceae			1	1	1	1
Alismataceae			1	1		
Amaranthaceae			1	1		
Anacardiaceae			3	7	1	1
Apocynaceae	9	33	24	48	41	177
Araceae			2	2		
Aristolochiaceae			1	1		
Asclepiadaceae	2	3	16	74	6	13
Balanophoraceae					1	1
Balsaminaceae			1	1		
Boraginaceae			2	2		
Buxaceae			1	1		
Campanulaceae			3	18	1	2
Cannabinaceae			2	3		
Cannaceae			1	1		
Capparidaceae			1	1		
Caprifoliaceae			2	10		
Caryophyllaceae			3	3		
Celastraceae			4	16	2	2
Chenopodiaceae			5	6		
Commelinaceae			2	5		
Compositae	1	1	77	264	16	61
Convolvulaceae			3	7		
Corylaceae			1	1		
Crassulaceae			1	2		
Cruciferae			4	5		
Cucurbitaceae			2	2		
Dioscoriaceae			1	3		
Dipsacaceae			1	1		
Ebenaceae			1	1		
Ericaceae			2	2		
Eucommiaceae			1	1		
Euphorbiaceae	3	4	12	86		
Fouquieriaceae			1	1		
Fucaceae			1	1		
Gentianaceae			1	1		
Geraniaceae			1	1		
Gramineae			1	1		
Guttiferae			1	1		
Hydrophyllaceae			1	1		
Labiatae			5	5		
Laminariaceae			2	2		
Leguminosae			24	25	1	1
Liliaceae			2	2		
Loranthaceae					1	2
Malvaceae			2	2		
Moraceae	5	12	3	13	6	62

TABLE III—*Contd.*

Family	Before 1900		Since 1900			
			North America		Elsewhere	
	Genera	Species	Genera	Species	Genera	Species
Myricaceae			1	1		
Myrtaceae					1	1
Nostocaceae			1	1		
Nyctaginaceae			2	2		
Nymphaeaceae			2	2		
Oleaceae			1	1		
Onagraceae			3	5	1	1
Orobanchaceae					1	1
Papaveraceae			2	2	1	1
Phytolaccaceae			1	1		
Plantaginaceae			1	3		
Plumbaginaceae			1	1		
Polemoniaceae			1	1		
Polygonaceae			3	4		
Polypodiaceae			1	1		
Primulaceae			1	1		
Ranunculaceae			2	2		
Rhamnaceae			2	4		
Rosaceae			4	5		
Rubiaceae			1	1		
Sapindaceae			1	2		
Sapotaceae	3	16	8	16	2	9
Saxifragaceae			1	1		
Scrophulariaceae			4	5		
Simaroubaceae			1	1		
Solanaceae			5	7		
Thymelaeaceae			1	1		
Typhaceae			1	1		
Umbelliferae			4	4		
Urticaceae			1	1		
Zygophyllaceae			1	1		
Totals	23	69	287	712	83	336
Total families	6		75		16	

Among the investigators in North America, Buehrer & Benson (1945) found rubber in plants from eighteen families, Polhamus (1957) reported rubber in plants from forty-four families, and Minshall (1957) reported rubber in plants from fifty-seven families. T. A. Edison studied plants from 150 families and found rubber in plants from eighty-three of them. Edison's collections involved a wide range of plants, including trees, shrubs, herbs, annuals, perennials, ferns, and horticultural forms of ornamentals—anything that caught the eyes of his collectors. A separate publication would be required to relate the details of Edison's rubber survey, whilst a mere listing of the genera and species tested and even of those found to contain rubber, would be beyond the scope of the present book.

IV

BOTANY OF HEVEA

The Pre-eminence of *Hevea* for Culture

It was far from apparent in the beginning that, of all plants being tested, *Hevea* would emerge as the most important source of natural rubber and finally as practically the sole source. In yield at any one tapping, *Castilla* was superior to *Hevea*; moreover the Ceara rubber tree, *Manihot glaziovii*, could be grown under drier conditions, where sanitation for men and trees was superior to that possible in the hot, humid areas that were favourable for the cultivation of *Hevea*; furthermore, *Ficus elastica* was endemic to areas of the East with large populations that would be available for estate operation.

Response to Tapping

Certain advantages of *Hevea* were quickly recognized. Native tappers of *Hevea* in Brazil knew that yields increased as tapping was continued, and this phenomenon was noted by the native tappers even though their system of tapping did not involve the reopening of the cut—a development that was the result of experimental tapping of planted trees in the East and came only much later. Native tapping was done with a small, long-handled hatchet (machadinho) with which the tapper chipped out segments of bark by cutting into the wood. On successive days, other bark segments were chipped out in a similar manner—close to but not touching the cuts made on the previous day. The flow of latex increased as the tapping operation was repeated. Later, the machadinho was replaced by the Amazonas knife, and grooves replaced the gashes resulting from the chipping. The grooves made by the Amazonas knives were similar to the tapping cuts made with gouges or the modern 'jebong' tapping knives—yet with an important difference in that, in the jungle, the cut made the previous day was never reopened, but a small ridge of unexcised bark was left between successive cuts (Plate 6 (*a*)). The propinquity of the cuts, however, was sufficient to induce the increased flow noted by the tappers, and later termed 'wound response' and finally 'dilution reaction' in the East.

Numerous small plantings of *Hevea* were made by early tappers at the camp-sites established for the exploitation of the native trees. These plantings can be recognized by the close, ordered location of the trees.

Such a planting that has been tapped successively by the machadinho, Amazonas knife and, finally, by the jebong knife (Plate 6 (*b*)), illustrates the increasing care that has been taken in tapping.

Chance as a Factor in Early Preference

Wickham. The introduction of almost pure *Hevea brasiliensis* into the East had many elements of chance. Wickham was not a botanist and must have depended largely on native knowledge for the selection of the trees to serve as sources of seed. *H. guianensis* is much more prevalent in Brazil than is *H. brasiliensis*, and is a good rubber tree. *H. benthamiana* has as wide a distribution in the Amazonian region as *H. brasiliensis*, and is the source of a rubber of equal quality. There are at least five other species that Wickham might have collected that would have given inferior types of rubber.

It happened that Wickham made his collection on the banks of the Tapajos River in an area where *H. brasiliensis* was the only species of *Hevea* available. As a result, Wickham's seeds were obtained from trees of this one species and this first and most important introduction set the scene for the sole use of *H. brasiliensis* in the initiation of the rubber plantation industry. Later, other species of *Hevea* were introduced; but extensive plantings of *H. brasiliensis* had already demonstrated its value.

Ridley. The early selection of *Hevea* for plantation use can also be ascribed to the chance that some of the seedlings were planted at the Singapore Botanic Garden, and that the Director of the Garden when the trees reached maturity was an outstanding botanist who took an active interest in this new product and in the tree from which it was produced. Actually, the seedlings were never intended for Malaya, Indonesia, or Ceylon—the centre of the rubber plantation industry today. The Wickham collection was made at the instigation of the India Office and the costs of the operation were borne by the Government of India. Fairchild (1928) states that cuts in an appropriation made it impossible to establish a rubber station at Tenasserim, Burma, as had been planned, and so the seedlings were sent elsewhere. The decision was to send the seedlings to established Botanic Gardens in the East, Ceylon being preferred. Singapore was chosen to receive a minor share of the shipment, but distinctly as a third choice.

H. N. Ridley became the Director of the Singapore Botanic Garden in 1888. He became greatly interested in the *Hevea* trees and took it upon himself to conduct tests to determine the best way of tapping the trees and producing rubber. He finally took the lead in championing the planting of *Hevea*. This championship was largely instrumental in getting the first plantings started, and it was for this that the rubber industry honoured him on the occasion of his hundredth birthday, in December 1955.

Parkin. The chance that sent the bulk of the seedlings resulting from Wickham's collection to Peradeniya, Ceylon, also exposed them to John Parkin. He took an interest in the preparation of rubber from the latex, and interested himself in devising a method of coagulation that would be better suited to estate operations than the smoking method of the Brazilian natives. Parkin (1910) was the first to use acetic acid to coagulate the latex. His tests were conducted in 1898 and 1899 and resulted in the recommendation of using 1 volume of acetic acid to 100 volumes of latex. On the face of it, this was not a major contribution to rubber technology and, as in the case of Ridley's tapping method, the use of acid for coagulation has been greatly improved and the proportions of acid decreased. Moreover, formic acid has largely replaced acetic acid in estate use; but the important thing is that this early contribution was basic to the bulk handling of plantation latex. The element of chance that resulted from the *Hevea* seedlings being sent from Kew to Peradeniya and Singapore, rather than direct to Burma, brought the trees to the attention of Ridley and Parkin. The cut in appropriations that prevented the plants from going to Burma may have had greater influence than has been recognized in the rise of the *Hevea* plantation industry.

The Taxonomy of *Hevea*

The Natural Distribution of 'Hevea'

The genus *Hevea* is confined to South America—primarily the Amazon Valley, though it has also been reported from the upper Orinoco Valley, the Guianas, and Mato Grosso. Schultes (1956) states:

> *Hevea* exhibits much morphological variability and chooses a wide range of ecological sites. Its members range from forest giants to shrubby, sometimes almost prostrate, treelets and are found growing in deeply flooded and alluvial land, in acidic boggy sites, on high well-drained upland, and on the tops of xerophytic quartzitic mountains. As in many groups of tropical trees, natural variability has led, in the past, to the description of too many specific concepts. At one time, specialists held that the genus comprised twenty or more species, but recent workers are in essential agreement that there are only eight or nine.

Detailed botanical descriptions of the rubber-bearing species need not be given in this book as these have recently been published by Schultes (1956).

The Rubber-bearing Species of 'Hevea'

Hevea brasiliensis is by far the most important of the species of *Hevea*. Ninety-nine per cent of all the natural rubber produced in the world comes from this one species. Other species have been introduced into the East since the time of Wickham, but only in small amounts for scientific tests. There have been no specific scientific comparisons of sizeable populations of the various species of *Hevea*. Chemical analyses of rubber from wild trees of some of the species have indicated that, in general, the rubber from *H. brasiliensis* is superior to that of most other species in that it has a lower percentage of non-rubber constituents. Samples of rubber that are in no way inferior to the best samples of rubber from *H. brasiliensis* have been obtained from trees of *H. benthamiana*, and samples of good quality have been obtained from *H. guianensis*.

Hevea brasiliensis is confined largely to the area of the Amazon Valley lying south of the Amazon River. It is found north of the river only in one small area west of Manaos, while Ducke (1946) has reported it outside the Amazon Valley in Mato Grosso and Parana. In the lower Amazon, it is found mostly in periodically flooded areas; but in Mato Grosso, Bolivia, and in the Madre de Dios area in Peru, it is found on well-drained upland areas and there it is reported to reach a height of 130 ft. Its latex varies from white to cream-white. Schultes (1956) states, 'Because of our fuller knowledge of this concept, some workers have thought *Hevea brasiliensis* to be the most variable of the species; in reality, it is no more variable—and probably less—than most of the other species'.

Hevea benthamiana, which has a pure white latex, is one of the most distinct of the species, and is found only north of the Amazon River in the northwestern part of the Amazon Valley and the upper Orinoco. Individual trees can be recognized readily by the golden indument on the undersurface of the leaves. There is comparatively little variability within the members of this species in the undisturbed forest. It is normally a medium-sized tree but may reach a height of 80 ft., and it is found in low, alluvial, flooded areas and often in all-year bogs. Its natural range overlaps that of *H. brasiliensis* only in a very small area west of Manaos. Natural hybrids of the two species have been found in that area.

Hevea guianensis is the most widespread of all the species of *Hevea*, and is found throughout the range of the genus. It exhibits much morphological variability, and Schultes (1956) suggests that its wide range and this variability may possibly indicate that *guianensis* is one of the oldest species of *Hevea*. Together with its variety, *lutea*, it may be recognized by the conspicuously erect leaflets. Both are tapped over a wide area, especially in eastern Colombia. *H. guianensis* is a giant tree that may reach a height of more than 100 ft., emerging through the jungle canopy. It prefers well-drained uplands or high river banks that are subject only to light flooding for short periods.

Hevea spruceana occurs in great abundance on low and deeply-flooded river banks along the Amazon River from its mouth up to about its confluence with the Ica or Putumayo, and along the lower courses of the tributaries of the lower Amazon. Seeds of *H. spruceana* are the largest in the genus (Plate 7). Its watery, white latex produces only small quantities of rubber of inferior quality, but it is included in the rubber-bearing species of *Hevea* because it has received more attention for possible use in plantation plantings than other species (apart from *H. brasiliensis*). At one time it was considered as a possible rootstock for *H. brasiliensis* in wet areas, but as such it has given uniformly poor results. Hybrids of *H. spruceana* and *H. brasiliensis* have been studied, and some of them have proved promising for disease resistance in the Americas. In the East, the hybrids are reported to have increased greatly the yields of high-yielding clones when the hybrids were used as rootstocks.

Morphology and Anatomy of Cultivated Forms

Rubber production in *Hevea* is entirely from the bark. The roots, wood, leaves, and other portions of the plant do not enter into rubber production directly. Tree stumps without leaves have been tapped and have continued to yield latex for long periods. In some cases, such stumps formed root-grafts with neighbouring trees. Frey-Wyssling (1932) tapped a felled tree for six weeks before it proved impossible to obtain a flow of latex any longer. A predominant portion of the rubber synthesis in *Hevea* is the result of bark activity at or near the point where the tapping is done. Following tapping, latex movement has been detected many feet from the tapping cut, and it can be assumed that cell activity in the regeneration of the latex constituents removed by tapping is stimulated throughout the area where flow occurs. Frey-Wyssling (1932) and Schweizer (1941) showed that the rubber in the latex that flows out after a tree is tapped, originates principally within 1 or 1·7 metres below the tapping cut. Lateral (horizontal) flow is at a rate of about one-ninth that of longitudinal flow. The drainage area, therefore, comprises the entire panel below the tapping cut to a depth of 1 to 1·7 metres, plus one-ninth of the vertical distance to left and right of the panel at the level of the cut, constricted to the width of the panel at the base of the drainage area, but with some drainage from above the tapping cut.

Rubber is the major constituent in *Hevea* latex other than water, making up normally some 30 to 35 per cent of the wet-weight of the latex. The tapping operation sets up a movement of latex in the latex vessels and, at the same time, a movement of water and water-soluble materials from the surrounding tissue into the latex tubes—to equalize the pressures resulting from the outflow of the latex. Notwithstanding the movement of latex in the vessels at considerable distances from the cut, a significant portion of the fluid removed from the tree at any tapping was not in the latex before the tapping cut was made: this movement of water and solutes into the latex vessels from the surrounding tissue is commonly termed the 'dilution reaction'. In some fractions of the latex, it has been estimated that nearly a quarter of the volume of outflow may have originated in tissue other than the latex vessels.

The bark is therefore the important tissue in rubber formation and, from the standpoint of rubber production, the anatomy of the bark, and the differences in the anatomy of the bark of individual trees or clones, are important in the selection and propagation of superior types. Bobilioff (1923) made an intensive investigation of the anatomy of *Hevea*, and his illustrations have since been drawn upon extensively to illustrate articles on this subject. From the standpoint of rubber production, the important structures in or related to the bark are the cambium layer from which all new tissue originates, and the specialized vessels, the latex tubes, in which the rubber is found. At the time of Bobilioff's studies, considerable attention was being given to the bark-latex-vessel relationships in the search for measurable characters that would have a sufficiently close relationship to yield to be of use in predicting, in immature seedlings, the performance of the mature tree. The development of bud-grafting has largely obviated the necessity for testing seedling performance in the establishment of plantations, and the measurement of bark thickness and the number of latex-vessel rows no longer assume the importance they once did.

Bark Colour

Bark colour is considered by native tappers in Brazil as having considerable significance. The rubber from the so-called 'black-barked' trees is reputed to be of particularly good quality, and the yield of the trees is said to be high. The colour of the inner bark of *Hevea* varies from slightly pink to a dark red or purplish (black bark), and the proportion of trees with dark bark varies with localities, the highest proportion being found in the southwestern part of the Amazon Valley. In some areas, pure stands of the black-barked trees were reported.

Bark Texture

Hevea bark varies from hard and gritty, with a high proportion of stone cells, to soft and cheesy or soft and corky. The texture of the bark has not been found important in the selection of seedlings for yield, but has been of great importance in the selection of high-yielding seedlings for vegetative propagation. The variation in bark texture is a normal variation in seedling populations; but vegetative propagation results in clones with uniform bark characters, and it is desirable to select those that can be tapped most easily.

Bark Thickness

Rutgers (1918) studied 8,787 seedling trees of *Hevea brasiliensis* and reported bark thicknesses varying from 6·5 to 15 mm., although nearly half of his measurements were from 10 to 11 mm. La Rue (1920) studied the variation in bark thickness in individual trees at varying heights from the ground. He reported that the mean thickness of the bark of the 160 eight-year-old trees that he measured was 10·5 mm. at a height of 1 ft.; 8·9 mm. at 2 ft.; 7·7 mm. at 3 ft.; 7·0 mm. at 4 ft.; and 6·5 mm. at 5 ft.

La Rue compared the bark thickness of a tree with a conical trunk (typical of seedlings) with that of a tree with a cylindrical trunk (typical of bud-grafts, but in this case a seedling). The conical tree had a bark thickness of 11·5 mm. at a height of 1 ft., whilst the bark of the cylindrical tree was 8·3 mm. thick at that height. At 5 ft., the bark thickness of the conical tree had decreased to 6·5 mm., while that of the tree with the cylindrical trunk had decreased little and was still 8·0 mm.

La Rue found a correlation of only 0·26 between the bark thickness and the annual yield of rubber. In other tests, La Rue (1921) found a correlation of 0·366 between bark thickness of mother trees and that of their seedling progeny, indicating that some factor is inherited for bark thickness but that it is partially masked by other factors.

Latex-vessel Rows

In *Hevea*, the rubber is contained in the tree as a latex in a system of articulated latex vessels, which are the conducting organs that allow the latex to flow to and out of the tapping cut. They originate from the cambium layer, and the latex vessels formed at any given time anastomose freely and form a cylindrical layer around the stele. The next layer is formed inside those formed previously and is largely independent, though some interconnection occurs between adjacent cylinders. The latex-vessel system consists of a number of lacy concentric cylinders contained in the bark of the tree. The outer cylinders are distorted and sometimes disrupted, owing to the pressures arising from increasing size of the tree, and some of the interconnections developed in the young cylinders are later destroyed by the growth pressures on the old cylinders. The number of these cylinders at different heights in any given tree varies considerably, and this variation is closely related to bark thickness which, in general, is greatest at the base of the tree and decreases with distance from the ground. The number of cylinders varies from tree to tree, and this variation is independent of the variation in thickness of the bark. La Rue (1921*a*) found a correlation of only 0·15 between bark thickness and the number of latex-vessel cylinders in a population of 1,004 mature trees studied by him.

In addition to the strain put, by the outward growth of the bark, on the latex vessels of any given cylinder, there is an increase in the distance between cylinders. The innermost cylinders are close together and the latex vessels comprising each cylinder are here close together. In tapping, each millimeter of deeper penetration of the cut intercepts a greater and greater number of the latex-vessel cylinders and gives progressively higher yields.

A bark segment cut for study of the bark structure and latex-vessel arrangement presents the latex vessels, in cross-section, in a series of rows. Thus the terms latex-vessel rows, latex-vessel cylinders, and latex-vessel rings are, for general reference, synonymous. The number of rows of latex vessels may vary from one or two in young seedlings to more than fifty in the bark of large trees.

Latex-vessel Size

The number of latex-vessel rows has been found to be correlated significantly with the yield of seedlings, the correlation reported by La Rue (1921*a*) being 0·513. This correlation is high but not sufficiently close to be used as an independent index of yield. In recognition of the fact that the size of the latex vessels, as well as their number, would have a strong effect on yields, Ashplant (1927, 1928) suggested the use of latex-vessel diameter as an index of yield. As the internal pressures of the growing bark distorted the vessels in the bark and made measurement of the diameters untrustworthy, Ashplant proposed that the diameter of the undistorted vessels in the leaf petioles be used. He held that a large proportion of the low-yielding trees could be eliminated at an early age by the simple device of discarding those with a small latex-vessel diameter. After a brief period of popularity, this criterion of yield was discarded because the method of determining latex-vessel diameter proved slow and cumbersome, and moreover the underlying principle was never substantiated as valid. Summers (1930) published an excellent review of this tube-bore (latex-vessel diameter) theory, finding some confirmation of Ashplant's claims but, nevertheless, general scepticism among scientific workers.

Bark of Clonal Trees

The wide-scale adoption of vegetative methods of propagating *Hevea* largely obviated the need for comparing new seedling production except in breeding tests for developing new, superior clone-mother trees. The vegetative progeny of a single clone-mother tree is known collectively as a clone, and is given a special designation consisting usually of an abbreviation indicating the originating estate followed by a number to differentiate it from other clones. In *Hevea*, the budding operation is accomplished by implanting a bud of a high-yielding scion in the bark at the base of a seedling rootstock. The details of this budding operation will be discussed later (pp. 183–4).

Bud-grafting brought about the development of an entirely new type of tree. The normal seedling *Hevea* stem tapers regularly from base to top, whereas trees resulting from the bud-grafting of high-yielding scions onto 'seedling' rootstocks lack the characteristic growth of 'seedlings' and take on the characteristics of branch growth rather than of stem growth. Thus clonal trees are cylindrical in form, with much less taper than is characteristic of 'seedlings', and a comparable growth character is also found in the bark of the clonal tree, which has a uniform thickness for a much greater height than does that of 'seedlings'. The maximum thickness of the bark of the clonal tree is less than that of a 'seedling' of comparable size (pp. 67–8), and greater care is needed in tapping it, although this need is partially compensated for by the fact that all of the trees of a monoclone planting have uniform bark and so the tapper does not need to readjust his tapping from tree to tree as is necessary in tapping variable 'seedlings'. This advantage of clones may be lost in some areas, as for example in the Western Hemisphere where polyclone plantings have been recommended to avoid building up specialized strains of disease organisms.

Brown Bast Disease Caused by Tapping

Standard tapping sequences and designations of tapping methods will be discussed elsewhere, as, at this point, we are interested in tapping as an innovation in the economy of the *Hevea* tree and its effect on the health and well-being of the tree. Early in the development of the plantation industry, it was found that there was considerable variation in the reaction of individual trees to tapping. Thus many seedlings, though mostly those with above-average yield, had a tendency to dry up and stop bleeding when tapped even with a conservative tapping intensity of alternate-day tapping on a half of the circumference of the tree. This phenomenon occurred frequently in 'seedling' areas and was known as brown bast. Rands (1921) showed that this condition resulted from a physiological reaction to being tapped, and consisted in the precipitation of wound gum in the severed ends of the latex vessels. In some cases, the wound gum merely clogged the vessels and impeded the flow, while in other cases it completely closed the vessels and caused a complete stoppage of the flow of latex. In most cases, it was found that reducing the intensity of tapping reduced the incidence of brown bast.

Cambium Injury Caused by Tapping

The bark of a *Hevea* tree can be pared off carefully in tapping, without any apparent injury to the tree. However, injury results if the cambium layer is cut by the tapping knife: yet it is necessary to cut as close as possible to the cambium layer to get maximum yields. Wounds resulting from injury to the cambium may develop into hard, scarified tissue that makes it very difficult to tap the renewed bark when the area of the tree is again reached in the tapping sequence. Skilled tappers do an almost incredibly good job of deep tapping with a minimum of injury of the cambium; but some wounding is unavoidable.

In the Brazilian jungle, where tapping has been done with the machadinho, the trees have ugly, prominent growths and may become greatly swollen at the base (Plate 8 (*a*)). The trees can recover fully from such wounding only by continued growth and the incorporation of the wound-scars into the wood of the tree (Plate 8 (*b*)), and such recovery may require many years. With planted trees, such a condition would be untenable. In the absence of disease, *Hevea* trees can be tapped continuously for many years, and there is no evidence at present that suggests a limit. Plate 9 (*a*) shows an ancient, wild tree that has survived many years of mistreatment but that, with numerous cuts necessitated by its misshapen trunk, was still yielding over 3,000 cubic cm. of latex at each tapping.

Disease, however, takes a greater toll in single-culture plantations than in nature (where individual members of a species may be separated by many and diverse plants). Continuing improvement in planting material makes the replacement of low-yielding trees commercially desirable, irrespective of disease.

Pre-tapping Yield Tests

In breeding and selection work, it is a matter of urgency to determine the yield of new selections at as early an age as possible. Exaggerated pricking tests such as that using the Cramer knife (Cramer, 1938), or early tapping to the wood as in the Morris-Mann test (Morris, 1931; Mann, 1932), have been used with some success. Other factors, such as bark renewal and rate of increase of flow, are tremendously important in assessing the value of new clones, but such measurements can be obtained only through tapping tests. Early initiation of the tapping tests, with attendant reduction in growth-rate, may have been the cause of the discarding of many selections that might have been outstanding if retained. When the Japanese overran Sumatra in World War II, breeding plots in many cases were abandoned before the new progeny could be tested, and before the discards could be eliminated in other cases. Enforced rest and growth during the war, made it possible to reassess many of these selections after a period of years. Some of the selections that were to be discarded as a result of the initial tests showed outstanding promise in these new tests and outyielded the ones formerly chosen for retention. There may be merit in delaying the testing of new selections, as well as in postponing the initiation of commercial tapping, to prolong the initial growth-rate for an additional year or so.

Bark Renewal

Tapping systems depend primarily on the reaction of the tree and the yield of rubber. There must also be a balancing of the rate of consumption of bark and the renewal of the bark. In the absence of disease, the bark is renewed rapidly if tapping is done conservatively and injury to the cambium is kept to a minimum. A period of at least seven years is needed for the complete renewal of the bark. Dijkman (1951) estimates bark consumption in daily tapping as 2 in. per month, in alternate-day tapping as 1 in. per month, and every-third-day tapping as 0·8 in. per month. He estimates that, if trees are tapped daily in alternate months, bark consumption will amount to 1 in. per month, and that daily tapping every third month will give bark consumption equivalent to 0·68 in. per month. His estimates of the tapping cycle (the time required to use up the original bark of the tree to a height of 1 metre) for three different lengths of tapping cut (one-half, one-third, and one-fourth of the circumference of the tree) are shown in Table IV.

TABLE IV

TAPPING CYCLE IN YEARS AND MONTHS IN RELATION TO INTENSITY AND FREQUENCY OF TAPPING *

Tapping intensity	Tapping frequency				
Portion of circumference tapped	Daily	Alternate daily	Every third day	Alternate month	Every third month
	years	*years*	*years*	*years*	*years*
One-half	$3\frac{1}{3}$	$6\frac{2}{3}$	$8\frac{1}{3}$	$6\frac{2}{3}$	10
One-third	5	10	$12\frac{1}{2}$	10	13
One-fourth	$6\frac{2}{3}$	$13\frac{1}{3}$	$13\frac{1}{3}$	13	20

* From Dijkman (1951).

Growth Characteristics

Leaf Storeys

The growth pattern of young *Hevea* trees is characterized by alternating periods of rapid elongation and consolidation. A flush of growth starts out very rapidly and the first internode may be considerably over a foot in length. The length of the next internode may be less than an inch, and the succeeding internodes are shorter and shorter until growth comes to a temporary stop. At first, the leaves of the new flush are pendant, bronze-red in colour, and quite small. But while terminal growth is halted, the young leaves increase in size, turn green, and become horizontal. As the leaves reach maturity and start their role of photosynthesis, the terminal bud becomes turgid, changes from brown to bright green, and prepares to initiate new growth. A young seedling consists of a series of these flushes of growth.

Growth Pattern and Distinguishing Characteristics of Clones

This flush type of growth can manifest itself in many ways, and many of the selections that have been made and propagated as clones (the vegetative progeny of a single seedling) have characteristic growth patterns by which they may be recognized. Prior to the initiation of branching, the clones may be distinguished with little difficulty by one familiar with the growth pattern. Excellent diagrams and clone descriptions have been published by Heusser (1932), Frey-Wyssling & Ostendorf (1932), Frey-Wyssling & Heusser (1932), and Ostendorf (1932). This established a pattern for the descriptions published later by the Java 'Centrale Proefstations Vereeniging' (Anon., 1939) and by Dijkman (1951).

The distinguishing characteristics used for the identification of *Hevea* clones are based principally on the observable growth-types of the young buddings and of those of the mature budding when ready for tapping. These observations are supplemented by a standardized latex reaction, and may be further supplemented by comparison of the seed-coat patterns which are characteristic for the individual clones but harder to reduce to written classification.

The young buddings are classified as to:

(*a*) *The stem:* its relative growth and physical appearance and particularly as to whether it is erect or leaning.

(*b*) *The bark:* separate observations are made on the bark characteristics of the green portion, the brown-green transition portion, and the brown portion of the stem. In the brown and brown-green portions, the size and shape of the lenticels are important and, in the brown portion where characteristic growth-checking has taken place, the type of bark pattern is observable and is distinct for different clones.

(*c*) *The node:* the points of observation are based on the characteristics of the dormant bud in the axil of the leaf and on the leaf scar, both of which are characteristic of individual clones. The observations are normal or abnormal and whether protuberant or sunken.

(*d*) *The composite shape and appearance of the leaves comprising the youngest full-grown leaf-flush.* The shape is designated as small or large 'hemisphere', small or large 'bow-shaped', or small or large 'truncate cone'. Particular note is made as to the separation between the flushes, as some clones have long separations between the successive flushes while in other clones the flushes appear more or less to merge. Some clones have a relatively dense concentration of leaves at each flush, while others are sparsely foliated. In some, the leaf margins at the periphery of the flush are separate (open umbrella), but in others they meet or overlap (closed umbrella). The relative size of the composite storey is designated by descriptive terms such as broad, narrow, large, small, high, or compressed.

(*e*) *The leaves:* being compound, the *Hevea* leaf is made up of a petiole, petiolules, and leaf-blades. Each of these is used in the description of the clones. For this purpose, the leaves of the youngest full-grown flush are used.

In describing the petiole, the geotropic orientation (horizontal, downward, or upward), the shape (straight; arched, bow-shaped, or convex; concave; sigmoid or S-shaped), and the relative size, are all noted.

With regard to the petiolules, notes are made regarding the geotropic orientation in relation to the petiole (parallel or upwards), the shape (claw-shaped or raised), and the relative size in comparison with those of other clones.

The middle leaflet is used for leaf-blade description and the distinguishing characteristics are:

(1) The colour, lustre, and texture.

(2) The shape and dimensions (the relation between length and width, the location of greatest width, and the manner in which the margins of the leaflet taper into the base and tip) give rise to three descriptive terms: *elliptical*, where the length is about three times the width and the greatest width is about in the middle of the leaflet, with the margins tapering equally towards base and tip; *ovate*, where the greatest width is between the middle of the leaflet and the base; also *diamond-shaped* variation of the elliptical form.

(3) The margin, apex, and base of the leaflets.

(4) The long-section profile (straight or convex) and cross-section profile of the leaflets (flat, V-shaped, boat-shaped—i.e. concave—or reverse boat-shaped—i.e. convex).

(5) Position of the lamina with respect to the petiole (whether open—outspread—or closed—hanging down—, as in an open or partially closed umbrella).

(6) Position of the leaflets with respect to each other (free, touching, or overlapping).

(7) Whether there is any abnormal number of leaflets.

Mature buddings that have reached tapping size differ chiefly from the young buddings in that the permanent branches have been formed and the tree is seeding. A general impression can be obtained by study of:

(*a*) *The stem* (leaning or vertical, round or oval, etc.).

(*b*) *The colour of the stem and branches* (reddish, grey, brown, black patches or blotches, etc.).

(*c*) *The shape of the crown* (broom-shaped, round, conical, oval, etc.). In some clones the main axis keeps on developing and the branches grow scattered along the upper portion of the trunk. In others, terminal growth of the main axis ceases and, with these types, the number of main branches and the other branching habits are important.

(*d*) *Leaf arrangement and density* have the same importance in differentiating between mature clones that they have in young clones.

The Seed-coat

The seed-coat is characteristic of the clone-mother tree and was used by Sprecher (1915) in an early classification of clones. All seeds from an individual 'seedling' are distinguishable from those of any other 'seedling' on the basis of size, shape, and colour pattern. The clones, being propagated vegetatively, reproduce the seed characteristics of the clone-mother. This characteristic is a specific means of differentiating between clones and depends only on having authentic seeds of the clones for reference. The expression of the characters may vary slightly, owing to growth conditions which may affect the size of the seeds. Unequal development of the ovules may result in differences in shape due to unequal pressures within the developing pod. A twenty- to fifty-seed sample is sufficient to determine whether there has been any mixing of clones, as any differences in size, shape, and colour pattern would be immediately apparent. In the East, the experiment stations maintain collections of seeds of commercial clones and are able to identify such clones. Elsewhere, it is necessary for individual workers to maintain their own reference collections.

The Latex Reaction

The latex also is useful in comparing and identifying clones. Many clones have a characteristic yellow colour about the latex and may be recognized readily in comparison with those with white latex. There is every gradation of yellow tingeing, and this character is chiefly of use in comparing clones in which the colour is intensified or lacking. Bobilioff (1931) originated a chemical reaction that is useful in differentiating clones. The method is not influenced by local environment; it can be used with buddings of all ages; and it can be performed in the field if adequate precautions are taken. However, it is slow and lacks the diagnostic precision of seed-coat comparison, as the common origin of many clones makes for similarity of latex reaction.

Latex reaction testing is performed on latex from leaf petioles. Three or four leaves are selected for the test and are designated:

'A', if the leaflets are very young, small, and firm, and brown-green to brown in colour.

'B', if the leaflets are rapidly enlarging, their colour is light brown-green, and their texture soft.

'C', if the leaflets are almost fully grown but still pendant.

'D', if the leaflets are fully grown and are assuming their mature horizontal position.

The leaves are cut off and the latex is caught on a porcelain spot plate. One or two drops of a 1 per cent aqueous solution of calcium chloride are added and the following notations made:

(*a*) *The time*

(i) The time to the first discoloration.
(ii) The colour changes at various intervals.
(iii) The time to the end of the reaction, when no further colour change is noted.

(*b*) *The colour*—red, pink, orange, violet, blue-grey, or black.

(*c*) *The character of the discoloration*, whether in patches or blotches, only around the margin, scaly, or glutinous.

(*d*) *The colour of the serum.*

Compatibility of Rootstock and Scion

The relationship of the clone to its rootstock has been given considerable study by numerous investigators. Studies of particular rootstocks have indicated that high-yielding or vigorous rootstocks affect the yield of the scions. Hybrid seedlings from crossing *Hevea brasiliensis* and *H. spruceana* were used as rootstocks by Schmole (1938, 1941), and gave increases in yield of up to 30 per cent. That clones budded on to seedling rootstocks from certain high-yielding clones gave increased yields was reported by Schmole (1936, 1940) and by the Rubber Research Institute of Malaya (1939). The latter also reported having found that vigorous rootstocks increased the vigour of the scions.

Growth irregularities resulting from the lack of compatibility of clones and understocks have been noticeable in the over-budding of clones for disease control in tropical America. The elephant-foot type of swelling at the bud juncture in base-budding has been accepted as a natural concomitant of budding and not as a result of incompatibility (Plate 9(*b*)) attributable to differences in growth-rate of the rootstock and the scion. In over-budding, the bud union is six to eight feet in the air and hard to ignore. In many cases, the compatibility of the clones is so good that the point of union is almost obscured after several years (Plate 10(*a*)). In other cases, the greater vigour of the top clone is so marked that there results an over-growth that means a union of inferior strength, highly susceptible to wind damage (Plates 10(*b*) and 11(*a*)). In yet other cases, the top is not able to maintain the growth-rate of the bottom clone and there is a resulting decrease in the growth-rate of the synthesized tree.

Lack of Uniform Rootstock

The study of clone and rootstock compatibility has been held back by a lack of uniform rootstocks. Loomis (1942) undertook to provide identical plants for rootstock, nutritional, and other studies by splitting young seedlings. In doing so, he used a modification of methods reported by Zweede (1940) for dividing freshly-germinated seedlings into two plants each, by cutting vertically through both the plumule and the hypocotyl. The cotyledons do not emerge from the seed-coat in *Hevea*, and Loomis's improvement on the methods reported by Zweede consisted in removing the seed-coat and separating the cotyledons, leaving one cotyledon attached to each of the two new plants. Muzik (1953) rooted three-weeks-old stems. This forced the growth of buds situated in the axils of the cotyledons. Splitting the tap-root, when these shoots reached 6 in. in height, provided three substantially equal plants from each original seedling.

Gregory (1951), in Costa Rica, developed a method of producing multiple rootstocks by vegetative propagation from a single plant, normal and adventitious buds being forced to develop. The young shoots were cut off and rooted while still very young, and thus while having the juvenile character of seedling stems that can be rooted with little difficulty. Similar studies were also reported by Wiersum (1955) in Indonesia.

The resulting techniques provide a tool for producing rooted plants of uniform character for use as rootstocks. The splitting method provides paired rootstocks but the Gregory method conceivably could produce unlimited quantities of identical rootstocks. The determination of the relative effect of rootstock and scion, and the study of other physiological problems, should be facilitated by the improvement and use of this rooting technique.

Plant Improvement in *Hevea*

Plant improvement in tree crops such as *Hevea* is a long and tedious process. In apples, it has been estimated that a period of thirty-five years is required for the production and establishment of a new variety. In rubber, it has been stated that about seventeen years are required before a new clone can be recommended for general use and that this does not include the years of breeding tests leading to the first establishment of the clone. Actually, the precise number of years required in a breeding programme is not important except in the financial justification of the research and in the fact that under present working conditions it approaches both the effective active period of individual scientific workers in the tropics and the economic life of rubber plantations. Coupled with the fact that financial recognition of outstanding scientists forces them into important but scientifically circumscribed administrative positions that limit their direct scientific contribution at a time when it could be of greatest importance to the industry, the long period needed for the proving of a new clone has been a distinct hazard to the rubber plantation industry in its contest with manufactured (synthetic) rubber. In the field of private research, the rigid enforcement of early retirement of tropical employees has constituted a distinct loss to the entire rubber-growing industry.

The 'Hevea' Flower

The staminate (male) and pistillate (female) flowers of *Hevea* are separate but are borne on the same inflorescence. The pistillate flowers are terminal to the central stem and major branches of the inflorescence (Plate 12(*a*)), but the staminate flowers are much more numerous than the pistillate flowers. Hand-pollination of *Hevea* is a comparatively simple task, since the flowers are sizeable, requiring at most a low-power lens for adequate vision. There are needed a small pair of scissors for removing the staminate flowers, tweezers to place the staminate flower of the chosen tree on the pistillate flower, and a small cotton plug to hold the staminate flower in place and exclude foreign pollen. Some skill is needed but not more than can be gained quickly by intelligent native assistants. The greatest difficulty of the pollinating operation is that the flowers are produced high up on the tree. This normally necessitates the use of ladders or the erection of scaffolding (Plate 11(*b*)), though Campaignolle & Bouthillon (1955) found it possible to espalier *Hevea* and thus produce flowers near the ground where pollination could be accomplished without climbing.

Cytology and 'Hevea' Breeding

Chromosome counts made by several investigators show a relative uniformity which would indicate that all species of *Hevea* have a normal 2n count of 36. Baldwin (1947) considers this as an approximation of a tetraploid condition with the diploid number $2n = 16$. Ramaer (1935), Paddock (1943), and Dijkman (1951) agree in counts of $2n = 36$. Heusser (1919) reported a count of $2n = 16$, $n = 8$, and Bangham (1931) reported a count of $2n = 34$, $n = 17$.

These chromosome counts do not agree exactly; but the ease with which the various species cross in nature indicates that, if there is any real difference in the chromosome numbers, such differences are not limiting factors in cross-fertilization. The work of Baldwin covered most of the known species of *Hevea*. Heusser, Dijkman, and Paddock reported on *H. brasiliensis* only. Bangham studied trees of *H. brasiliensis*, *H. guianensis*, and *H. spruceana*. Ramaer studied the same species as Bangham and also a hybrid, *H. spruceana* × *H. brasiliensis*. Perry (1943) studied *H. brasiliensis* and *H. spruceana*. Each of the investigators, except Baldwin, found the same number of chromosomes in all of the material which they studied. The differences reported are not related to those existing between the species, but relate either to differences within the species or to those attributable to the techniques of the investigators. Baldwin reported that one specimen of *H. guianensis* had a 2n count of 54 and one of *H. pauciflora* a 2n count of 18. These counts are exceptions, however, since Baldwin found $2n = 36$ to be the prevailing count for these species.

Rubber Production an Abnormal Function

The large-scale production of rubber by *Hevea* is forced on it by man and is not normal for the tree. As compared with the production of fruit or seed, it is an abnormal function. It is not directly comparable to the production of sugar or starch, which are directly related to the nourishment of the plants that produce them, as are the fruit and seed to propagation. Although rubber is obtained in a liquid form (latex), its production within the plant is not like that of the sap which is drained from the maple tree. The circulation of the sap from root to twig and from leaf to cambium is a normal function not only in the maple tree but in all trees, including *Hevea*. Free movement of latex within the specialized latex vessels is not normal, though osmotic transfer of substances undoubtedly occurs. Only when the bark is cut does an actual flow of latex take place.

Rubber Formation a Normal Function

The biological formation of rubber within the plant is, on the other hand, a normal process that continues as long as the cell is active. There

Photograph by permission of ARS, U.S. Dept. Agric.

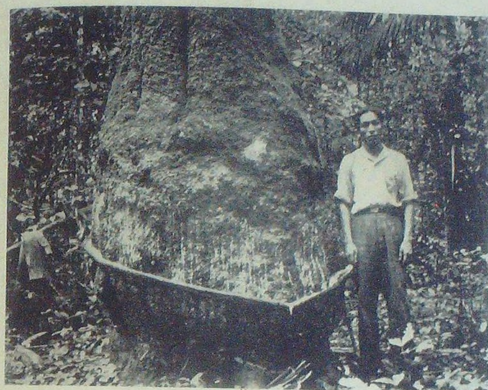
(*a*) Wild tree of *Hevea brasiliensis* that has been tapped with the aid of native machadinhos, tapped over the old scars and burrs with an Amazonas knife, and finally tapped far up the trunk with the Amazonas knife after the bark at the base had become too scarred for further tapping.

Photograph by permission of E. G. Holt

(*b*) Planted 'seedling' *Hevea* trees in the Brazilian jungle. These trees have been tapped successively by the machadinho, Amazonas knife, and jebong knife.

Photograph by permission of ARS, U.S. Dept. Agric.

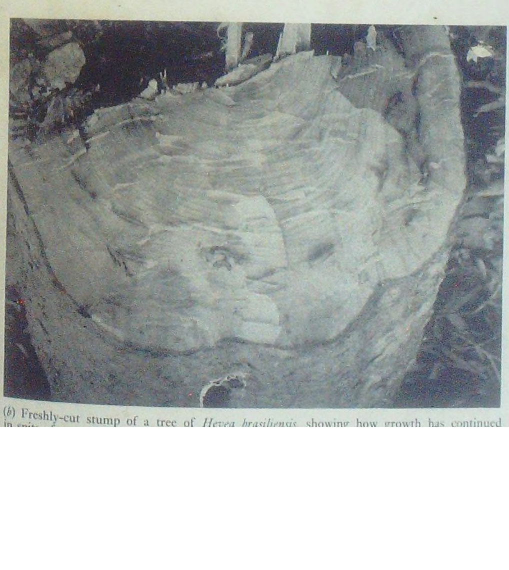
Seeds of *Hevea brasiliensis* (*d*) compared with those of H



Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Base of a tree of *Hevea brasiliensis* badly swollen from repeated tapping with a machadinho. Instead of individual cups for each cut, Indian tappers near Boim, Para, Brazil, constructed a trough to collect the latex from numerous cuts.

PLATE 10

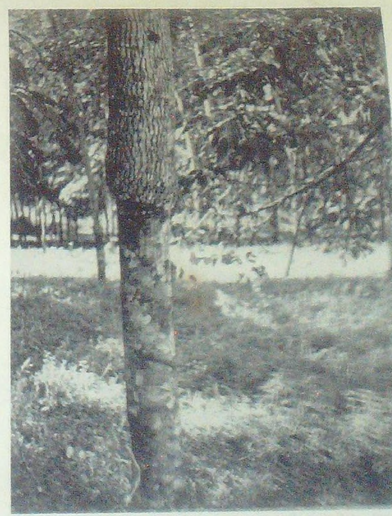


(*b*) Freshly-cut stump of a tree of *Hevea brasiliensis* showing how growth has continued

(*a*) Ancient jungle tree of *Hevea brasiliensis*. It is 5·4 metres in circumference and has survived years of mistreatment, but still yields more than 3,000 cubic cm. of latex per tapping.

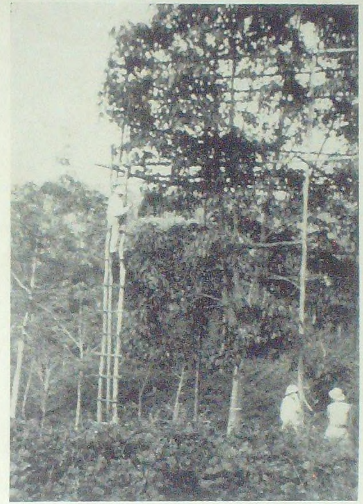
Photographs by permission of ARS, U.S. Dept. Agric

(*b*) Incompatibility and over-growth of a bottom-bud union.



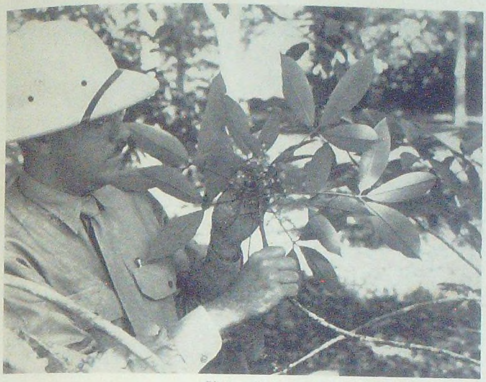
Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Over-growth typical of incompatible clones.



Photographs by permission of ARS, U.S. Dept. Agric.

(*b*) Scaffolding erected for use in hand pollination of *Hevea* flowers at Fordlandia, Brazil.



Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Flowering branch of *Hevea brasiliensis.*

(*b*) *Hevea* planting converted to a breeding garden by cutting back all trees, allowing two or three shoots to develop on each stump, and budding each shoot with a different high-yielding or disease-resistant clone.

PLATE 12

(a) A tree of *Castilla elastica*.

Photographs by permission of ARS, U.S. Dept. Agric.

(b) A large tree of *Castilla elastica* with exposed buttress roots.

PLATE 13

is a concentration of rubber within the latex vessels that is not normally exceeded but, when that concentration (some 50 to 60 per cent of the wet-weight of the latex) is reached, there is no evidence that biological action stops or that the rubber thereafter remains unchanged, without further chemical transformation. However, the latex remains relatively static and no appreciable movement occurs until there is an injury comparable to the onset of tapping. The rapid renewal of the rubber removed from the tree by tapping constitutes an abnormal magnification of a normal function. A tapped tree produces hundreds of times as much rubber as it would have formed if it had not been tapped.

Breeding for High Yield

The development of high-yielding rubber trees therefore involves the intensification of a normally low rate of rubber formation into a high rate of rubber renewal. Genetically, this could involve merely a single gene and be inherited as a simple Mendelian factor. The involvement of growth and nourishment factors and adaptation to soils and climate would offer, in that case, no greater difficulties than are encountered in the breeding of any other plant.

Experience in breeding *Hevea* for rubber-yield tends to indicate that yield is controlled by a relatively limited number of factors and that these factors can be manipulated in a breeding programme to obtain a higher and higher intensification. Clonal propagation of *Hevea* has made it possible to take advantage of each gain in level of yield, but the prospect for continued gains, both within the germ-plasm previously available in the East and by utilizing new germ-plasm made available by late jungle exploration, is very great.

Germ-plasm Available in the East

Bouychou (1956*a*) has made a study of the available records on the introduction of *Hevea* into the East, on the distribution of the seedlings to various plantings, on the first seed production, and on the performance of the first 'seedling' populations in the East. He found the written record confused and contradictory, but was able to elucidate the first distribution of the Wickham material which has been the source of nearly all of the *Hevea* planted in the East.

In his studies regarding the origin of the Wickham seed, Bouychou was impressed with the performance of the first generation of plants produced from seed grown in the East. In private correspondence prior to the publication of his article on the origin of the Far-East rubber tree, Bouychou (1956) speculated that the great isolation of the *Hevea* trees in the Amazon Valley had led to a high rate of inbreeding. In this speculation he was greatly influenced by the findings of Warmke (1951, 1952), who showed that heleid midges are chiefly responsible for the natural pollination of *Hevea*. These minute insects cannot operate at the distances required for the cross-pollination of the scattered trees on the Tapajos River where Wickham made his collection of seed. On this basis, Bouychou postulated that it was quite possible that the native *Hevea* trees in the Amazon jungle where Wickham's seeds were obtained are highly inbred, and that the individual trees represent genetically pure lines.

A significant portion of the first seed produced in the East could therefore have resulted from the hybridization of seedlings from different inbred lines. Not all of the original seedlings represented individual pure lines, since most or even all of the seed in any given planting could have come from a single mother-tree in the Amazon. An unexpectedly large proportion of high-yielding selections was made from the first plantings resulting from seed produced in the East. Later, tests of cross-bred, unselected seedling populations in the East showed that few were outstanding in their productivity, and that only a fractional percentage could be chosen as promising new clones for vegetative propagation.

Some 2,700 'seedling' trees were obtained from the 70,000 seeds and seedlings taken by Wickham from Brazil to England. The seedlings were sent to the East in Wardian cases. Other seeds of *Hevea brasiliensis*, as well as of *H. spruceana*, *H. guianensis*, and a species called *H. collina*, were introduced later, but the great majority of the high-yielding clones which are being planted at the present time were selected from the direct progeny of the Wickham collection. That collection originated in a relatively small area on the Tapajos River only a short distance from where this enters the Amazon. The source of the overwhelmingly predominant portion of all of the rubber trees, both clonal and unselected, in the East was the Wickham collection, and the source of those seeds was only a few square miles of jungle out of a natural distribution measured in thousands of miles of winding rivers and still only partially explored jungle.

Specific Origin in 'Hevea'

Seibert (1947, 1948) and Schultes (1956) have pointed out that the first usage for *Hevea* by aboriginal natives of the Amazon Valley was probably of the seeds for food. Seibert postulated that the natural development of the *Hevea* genus was greatly affected by the transportation back and forth of the seeds for food, the preservation of native trees in clearings, and the planting of additional trees. Schultes recognized the use of *Hevea* seed as food, and particularly its ceremonial usage, but found that such usage had been confined largely to the northwestern portion of the Amazon Valley. Elsewhere, the use of *Hevea* seed as food was not unknown but must have been limited to periods of famine, when no other food was available. Furthermore, Schultes emphasized that man's relatively recent interest in *Hevea*, either as a food or as rubber, could not account, as Seibert postulated, for extensive alteration in the evolution of the genus.

New Germ-plasm in the West

Hevea is a long-lived tree and, in the jungle, a century makes little change in the resident population. Many centuries of isolation must have preceded Wickham's collection of seed on the Tapajos River, although equal isolation may not have obtained in other areas where the stands were much heavier and thus cross-pollination by midges was more probable. Germ-plasm from these other areas has become available within the last couple of decades, because of the increased exploration possible in the period of intensified exploitation of jungle products due to war-time needs. The major portion of the new selections is at Belterra, Para, Brazil, where the Brazilian government is maintaining a production plantation and experimental area. Some of the new material is available at the Peruvian Experiment Station at Tingo Maria, Peru; some is in the Colombian Experiment Station at Villa Arteaga, Colombia; and some is at experiment stations in Costa Rica and Guatemala. A few selections, chosen for resistance to disease rather than for yield, have been exchanged by the Brazilian Government for high-yielding clones from Malaya. But, as in the case of 'seedling' populations derived from the Wickham collection after several generations of mixing, the major portion of the 'seedlings' under test in experiment stations in the Americas are low-yielding. To date, selection has been predominantly for disease resistance, and only a beginning has been possible in the establishment of lines selected for yield.

Breeding Problems in the East

Breeding operations in the East have been confined largely to the progeny of the Wickham trees, and have consisted in the development of clonal parents that show the ability to pass on to their vegetative progeny the factors involved in high yield. To produce clone-mothers, breeding lines have been established by controlled pollination, using as parents clones known to produce high-yielding progeny. A potential yield of a ton of rubber per acre per year would seem feasible through a continuation of the breeding work now under way at the rubber research institutes in the East; indeed, plot yields exceeding that amount have been reported.

Getting *Hevea* to the East without its worst American enemy, the South American leaf-blight, was a stroke of luck. This disease is caused by a parasitic fungus, *Dothidella ulei*, that is native throughout the natural range of *Hevea* and has now spread throughout the areas of the Americas where rubber growing is being attempted—except in the northern part of the Caribbean area, where at least temporary protection has been given by the prevailing trade winds.

Several diseases soon manifested themselves in the East, and disease control has become an important factor in the development of the rubber plantation industry. In the Americas, the attacks of leaf-blight prevented or retarded planting for nearly fifty years. Well-organized research and intensive disease-control measures were needed in the East to protect the plantations and make rubber farming possible, but their counterpart was not available in the West where leaf-blight made the culture of rubber impossible.

Sanitation measures and fungicidal treatments served to protect the Eastern plantations from disease, though several selections were found with some resistance to foliage diseases such as those produced by *Phytophthora* and *Oidium*. In the case of the latter, chief reliance has been placed on sulphur dusting to keep the disease in check. One outstandingly resistant clone was found, but its yield has been disappointing.

Breeding Problems in the West

Rubber production was not found possible in the Western Hemisphere until control measures were developed for leaf-blight. The Ford Motor Company of Detroit, Michigan, obtained from the Government of Brazil a million-acres concession on the Tapajos River slightly to the south of where Wickham collected his seed. Here a plantation headquarters was set up and called Fordlandia. Extensive planting operations were promptly initiated, but it was found impossible to combat the leaf-blight, and the only healthy trees were those on the tops of the small hills that made up the bulk of the plantation. It appeared that good air-drainage was protecting the trees in these exposed situations and so another site was sought that might afford better conditions. The unplanted portion of the concession was returned to the Brazilian Government in exchange for a similar concession nearer the mouth of the Tapajos River, and a second attempt was made to start a plantation on a high plateau some 90 ft. above the river level. This site was called Belterra and on it there are now some 17,000 acres of healthy rubber trees. However, these trees are healthy today because of control measures that were finally adopted, and not because of the good air-drainage that had been expected to give them protection.

The Goodyear Plantations Company started plantings in Panama, making use, in the beginning, of a small nursery originally established by the United States Department of Agriculture at the Canal Zone Experiment Station at Summit. The plantation purchased by Goodyear was on the northwestern edge of Gatun Lake. Leaf-blight entered the plantings almost immediately and spread rapidly. Goodyear looked for another location that might be free from the disease and, after detailed surveys, felt that a suitable area could be found in Costa Rica. Although a small plantation of *Hevea* rubber trees at Turrialba was found to be diseased, a small plantation of healthy trees was located at Cairo. The rubber trees on this plantation had been abandoned and were badly overgrown with secondary jungle, but showed no evidence of any infection by leaf-blight. Goodyear arranged to take over the plantation at Cairo and immediately started cleaning out the non-rubber trees that had invaded the plantation. Almost simultaneously, the plantation was attacked by South American leaf-blight and it was evident that the freedom of the plantation from infection had been due to the protective canopy of the secondary jungle trees. It was apparent that there could be no effective *Hevea* plantation development in these areas of Panama and Costa Rica without some control of the leaf-blight.

First Top-working of 'Hevea' in Brazil

Under the technical leadership of J. R. Weir and Carl D. La Rue, and with the active co-operation of the Goodyear Plantations Company, which furnished the occasional services of Walter N. Bangham, the Ford Company initiated trials of top-budding with disease-resistant selections that had been established on their estates in Brazil. Some of the top-working clones were selections from *Hevea brasiliensis* from various parts of the Amazon Valley. Some use was made of bud-wood from other species of *Hevea* that were known to be highly resistant to the disease. Owing to lack of precise evidence regarding the degree of resistance of the top-working clones used, the top-working experiments were not entirely effective; but they were sufficiently successful to encourage continuation.

The United States Department of Agriculture

The United States Department of Agriculture was brought into the picture at the request of the Goodyear Plantations Company in 1937, and initiated, at Cairo, Costa Rica, the first breeding tests to produce trees resistant to the disease. Unfortunately, the trees that had been considered disease-resistant, and that had been selected for the breeding tests, had only recently been freed from the weed trees which had been allowed to take over the planting by the former owner. Both the trees and the progeny developed by hand-pollination soon became diseased.

In 1941, the United States Department of Agriculture initiated a long-range programme to encourage rubber production in the Western Hemisphere. A pathologist, M. H. Langford, was dispatched to Panama to study the leaf-blight, and he was later transferred to Costa Rica to an experiment station that had been established at Turrialba. Langford made two important contributions to the control of leaf-blight. He first developed (Langford, 1943) a satisfactory method of fungicidal control of the disease, that made it possible to grow susceptible seedlings to the budding age and successfully budded plants to top-budding age. Field spraying was never contemplated, except in the case of young trees to be top-worked, because of the cost. Langford's second contribution (cf. 1945) was the development of a rating code that could be used in evaluating disease-resistance of seedlings. This code has proved satisfactory in establishing uniformity in rating terminology in the different countries and thus in establishing some comparability of ratings.

Selection for Resistance to Leaf-blight

Fungicidal control and the development of a reliable gauge for disease resistance, established the first firm foundation for rubber production in areas of the Western Hemisphere where leaf-blight is prevalent. In the beginning, it was necessary to depend on three-component trees (rootstock, high-yielding panel clone, and disease-resistant top), since the development and proving of new clones combining disease resistance with high yield would take many years. Disease resistance could be determined usually in a single year, and subsequent readings have seldom changed the disease rating.

Effective fungicidal protection made it possible to use any available seed for the production of rootstocks without regard to their resistance to leaf-blight, and also to grow the base-budded plants with high-yielding scions to an age where they could be top-budded with disease-resistant clones. As will be seen later, these statements oversimplify the resulting developments; for a long period followed, during which clone compatibility, the effect of top-working on growth and yield, and the specialization of strains of the causal fungus, were all tested. But the important thing was that this development laid a suitable basis for immediate planting.

Using Langford's gauge as a basis of comparison, duplicate test blocks of top-working clones were established in several different countries of Latin America. In each case, the test blocks were alternated with blocks of highly susceptible clones to provide a source of constant inoculum. As was to be expected, some of the clones first recommended for top-working proved undesirable later. This was due partly to incompatibility with certain of the high-yielding clones, partly to lack of precision in the first disease-resistance ratings, and partly, perhaps, to the development of new strains of the fungus. Later, the resistance readings were much more accurate. Protection against specialization of the fungus in field plantings was sought through the use of clone mixtures, to provide a variety of tops rather than a single monoclone top that would have encouraged specialization.

Three classes of clones were tested and found promising for top-working of high-yielding budded trees: (1) Jungle selections of *Hevea brasiliensis* and crosses between *H. brasiliensis* selections. (2) Crosses between jungle selections of *H. brasiliensis* and high-yielding clones from the East. These were the primary clones tested both for disease resistance and for high yield, and later used in the back-crossing programme to develop new clones combining resistance and yield. (3) Interspecific hybrids, particularly those between high-yielding Eastern clones of *H. brasiliensis* and selections of *H. benthamiana*. Some of these show outstanding resistance to leaf-blight and a sufficiently high yield to replace the high-yielding Eastern clones for base budding.

Resistance to Diseases Other Than Leaf-blight

In the foregoing discussion, resistance only to leaf-blight has been given consideration. Although the control of leaf-blight has been the chief concern of the disease investigations in the Western Hemisphere, an outbreak of target leaf-spot, caused by *Pellicularia filamentosa* (Pat.) Rogers, occasioned concern in Peru, whilst a virulent epidemic of *Phytophthora* leaf-fall and dieback, caused by *Phytophthora palmivora* Butler, was experienced in Costa Rica.

Carpenter (1951) developed control measures for target leaf-spot in Peru and conducted resistance tests that laid a basis for breeding for resistance. The most promising clones for resistance were of *Hevea rigidifolia*, which appeared to be highly resistant in general. Clones of both *H. benthamiana* and *H. pauciflora* showed some tolerance to the disease.

Carpenter (1954) and Manis (1954) made a study of the more serious outbreak of *Phytophthora* leaf-fall and dieback in Costa Rica. They were able to demonstrate that certain clones have a significant degree of resistance. Of eleven clones listed by Manis, only one was straight *Hevea brasiliensis*. One was a natural interspecific hybrid between *H. spruceana* and *H. brasiliensis* and, of the rest, six were interspecific hybrids between *H. benthamiana* and *H. brasiliensis*, and three were 'seedlings' or clones of *H. benthamiana*. The breeding project in Costa Rica was terminated before the work could be carried to a successful conclusion, but the efforts of these investigators and of E. P. Imle, who headed the research work in Costa Rica, demonstrated clearly that resistance to *Phytophthora* leaf-fall and dieback can be attained by breeding.

Inbreeding of 'Hevea'

The theory propounded by Bouychou (*see* p. 79), that the existing trees in certain parts of the Amazon Valley are highly inbred, is one which a person would like to accept, if possible, because of the difficulties involved in artificial creation of inbred lines. For that reason, it is particularly important to use care in the evaluation of the evidence. The development of high-yielding plants by induced polyploidy or by hybridization of pure-line selections obtained by repeated self-pollinations has been highly successful in the improvement of farm crops. *Hevea*, however, appears to be a tetraploid, and the use with it of colchicine or X-ray treatments has produced only abnormalities. Therefore, of these two lines of improvement, only inbreeding is left, and the degree to which nature may have already purified or segregated the strains may be of great importance in future breeding programmes.

Normally, there is a very low rate of set of seed after hand-pollination in *Hevea*. A rate of 2 to 4 per cent seed-set is seldom exceeded. Selection of heavy seeders as mother trees has greatly increased the yield of seed, but such selection is limited by the consideration of other breeding qualities as well as seed-set.

In self-pollination in *Hevea*, the seed-set is very low and some clones are at least partially self-sterile. With most clones, seed production in monoclone blocks is low. It is possible to pick seed in the borders of adjacent monoclone blocks with the great assurance that the majority of the seeds will be crossed rather than selfed. A few clones have been found that give good yields of seed in isolated monoclone blocks, and these clones have been used as sources of clonal seed for field planting without budding. The general rule in *Hevea*, however, is cross-pollination rather than self-pollination. This may stem from the tetraploid character of the cytogenetic make-up. It adds a difficult and possibly almost insurmountable obstacle to the establishment of the pure lines needed in the improvement of rubber trees by intraspecific hybridization.

Detailed studies of all populations of *Hevea* in the Amazon Valley are justified, to determine to what degree there has been pure-line selection in the individual populations, and also to study the variation between the populations of widely separated areas.

Interspecific Hybridization

Many interspecific hybrids of *Hevea brasiliensis* and other species with common habitats have been found, usually in disturbed sites, or rarely in virgin jungle, and many others have been created artificially. Some of the interspecific hybrids studied in Brazil are among the best of the disease-resistant selections. As has been shown above, there is no cytological bar to the interbreeding of the species, and no difficulty has been experienced in the production of interspecific hybrids artificially. Less than half of the known species of *Hevea* have been used in the hybridization tests, and, even in those species that have been used, only a small part of the available variability has been sampled. The success of the hybridization tests to date indicates that interspecific hybridization represents a highly promising line for the establishment of high levels of disease resistance.

Some of the clones that have resulted from the study of interspecific crosses may also be of exceptional value for yield. In their early years these clones were not outstanding, but yields in the fourth, and later, years of tapping indicate that their productivity may be sufficiently high to justify their use in areas where their resistance to disease will avoid the necessity of top-working. Under such conditions, they may be expected to yield somewhat less than good high-yielding Eastern clones but at least double the yield of unselected seedlings. As it is possible to use them without top-working, they can be established in the field at less cost than other stock, and their use, together with some of the straight *Hevea brasiliensis* selections that have proved high-yielding and disease-resistant, has been recommended for small-farm plantings in Brazil.

Back-crossing and Out-crossing

Tysdal & Rands (1953), and Rands & Polhamus (1955), have given details of the back-crossing programme outlined for the improvement of *Hevea* in the Western Hemisphere. The progeny obtained by crossing a high-yielding Eastern clone with a disease-resistant American clone are normally at least 50 per cent commercially disease-resistant, and individuals can be selected that have a high degree of resistance. Yields have been poor, though higher than would be expected without the Eastern parent. Back-crossing to the Eastern parent has given progeny that retained the disease resistance of the American parent and that had a higher yield than the F_1 population. For yield intensification, the Eastern clones as a whole have been used as the recurrent parent—rather than back-crossing only to the specific Eastern clone in the primary cross.

In practice, the F_1 hybrid seedlings are subjected to intensive disease tests in the nursery, where they are alternated with highly susceptible seedlings to assure abundant inoculum. Only the seedlings with the highest ratings for disease resistance are retained for further tests. All disease-susceptible seedlings are eliminated immediately. Seedlings retained for further study are made into clones for comparison, both for continued disease resistance and for yield.

Most of the progeny established in the effort to breed high-yielding disease-resistant clones have been obtained by controlled pollination. A convenient device for eliminating the tedious hand-pollination has consisted in making breeding-garden plantings of high-yielding Eastern clones interspersed with selected disease-resistant clones (Plate 12(*b*)). When the trees start seeding, the seeds are collected only from the high-yielding clones, and the resulting seedlings are subjected to intensive disease-resistance tests. The Eastern clones have been found to be 100 per cent susceptible to leaf-blight. If any of the seedlings show disease resistance, it is at once apparent that the male parent must be disease-resistant, since the mother tree is known to be without resistance. Susceptible seedlings are eliminated immediately.

The seeds from the disease-resistant trees are known to carry the factor for resistance. Only those resulting from pollen from the Eastern clones, however, would carry the factor for high yield. A much longer period would be required to determine yield than to test for disease resistance and eliminate the susceptible seedlings. It was considered better, for the American programme, to discard the seeds from the disease-resistant trees and collect only those from Eastern clones. Co-operative tests were considered, under which the seed would be collected from the disease-resistant trees and sent to the East for yield tests. All would have some disease resistance, and high-yielding selections would have a fifty-fifty chance of having sufficient resistance for commercial use. Bud-wood from high-yielding selections could be returned to the Americas for disease-resistance tests.

Testing for Disease Resistance

Testing for resistance to South American leaf-blight must be done in areas where the disease is severe, but the testing is relatively quick and easy. In early resistance tests, Langford (1945) increased the natural incidence of inoculum by making suspensions of the spores of the leaf-blight fungus and spraying them on the seedlings under test. Later on it was found that, by interspersing with nursery-beds of highly susceptible seedlings the nursery-beds of seedlings that were being tested, a sufficiently high spore-load could be maintained during the sporulating season to give fully accurate estimates of disease resistance. One or two disease ratings could be made in a year, and the worst rating given at any time or in any location was adopted. Seedlings showing distinct susceptibility could be eliminated readily. While there is continued weeding out of seedlings in succeeding years or other localities, a high percentage of the susceptible plants can be eliminated during the first year.

Testing for Yield

Testing for yield is a much more difficult procedure, and no early test yet devised is equal to actual tapping tests—whilst these, to be reliable, should not be started until the 'seedlings' have reached a size of 18 to 20 in. in girth at a height of about 3 ft. from the ground. This requires a growth period of from four to six years before testing can start. Really reliable testing requires that the trees be tapped for four to six years to measure the rate of increase in yield from initiation of tapping to complete maturity of the tree. Both growth-rate and bark-renewal during this period are important in the evaluation of the tree, while time is needed to determine the cloning qualities of the 'seedlings' and the growth and yield characteristics of clonal plantings.

Space, funds, and time restrict the number of clones that can be given adequate field testing in accordance with the above schedule. Numerous tests have been suggested that would give an early indication of yield. Bark thickness, the number of latex-vessel rows, the diameter of the latex vessels in the leaf petioles, and other measurements of morphological characters, proved to be uncertain indices of future yields. Cramer (1938) developed a pricking test in which the flow of latex from five vertically arranged triangular notches was estimated with respect to the flow from notch to notch, and from the bottom notch to the ground, but this test has not proved to be reliable. The flow from 'seedlings' from jungle collections made by Seibert in Peru was so great that all of the Cramer lower classifications had to be discarded; yet none of the 'seedlings' had a significant yield after regular tapping was initiated.

The Morris-Mann test (Morris, 1931; Mann, 1932) involved tapping young trees by cutting entirely through the bark to the wood each day for ten days. The first five days of tapping were to establish flow, and no yields were recorded. Yield records were kept for the last five days of tapping. The young trees were found to recover rapidly and completely from this severe treatment, and the data are more reliable than those obtained by any other test yet devised to determine the yield potential of young trees before they reach the size for normal tapping. Further refinements of techniques to identify superior clones at an early age are needed to speed-up the breeding of clones that will keep the production of natural rubber on a par with the production of synthetic rubber.

International Co-operation in Clone Development

International and inter-commercial-company jealousy and rivalry is notorious in rubber production and manufacture. Brazil's attempt to control the prices of wild rubber during the period of her virtual monopoly, and her anger when seeds were successfully transferred to the East; the attempts of Eastern producing countries to restrict plantings and prohibit the export of high-yielding planting material; and, lastly, the tremendous efforts of 'have-not' countries such as Canada, China, Germany, Russia, and the United States to produce their own rubber, either natural or synthetic; all illustràte the tremendous political scale on which rivalry in rubber production has been maintained. Rivalry of commercial agencies in production and manufacture has been no less intense and widespread.

The ability to co-operate within spheres of common interest, however, is a significant element of modern commercial and political association. Nowhere is this co-operation better exemplified on an international level than in the development of improved planting material for rubber plantations that may be established, or for the replanting of obsolescent plantations already in bearing.

An early manifestation of this friendly co-operation was the agreement of the countries of tropical America to co-operate in a programme of rubber development. Although the United States Department of Agriculture took a leading part in this, the active co-operation of the tropical American countries was all-important. Another illustration was the mutual arrangement between Brazil and Malaya by which Brazil furnished disease-resistant clones to Malaya and the latter sent the best of their newly-developed high-yielding clones to Brazil. This interchange was bilateral in character but multilateral in effect, as each of the two recipients acted as a distributing agency and supplied stocks of the clones to other countries in their respective areas. The co-operation of the United States was utilized for quarantine propagation of the interchange clones at Coconut Grove, Florida, while England contributed quarantine inspection and re-packaging at Kew Gardens to avoid any possibility of interchange of diseases.

At the same time, tentative arrangements were made for future co-operation in breeding tests to combine resistance to leaf-blight with high yield. In the Americas, there was a need of high-yielding selections; yet the best continuing breeding work was being done in the East, where there was recognition that the rubber plantations were stocked with planting material that had been proved to be 100 per cent susceptible to leaf-blight. With rapid air communications, Eastern countries were no longer protected by distance from the encroachment of the disease. They did not feel themselves to be in imminent danger, but they felt the need for the insurance offered by disease-resistant clones.

The tentative arrangements that were made involved taking advantage of the conditions and facilities unique to the East and to the West, for the common good of both. The disease, so far, occurs only in the Western Hemisphere, and all resistance testing would, therefore, be done in the Americas, since the presence of the disease is essential to the determination of resistance. It would be foolhardy to introduce the disease for scientific studies on resistance in the expectation that it could be controlled under quarantine. The East, with its fine facilities and research scientists, would be in a position to make a considerable contribution in the way of yield testing and determination of commercial characteristics of the new progeny.

This international co-operation in breeding and plant improvement is by no means solely a governmental operation, for the Goodyear Plantations Company and the Firestone Rubber Plantations Company have each taken an active part in the mutual testing. Goodyear furnished many high-yielding clones, the facilities of their plantations in Costa Rica (and formerly the one in Panama also), and invaluable data from their plantations in Sumatra, whilst Firestone established a research planting in Guatemala and undertook breeding and yield tests on their Liberian plantations. In addition to experimental areas furnished by the co-operating governments of Latin America, the United Fruit Company established sizeable experimental plantings in Costa Rica and Guatemala, and L. Lind Pettersen furnished land in Guatemala at a token rental.

V

BOTANY OF CASTILLA

INTRODUCTION

It is probable that rubber was obtained from *Castilla* trees (Plate 13(*a*)) in the Americas for generations or even centuries before any other tree was tapped for rubber. Pre-Columbian use of rubber outside the main area, in the Amazon Valley, of natural distribution of *Hevea*, was undoubtedly based on the use of the rubber from the *Castilla* tree. Even in the native home of *Hevea*, *Castilla* rubber may have predominated as late as the time of Columbus. There can be little question that where the two genera exist side by side, tapping of the rapidly bleeding *Castilla* would precede the tapping of the slower-bleeding *Hevea*. Only after the depletion of the native stands of *Castilla* would alternative sources of latex be sought.

Differences in the quality of the latex were not important in native uses of the rubber, as the copiousness of flow undoubtedly was of much more importance to the native tapper than any immediately apparent difference in the quality of the latex or of the rubber prepared from it. The stability of the *Castilla* latex made it more desirable than other types for the coating of fabrics and water-proofing of boats, utensils, apparel, etc. Had there been any *Hevea* in the northern range of *Castilla*, it might, because of the superior quality of the rubber, have been an early choice for making the rubber balls used in native games; but there was no *Hevea*, and the development of rubber usage was almost entirely with rubber from *Castilla*—though guayule rubber also was used at an early period.

Schurer (1957) has made a comprehensive survey of the early literature and has demonstrated quite clearly the pre-Columbian use of *Castilla* rubber in religious ceremonies in Peru, and in Yucatan and elsewhere in Mexico. That *Castilla* was indeed the source of the rubber used in Peru during the Inca civilization seems to be fairly well established. Moreover, there can be no doubt that the ceremonial usage of rubber in Yucatan and elsewhere in Mexico was through exploitation of *Castilla* trees, as certain of the ceremonial usages depended on liquid rubber (latex) and, without modern knowledge of preservatives, it would not have been possible to transport *Hevea* latex to Mexico even if communication lines to Brazil had been established.

The Original Description

The Generic Name

The genus *Castilla* was established by V. Cervantes in 1794 in his inaugural lecture on botany at the Real Jardin Botanico (Royal Botanic Garden) of Mexico City. This lecture was later published, with an illustration, in a supplement to the Gaceta de Literatura in Mexico City.

The generic name selected by Cervantes was *Castilla*, in honour of Juan del Castillo, a prominent pharmacist and economic explorer, whilst the specific name, *elastica*, referred to the quality of the gum obtained from the latex of the tree. Thus Cervantes gave the first botanical description of the Mexican rubber tree under the name of *Castilla elastica*. He listed common names as 'Holguathuitl', and the half-Spanish 'Arbol del Hule'.

The generic name, *Castilla*, received immediate criticism from a local contemporary who signed himself only with his initials, J. L. M. This individual contended that, in honouring Castillo, Cervantes should have first Latinized Castillo's name to Castellum, and that the correct derivation from that should have been *Castella* rather than *Castilla*.

Early Concepts of 'Castilla' Species

One of the criticisms aimed at Cervantes by J. L. M. was that, as there was only one species, there was no need for a specific name in his description. The belief that there was only one species of *Castilla* persisted for more than fifty years. All specimens of *Castilla*, from Mexico southwards to Peru, were referred to that single species. The first recognition that more than one species was to be found was contributed by Liebman (1851), whose description of the additional species *Castilla costaricana* was based on incomplete specimens collected at Turrialba, Costa Rica. Liebman, however, had studied *Castilla* in six different localities in Mexico, and did not hesitate to describe the new species as separate and distinct from that found in Mexico.

Pittier (1910) stated that the presence on the Isthmus of Panama of a rubber tree identified as that described by Cervantes had been reported in 1800. Sutton Hays confirmed this in the eighteen-fifties. Subsequently, Collins (1872) mistakenly furnished a picture and description of 'Ule-ule' or 'Panama rubber' under the name *Castilloa markhamiana*, though this was later found to be a species of *Perebea*.

These descriptions of *Castilla* rubber trees on the Isthmus of Panama caused the India Office of the British Government to seek more precise information concerning these trees, with the purpose of obtaining seeds and seedlings for transport to British colonies having suitable soil and climate. Thus, while Wickham was trying to export *Hevea* from Brazil, Robert Cross was being dispatched to Panama to study and collect *Castilla*.

'Castilla'—not 'Castilloa'

An English translation of Cervantes's description was published anonymously in 1805. Cook (1903) states that this translation was said to have been the work of Charles Koenig, keeper of the mineralogical department of the British Museum. By chance, typographical error, or deliberate attempt to improve the name, the translator changed the generic name from *Castilla* (as given by Cervantes) to *Castilloa*. This was done without any explanation and could not be considered a valid change. Nevertheless, the name *Castilloa* stuck and occurs much more widely in literature than does the correct name, *Castilla*. The 'Gaceta de Literatura', in which the original description was published, is extremely rare and most writers evidently have depended on the English translation. Cook, in referring to the 'Supplemento a la Gaceta de Literatura', states, 'According to Collins the British Museum copy lacks the illustration of the plant, but that of the Library of Congress at Washington is complete . . .'. Plate II in Cook's bulletin is a reproduction of Cervantes's original plate, which was titled *Castilla elastica* and constitutes irrefutable proof of the original name. Pittier (1910) also pointed out the error of *Castilloa* as a generic name, and in his treatment of the genus considered both *Castella*, suggested by J. L. M., and *Castilloa*, introduced by an anonymous translator in 1805 without explanation, as synonyms.

Early Misconceptions of Yield

The substitution of *Castilloa* for *Castilla* was not the only error committed with regard to this tree. When *Castilla* is tapped, the latex flows out with such rapidity and in such abundance that anyone who has ever seen another tree tapped cannot but be amazed. The immediate response is to attribute to *Castilla* yields in excess of anything ever experienced. As is true of many fishermen, native tappers are skilled in the art of magnifying their take, and the quick response of the *Castilla* tree to tapping has often been accepted as a sufficient demonstration of the truth of their claims.

The reports of Collins (1872) and of Cross (1881) were among the early records that greatly exaggerated the prospective yields of *Castilla*. Collins stated:

> A tree of about 18 inches in diameter bled by skilful hands in April would yield about 20 gallons of milk capable of giving 50 pounds of caoutchouc. This is, however, the maximum yield; the average is a little below this. A tree from 20 to 30 feet to its first branches is expected to yield 20 gallons of milk, and each gallon of milk to give 2 pounds or 2 pounds 2 ounces of good dried rubber.

Cross was considerably more conservative in his estimates and stated: 'A *Castilla* tree, with a diameter of $1\frac{1}{2}$ to 2 feet, if carefully and judiciously tapped, may be expected to yield about 12 pounds of rubber per annum. Of all the different species of rubber-producing trees, the *Castilla* should prove, under cultivation, the most remunerative.'

Botanical Characteristics

Habit

When fully developed, all species of *Castilla* are trees of large size and striking habit. Both Cook (1903) and Pittier (1910) note that they are seldom true forest trees but that they nevertheless avoid the open, grass-covered savannas. Their natural habitat is in the clearings and other open spots of the virgin forest, where they are commonly found in company with *Cecropia*, or in the fertile, sparsely-wooded alluvial flats of the valley bottoms. In Brazil, *Castilla* is confined to the high ground and is not found in flooded areas.

Roots

The root system of *Castilla* consists of a rather short tap-root and of several lateral roots spreading horizontally, these latter being so near to the surface of the soil that they can often be followed for 20 to 30 metres. In the level, shady forest, the roots often assume a buttress-like shape at their emergence from the main axis (Plate 13(*b*)). The lateral roots are more or less ramified, and numerous rootlets spread into the surrounding soil from their lower side.

The buttress roots of *Castilla* are also characteristic of planted trees and have been used as an index of maturity. Though the growth of the trees is rapid in the early stages, it was found under cultivation in Haiti that the formation of buttress roots did not commence until the trees were from ten to twenty years of age. The relationships between the formation of buttress roots and maturity, or between the formation of buttress roots and tapping response, have not been determined. It is clear, however, that formation of buttress roots comes only after full maturity of the tree, and it is equally clear that *Castilla* trees cannot be tapped at an early age (as is done with *Hevea* trees). In view of the disappointing results that have followed the tapping of cultivated *Castilla* trees, it is probable that delaying tapping until the initiation of the buttress roots would be beneficial both to the health of the tree and to the initial yields of latex.

Trunk

There is a great diversity in the appearance of the trunk of *Castilla*, which varies with species, exposure, and climate. Pittier (1910) reported a tree of *Castilla daguensis* that was 50 metres in height and had a trunk 1·05 metres in diameter. Cook (1903) reported a tree of *C. lactiflua* that was about 25 metres in height with a trunk diameter of 1·5 metres. Koschny (1901) speaks of trees having trunks from 1 to 1·72 metres in diameter as not uncommon in the forests of Costa Rica. La Rue (1926) reported that the *Castilla* trees in Brazil approach the height of the *Hevea* trees, but that he did not encounter any *Castilla* tree with as great a diameter as the largest Heveas. In the dark rain forests of Costa Rica and Panama, adult trees are often seen that shoot up to 15 metres and more, smooth and slender, and supporting only a flat, thinly developed crown. In the open dry districts, the branching commonly begins at 3 metres or less above the ground, and the trees assume a stouter habit.

Two Forms of Branches

The first branches formed by a young *Castilla* tree arise from buds in the axils of the leaves. These were distinguished by Cook (1903) as temporary or deciduous branches. On the main stem they persist only during the *juvenile stages* of the tree's growth and are replaced by permanent branches arising from adventitious buds at the side of the temporary branches. These temporary branches are confined chiefly to the main stems of young trees, but are found also on young growth of the *larger permanent* branches. The temporary branches are almost horizontal, never more than 3 cm. in diameter, and up to 3 or 4 metres in length, whilst the permanent branches are never horizontal but slope up at an angle of roughly 45° and are easily distinguishable from the temporary branches. The leaves of the initial temporary branches sometimes measure 46 to 61 cm. in length, but may be reduced to less than half that length on temporary branches formed on new growth after the tree has attained the mature branching habit.

Leaves

The leaves of all species of *Castilla* are deciduous. They tend mostly to be unifor m|n size, shape, and similar details; in other respects they are so variable, even within a single species, according to age, exposure, etc., that they furnish few reliable specific characters. In young trees, and particularly on the temporary branches, they are generally larger than otherwise; the petioles are often quite long, attaining no less than 5 cm. in some specimens, and the lamina is more rounded. In mature trees, the southern species seem to have a tendency to have short petioles while the northern species are long-petiolate. The petioles of mature trees are very short (0·5 cm.) in *C. ulei*; short (0·8 to 1·5 cm.) in *C. australis*, *C. daguensis*, *C. lactiflua*, *C. panamensis*, and *C. nicoyensis*; relatively long (1·5 to 2 cm.) in *C. fallax*, *C. costaricana, and C. elastica*; and longest (up to 2·5 cm.) in *C. gautemalensis*.

The adult leaves vary from ovate and sublyrate to elliptic-lanceolate. They furnish a good taxonomic character in the form of the blade at the insertion of the petiole, this being in some species deeply cordate, in others subacute or scarcely emarginate. This differential peculiarity again seems to have some connection with geographical distribution of the several forms, deeply cordate ones occupying the northern part of the generic range, while the others are Andean (with the exception of

C. fallax). *Castilla ulei* has the smallest leaves, and *C. costaricana* and *C. elastica* have the largest. There is a great variation in all species, and the dimensions given in the descriptions do not apply to the very large juvenile leaves.

Flowers

Castilla is normally monoecious, with both pistillate and staminate flowers in the same cluster. There is, however, some variation, and young trees blooming for the first time invariably bear male flowers only. Some mature trees also bear only male flowers, but it has not been demonstrated that such trees are permanently male. A decided, characteristic difference exists between the male flowers borne on trees without female flowers and those borne in clusters containing female flowers. Cook (1903) designates the all-male flower 'primary' and the staminate flower found on the monoecious plants 'secondary' or 'complementary'.

The stamens are fertile in both kinds of male flowers. Wind seems to be the chief agent of pollen distribution, but pollination by insects may occur as well. The male flowers are usually crowded with small thrips that are also found, but not so abundantly, on the female flowers.

Primary Male Inflorescences

The primary male inflorescences appear in pairs in the axils of the leaves, or in the defoliate axils, and have the general appearance of a flattened or depressed cone, or of a fan that is more or less emarginate at the base. This fan opens longitudinally, sometimes only by a narrow slit at the top (*C. fallax*), and sometimes with the lobes spreading out into a flat disk (*C. nicoyensis*). In other cases, the inflorescences are more or less distinctly three-winged (*C. costaricana*), or the lobes are diversely lobulate or distorted (*C. elastica*). The number of receptacles in each axis varies from two to eight.

Of the six rubber-producing species of the Isthmus of Panama, half (*C. lactiflua*, *C. guatemalensis*, and *C. panamensis*) have emarginate or kidney-shaped male receptacles, while the remainder do not present this peculiarity on account either of their irregular shape (*C. costaricana*, *C. elastica*) or of their mode of dehiscence (*C. nicoyensis*).

Complemental Male Inflorescence

The complemental male inflorescences that accompany the female flowers in the monoecious clusters differ only slightly in shape from the primary flowers but are much smaller. They are geminate and clavate or pear-shaped, except in *C. lactiflua*, where they are flabellate. In this species, they also seem to open more widely than in the other ones, but the dehiscence is always more or less slit-like, except in *C. costaricana*, where the opening is rounded, and in *C. nicoyensis*, where the receptacles hardly open at all.

Pistillate Inflorescence

In all species of *Castilla*, the female inflorescence consists of a cup-like 'receptacle', more or less open, according to the number of included flowers and also to the stage reached in their development. The development of the flower takes place successively from the centre to the periphery, maturity being reached with the appearance of the stigmas. The number of flowers on each receptacle is variable within certain limits for each species, and there usually remain on the outside numerous undeveloped flower-buds that are not easily distinguished from the bracts or scales. Each flower contains one pistil. The ovary is one-celled and partially adherent to the perianth. There is only one ovule, which is more or less lobulate in the lower part, and inserted on the placenta near the top of the ovary cell in such a way that the funicle is very close to the micropyle.

Fruit and Seed

Directly after pollination, the perianth usually begins to thicken and then gradually turns into an orange-red pulp. More space is required by the growing seed, and the receptacle etc. increases its surface—in all its parts, but chiefly as regards the outer scales, which alter their original size, shape, and texture. An exception to the thickening and coalescence of the perianths is found in *Castilla fallax* in which they remain free, green, and hairy, more or less adhering to the seeds. In the other species, the ripe pulp is sweetish and eagerly sought by certain birds; in *C. ulei* it is even a favourite delicacy of the native Indians. In this latter species, the infructescence has a quite characteristic appearance, being globose and entirely covered with scales, and containing only 3 to 5 achenes. In *C. daguensis* and *C. panamensis*, the cup-like receptacle remains rather deep and closed, while it is quite shallow and open in *C. fallax*, *C. lactiflua*, *C. costaricana*, *C. guatemalensis*, and *C. nicoyensis*. The counterpart of the closed receptacles of *C. ulei* is found in *C. elastica*, where these organs are more or less distorted and reflexed so as to embrace the twig on which they grew. They are exceptionally large in both *C. elastica* and *C. costaricana*.

Precise information is lacking regarding the seeds of *C. australis*, *C. daguensis*, and *C. lactiflua*. Of the other species, *C. fallax* has the smallest seeds, while *C. panamensis* and *C. ulei* have the largest. The seeds are roundish and small in *C. nicoyensis*, ovoid-elongate and rather large in *C. ulei*, and distinctly ovoid in the remaining species. In all cases, they are more or less flattened by being pressed against one another (Plate 14).

TAXONOMY

The Genus

Castilla Cervantes in *Gaceta de Literatura de Mexico*, Suppl. 2 July 1794.

Synonyms: *Castella* J. L. M.
Castilloa first used in Tracts Relative to Botany, London, 1805.

A genus with about ten species, generally distributed from Mexico to Bolivia and Brazil. All are laticiferous trees, but there is considerable variation in the quality of the gum obtained from the latex in different species. The most important from the standpoint of actual production of rubber has been *C. ulei*. The most important for cultivation has been *C. elastica*, but the confusion in nomenclature has resulted in the planting of several other species under the name of *C. elastica*. *Castilla fallax* is deficient in rubber and its latex dries into a hard, sticky, inelastic mass.

The Species

As in the case of *Hevea*, full botanical descriptions will not be given here as they may be found in Pittier (1910).

Castilla ulei Warburg, *Bot. Jahrb. Engler*, 35, 654, 1905, is a tree from 20 to 40 metres high with long, spreading, superficial roots. This species occurs extensively in Brazil and is the source of the rubber known commercially as caucho. The fresh fruits are reported to be edible. The leaves are smaller than in any other species and the seeds are proportionately larger.

Castilla fallax Cook, *Science*, new ser., 18, 438, 1903 (including *Castilloa tunu* Hemsl., Hook. *Icon.* Plate, IV, 7; Plate 2651, figs. 1–7 (figs. 8–15 excl.) 1900, in part), is a medium-sized tree found in Costa Rica, Panama, and Nicaragua. This tree is known locally as 'Hule-macho', 'Hule-colorado', or 'Gutta-percha' by Spanish-speaking natives, or as 'Tunu' by the Misquito Indians of Nicaragua. The name of 'Hule-macho', or male rubber, refers to its lack of a commercially desirable rubber gum. The 'Tunu' tree of British Honduras may be a separate species.

Castilla australis Hemsl., Hook. *Icon.* Plate, IV; Plate 2676, 1901, is found at an elevation of 1,300 to 1,700 metres in Peru and is reported as common in the woods in the vicinity of Morro Zungo.

Castilla daguensis Pittier, *Contr. U.S. Nat. Herb.*, 13, pt. 7, p. 268, 1910, is found in the Dagua Valley of Colombia on the road from Buenaventura to Cali. Pittier reports:

> These trees are remarkable for their size; several individuals seen from the road below San Jose del Dagua assumed truly gigantic proportions, with a somewhat striking habit. The shaft-like trunks attained a height certainly

not under, and perhaps over, 50 meters, and the divaricate limbs mostly projected horizontally, beginning about 5 meters from the ground. The tree from which the type specimens were obtained grew near the probable upper limit of the species, and was of much lower stature, with a rounded crown and a trunk no less than 60 cm. in diameter.

Castilla lactiflua, Cook *Science*, new ser., 18, 438, 1903, is a medium-sized tree attaining a height of 25 or more metres. The young twigs are densely hairy and have a thick white pith. The type specimen was collected at La Zacualpa, Chiapas, Mexico. *C. lactiflua* is closely related to *C. elastica*, but differs from that species in the flat lobes of its primary male inflorescences, in its flabellate receptacle, its fewer interstaminate bracts, and its shallow, flat fruiting receptacles each bearing fifteen to twenty-five seeds.

Castilla costaricana Liebm., *Dansk. Vid. Selsk. Skr.*, V, 2, 319, 1851, is a tree generally 12 to 15 metres high, but sometimes reaching 18 to 22 metres. It is found in the northeastern watershed of Costa Rica and the adjoining districts of Nicaragua and Panama, where the climate is characterized by perennial rains and almost perpetual dampness of both soil and air. It occurs from sea-level to about 1,000 metres' elevation. The natives believed that the rubber-content of the latex and also the quality of the product decreased with increased elevation. The tree does not thrive in sandy or saline soils, or when directly exposed to sea-breezes. It is never found in close proximity to the coastal swamp.

As with many other trees of the tropics, the surface of the bark is covered with dense colonies of lichens, the colour of which varies in part with the intensity of the light. This fact has given rise to the belief that there are several varieties of this species, distinguished mainly by the colour of the bark but also by the correlated fluidity or richness of the latex. Thus, the trees that grow in the thickest forest have also the darkest bark, and their latex is very thin and easily collected, containing less rubber than that of others, whilst trees that grow in full sun exposure have a light-coloured bark and a very thick, rapidly coagulating latex.

Castilla guatemalensis Pittier, *Contr. U.S. Natl. Herb.*, 13, pt. 7, 272, 1910. This is a medium-sized tree with divaricate, spreading limbs, found in the States of Tabasco and Yucatan in Mexico, and also in Guatemala.

Castilla panamensis Cook, *Science*, new ser., 18, 438, 1903, is a medium-sized or large tree, or rather low and spreading when growing in the open. Its limbs are divaricate, obliquely ascending, and nude. Bark of young twigs is longitudinally plicate (in dry specimens) and densely hairy. Pittier states:

> The above description is based on the fresh material kindly sent from Ancon by Mrs. Gaillard, but the first idea of the specific status of the Panama type was gathered from the comparison by Mr. O. F. Cook of Hooker's plate

(1885) with material of the other Central American species. Our specimen are found to possess all the characters attributed by Mr. Cook to his *C. panamensis*, and to agree also fairly with Hooker's descriptions and illustrations so that there is little doubt left as to the identity of our tree with the one grown in Ceylon from seeds or cuttings collected on the Isthmus.

Castilla nicoyensis Cook, *Science*, new ser., 18, 438, 1908, is a medium-sized tree, 10 to 20 metres high. Its limbs are divaricate, ascending, or horizontal. The flower-bearing twigs are covered with a dense coating of rather long, brownish hairs, longitudinally striate when dry and filled with a thick, white pith. This species is confined to the Nicoya Peninsula in Costa Rica. In common with *C. elastica*, it has long-stipitate male receptacles, but it differs from that species in having these only in clusters of four and each opening into a flat circular disk. These receptacles are also smaller than in *C. elastica*, with more slender stipes and larger scales. There are no interstaminate bracts on the complemental inflorescences, and few on the primary male receptacles. The styles are glabrous and the pubescence on the twigs and leaves is longer, not so dense, and more erect than in *C. elastica*.

Castilla nicoyensis is a good rubber producer, the latex being particularly abundant toward the end of the dry season, although wild stands were greatly depleted by over-tapping due to the high quality of the rubber. Several small plantings of this species were established near Puntarenas, Costa Rica.

Castilla elastica Cervantes, *Gac. Lit. Mex.* Suppl., 1794, is a large tree attaining a height of 20 and more metres. Young twigs are densely covered with yellowish or greyish hair. This is the species to which nearly all cultivated types have been referred. Rubber literature refers only to *C. elastica* as the species planted throughout the world, and to *C. ulei* as the source of the caucho rubber of Brazil. Not enough is known of the South American species to state definitely that *C. ulei* is the sole source of caucho rubber. There can be little question that in Central America, and probably in Mexico, several species of *Castilla* have been important wild sources of rubber, and that the planted *Castilla* belonged to several species. It was the opinion of O. F. Cook that a planting of *C. elastica*, which was under observation by the United States Department of Agriculture at Bayeux, Haiti, in the nineteen-twenties, was a mixture of three species, but the study necessary to establish this as a fact was never completed.

Morphology and Anatomy with Respect to Propagation and Yield

Seeds

The seeds of *Castilla* are enclosed in the fleshy fruit and, under natural conditions, are scattered by birds and other animals that enjoy the fruit. After being removed from the fruit, the seeds are perishable and difficult to ship long distances, although in the fresh condition they germinate readily. Seeds represent the chief method of propagation that has been used with *Castilla* (*see* Chap. XII). Propagation by cuttings is feasible, and early introductions of *Castilla* into the East and into Africa were by rooted cuttings—after the first shipments of seed had been total failures. Later tests demonstrated that seeds could be shipped long distances if they were first cleaned thoroughly, slightly dried, and packed in moist charcoal. Leaf-mould, sand, and sawdust are also useful as packing materials, but they do not preserve the seed as well as does charcoal.

Propagation by Cuttings

In addition to the original importations of rooted plants into the East, a number of experimental plantings were established vegetatively in Mexico. On the whole, however, it was much more satisfactory to use seed in areas where *Castilla* was native and seeds were abundant. Branch-wood suitable for making cuttings could only be obtained high up in the tree. The differences in the branching habits have already been pointed out (p. 95). The first-formed branches assume a horizontal habit of growth and are temporary, being replaced later by permanent branches that come off at an angle from the trunk of the tree rather than grow horizontally as do the temporary branches. The temporary branches root but do not form normal terminal buds, and are quite unsatisfactory for use as cuttings. Cook (1903) states that a tree originating from a *Castilla* post used in making a fence, developed into a large tree some 80 ft. in height, with a circumference of 7 ft. at 5 ft. from the ground. It had a clean stem, with a height of some 33 ft. to the first branch, and had yielded 6 lb. of rubber at one tapping up to about half the height to the first branch.

Cook (1903) suggested obtaining cuttings from different wild trees in the local forests as a means of initiating plantings for the selection and testing of particular wild trees on the basis of growth-rate and yield. He stated that stakes 5 or 6 ft. long and 2 or 3 in. in diameter would take root and grow when simply set in the ground, and that propagation from cuttings would be an easy method of establishing row plantings of vegetative progeny from individual trees of the forest that were known to be high yielders. There is no record that this suggestion was carried out or that any other method of selection or improvement of *Castilla* was ever attempted.

The Bark

Castilla has a relatively smooth bark and normally has a considerable length of trunk up to the first branch. As tappers resort to ladders and climbing ropes to tap the trunk to a maximum height, this length of unbranched trunk is an important advantage. The bark is difficult to tap and requires the use of a machete or a very sharp knife. Because *Castilla* yields large quantities of latex at one tapping and does not recover quickly from the effects of the tapping, the re-opening of the cut, as may be done with *Hevea*, is not possible with *Castilla*. The tapping cut must be to full depth and it is not possible to approach the cambium layer carefully as in tapping *Hevea*, in which some five successive tappings are required to bring the tapping cut to the required depth. At that point, the delicate green of the cambium can be seen through the thin layer of uncut bark at the bottom of the cut, and subsequent tapping can thus be done with full knowledge of the location of the cambium and consequently with a minimum of damage. In tapping *Castilla*, the full depth of cut must be reached at each tapping and, to obtain maximum yields, the cut is made through the cambium into the wood.

Unlike *Hevea* bark that has been pared off gradually and carefully, the bark of *Castilla* does not grow back uniformly, but forms thick layers of callus tissue at the margins of the cuts. This tissue is hard to cut, and subsequent tapping is made even more difficult. So far as possible, each new tapping cut is made in virgin bark—at first between the old cuts and then, finally, diagonally across them. As trees are tapped only from once to four times a year, it has been possible to continue tapping individual trees for several years, and claims have been made that individual trees have been under tap for up to twenty-five years.

The Latex-vessel System

The latex vessels of *Castilla* consist of elongated single cells. They do not anastomose as do the articulated latex vessels of *Hevea*. The latex vessels are found in the bark of the roots, trunk, and branches, and also in the pith and in the leaves and fruit. The only important vessels for rubber production are those in the bark of the trunk. When the tree is tapped, latex is obtained only from those latex vessels that are intercepted by the tapping cut. The latex flows freely from all vessels that are cut, and a relatively large quantity of latex can thus be obtained. Unlike that of *Hevea*, the latex of *Castilla* does not become highly concentrated in dry weather but remains dilute and fluid. No further dilution of the latex is necessary to obtain a free, rapid flow of the latex from the cut vessels. The large flow of rubber at a single tapping of *Castilla* is not due to a high rubber-content, such as is found in guayule or the Russian rubber-bearing salsify, *Scorzonera tau-saghyz*. The single-cell latex vessels of *Castilla* offer less obstruction to the flow of latex than the articulated vessels of *Hevea*, and the fluidity of the latex allows it to flow from relatively long distances to the tapping cut. The stability of the latex permits the flow to continue until the bark pressures become equalized with that of the surrounding atmosphere, as there is no coagulation of the latex in the latex vessels to stop the flow.

The Latex

The latex of *Castilla* is more complex than that of *Hevea*. Non-rubber constituents of the latex make up some 25 per cent of the dry-weight of the gum from mature trees, and even larger percentages of that from young trees. Weber (1903) tested the rubber from trees of various ages and found resin contents (acetone-soluble materials) as follows:

	per cent
Two-year-old trees	42·33
Three-year-old trees	35·02
Four-year-old trees	26·47
Five-year-old trees	18·18
Seven-year-old trees	11·59
Eight-year-old trees	7·21

The proportion of albuminous materials in *Castilla* latex is much higher than in *Hevea* latex. The stability of the *Castilla* latex and the difficulties in coagulation have been attributed to this fact. The latex can be purified by diluting it with several volumes of water and then allowing it to cream. The albumins separate in the serum. A single creaming produces a relatively pure rubber suspension, and repeated creamings produce a rubber suspension of high purity.

Weber also studied the resin content of rubber from different parts of an old tree and reported them to be as follows:

	per cent
Trunk	2·61
Largest branches	3·77
Medium branches	4·88
Young branches	5·86
Leaves	7·50

The latex of *Castilla* has been uniformly reported as white, and the colour differences reported for *Hevea* are lacking. All investigators have reported that the latex is pure white at first, but that it darkens quickly on standing in the air. This has been ascribed to an oxidase that Parkin (1900) studied and found could be inactivated by heating, or removed by creaming.

The primary separation of *Castilla* latex into two fractions can be observed as it flows from fresh cuts on the tree. The white droplets of pure latex appear to be washed along the cut by a larger flow of a thinner, coffee-coloured fluid, which can then be observed floating on top of the white latex in the cups or other receptacles used to catch the latex. In gathering the latex for transport to coagulating centres, the fractions become thoroughly mixed and the resultant latex mixture appears pure white.

The latex of *Castilla* is quite stable, and it is probable that the original tests on latex in England and elsewhere were conducted with *Castilla* latex which might well have stood the trip to Europe without the aid of preservatives. *Hevea* latex could not have been shipped so far without coagulation taking place. If carefully packaged and sealed against the air, *Castilla* latex will keep for more than a month without appreciable deterioration. If, on the other hand, the container is opened, coagulation takes place, with the development of considerable pressure and, should the container have a small orifice such as the neck of a bottle, the coagulated rubber is forced through this orifice in the form of a long, rope-like strand the size of the orifice. In some instances, rubber 'ropes' nearly 2 ft. long have been formed from the rubber contained in a one-gallon bottle of *Castilla* latex.

Weber (*see* Cook, 1903) found that the latex of *Castilla* could be coagulated by a creaming method. He diluted fresh latex with five times its own volume of boiling water and added 8 oz. of formaldehyde to each barrel of latex. He stated that after twenty-four hours the white rubber could be lifted off as a snow-white cake, and that rubber so prepared was fully equal to the best grade of Para rubber. Parkin (1900), in Ceylon, compared the susceptibility of *Castilla* latex and that of *Hevea* to creaming. The *Castilla* latex creamed when water was added, and within an hour or two the rubber particles all floated in the form of a thick cream. The diluted *Hevea* latex showed no sign of creaming even when submitted to a low temperature. Parkin attributed the difference in reaction to the larger size of the rubber particles in the *Castilla* latex.

The Flowers

The nature of the *Castilla* flowers has been discussed. Pollination appears to be primarily by means of wind dissemination of the pollen, and the only insects that have been recorded as visiting the flowers are crawling insects that would not be expected to do more than carry the pollen from the staminate flowers to the adjacent pistillate flowers of the same tree. There are no known trees with pistillate flowers only, the sole unisexual trees reported being invariably male. Such trees would not be expected to be involved in pollination by crawling insects. The complete separation of the staminate and pistillate flowers should facilitate controlled pollination of *Castilla*, but there is no record of any breeding programme to develop superior types of *Castilla* trees.

Growth and Minimum Tapping Age

Castilla is reputed to be a fast-growing tree and this reputation was an early factor in stressing its value as a potential source of plantation rubber. Precise growth-rate data are lacking, but there is every indication that *Castilla* was indeed a fast-growing tree wherever it was planted. It was found, however, that the initiation of tapping had to be delayed much longer in the case of *Castilla* than with *Hevea*. Weber (1903), on the basis of his comparison of the latex from trees of different ages, concluded that the tapping of *Castilla* should not be started until the trees had reached an age of at least eight years. Research workers in Haiti during World War II expressed the opinion that successful tapping could not be initiated until after the trees had started forming buttress roots. This would delay tapping until after the tenth year of age and possibly longer. It is quite probable that most plantation trees of *Castilla* have been tapped initially at too early an age, and that better results would have been obtained with delayed initial tapping. There is no evidence that *Castilla* could rival *Hevea* for plantation use.

Because of the rapid initial growth of young trees and the high yield of individual trees, it was suggested during World War II that *Castilla* might be grown thickly in nursery rows and harvested for mechanical extraction of the rubber at the end of the first year. Under the technical direction of the United States Department of Agriculture, plantings were made in Florida and at Mayaguez, Puerto Rico. At the end of a year, chemical tests showed that the total rubber-content of the plants amounted to only a few pounds of rubber per acre, and that *Castilla* could not rival guayule in the accumulation of rubber.

VI

BOTANY OF PARTHENIUM

Guayule *

Introduction

The guayule rubber plant, *Parthenium argentatum* Gray, is a native of the high central plateau in northern Mexico and the area in Texas just north of Big Bend. As a rubber plant, it is unique in that it does not have easily apparent latex, the identifying characteristic of rubber-bearing plants practically throughout the world. Rubber does occur in guayule in the form of latex, but it is contained in individual cells rather than in more or less continuous latex vessels as in *Hevea* and other well-known rubber plants of the tropics. Many plants that contain rubber have the rubber in individual cells, but guayule is the sole plant of this nature that has been the source of significant quantities of rubber. Lloyd (1911), the dean of the scientists who have contributed to the study of guayule, did not realize that the rubber in guayule was in the form of latex. He stated, 'Well-nigh nothing is known about the cytology of rubber-secreting cells. The great initial difficulties in the investigations have arisen from the fact that in most rubber-producing plants this material occurs in latex. In the guayule, as in few other known plants, the rubber is laid down within certain cells, in a manner analogous to the formation of starch.'

Nearly twenty years later, Lloyd (1932) realized his mistake and wrote, 'The account which I published in 1911 of the mode of occurrence of caoutchouc in guayule, *Parthenium argentatum* Gray, is incorrect. . . . In the guayule, as in some other rubber-bearing plants, the rubber occurs in the parenchyma cells and is thus segregated. In contrast with this condition is that in the so-called latex-bearing rubber plants, such as *Hevea*, *Manihot*, *Ficus*, *Euphorbia*, *Scorzonera*, *Chondrilla*, etc., in which the rubber is a constituent, more or less prominent according to the species, of a white or colored milky fluid, which is stored in tubes from which, when opened, the fluid flows more or less freely. . . . This general statement may now be extended to the guayule for, as will be shown, the rubber associated with other substances occurs in the same manner. The fluid here is equally a latex confined to individual cells.'

* Pronounced Gwī ōṓ lĭ or wī ōṓ lĭ.

In spite of having rubber in the form of latex, guayule cannot be tapped as are other plants to obtain the rubber. However, processes have been developed for extracting the rubber in the form of latex. Spence (1938) obtained a United States patent on a process for extracting rubber from guayule in the form of latex and, during World War II, Clark & Place (1945) perfected the process. They extracted the latex from fresh guayule plants and concentrated it to some 20 per cent of rubber by high-speed centrifuging. On the whole, however, the extraction of the latex has not proved commercially feasible and the rubber is obtained from the shrub in a solid form by a system of mechanical manipulation. Chewing of guayule plants to obtain the rubber undoubtedly preceded the discovery of America. Mechanical processes were also used at an early stage to obtain rubber from species of *Landolphia* in Africa, and there might be some question as to what plant was the first to be treated mechanically to obtain the rubber for modern usage.

There can be no question that, outside of Russia, guayule has been exploited to a greater extent than any other rubber-producing plant requiring the use of mechanical extraction. By far the major portion of the rubber extracted from guayule has been obtained from wild plants in Mexico. A small quantity has been obtained from wild plants in Texas—once by a private company at Marathon, Texas, and again during wartime by the Forest Service of the United States Department of Agriculture. The operation by the latter was so thorough that, a decade later, no regeneration of wild plants had occurred in areas where guayule formerly had been common. The lack of regeneration was partly due to over-grazing of the area during a subsequent period of drought, and not entirely to the wartime harvest.

A small quantity of rubber was also obtained from cultivated guayule in the United States. The largest harvest was in the depression years of the nineteen-thirties, when some 7,000 acres of guayule shrubs were harvested by the Intercontinental Rubber Company. During the war, the Government of the United States planted some 32,000 acres of guayule, but eventually harvested only a small quantity for rubber. Most of the shrubs were destroyed after the war without recovering the accumulated rubber.

The Natural Range of Guayule

Numerous investigators have studied the native stands of guayule in Mexico and Texas. Lloyd (1911) gives the geographical distribution as follows:

> The northern limit of distribution of the guayule is in the southwestern part of Texas, where it occurs in Presidio, Brewster, and Pecos (near Langtry) Counties. This area is continuous with its area of distribution in Mexico, throughout which it occurs with greater or less frequency. The periphery of this area runs approximately as follows: from the western extremity of

Presidio County in Texas, the western boundary will run somewhat west of south till it reaches the northern boundary of Durango, near Santa Barbara, Chihuahua. From this point, the limit turns approximately toward the south-east, running parallel with the Mexican Central Railway at a distance of about 100 kilometers (Endlich, 1905). Beyond the state of Durango, the boundary turns still farther to the east, curving northward again not far from the city of San Luis Potosi. The 101st meridian marks roughly the eastern boundary, lying somewhat west of it till beyond Saltillo, where the boundary then curves slighlty west of north, reaching the eastern limit in Texas at about Langtry. The northern limit is marked approximately by Fort Stockton.

Lloyd estimated that the area (cf. Fig. 1) so bounded comprised a total of some 130,000 square miles and that about 10 per cent of this area carried guayule.

The Distribution of Guayule within Its Natural Range

Within its natural range, the distribution of guayule is extremely spotty, and there are few large continuous stands. The elevation varies from about 2,000 ft. to some 7,000 ft., with the major stands in Mexico at elevations of 5,000 to 6,500 ft. Guayule is usually considered a typical desert plant. Muller (1946), however, classified it as a semi-desert plant which, in its altitudinal range, is restricted to a narrow transitional zone lying between desert and grassland elevations (Plate 15).

In nature, guayule is limited largely to limestone ridges and highly calcareous soils. A high lime-content has not been found necessary in soils for the cultivation of guayule but, in nature, it is never found on acid soils; nor is it found on heavy soils with poor drainage. The natural stands of guayule are found in spots not suited to general plant growth, and there is every indication that the occurrence of guayule is limited not by lack of adjustability to soil and climate, but by its inability to compete with other vegetation. On limestone ridges, the guayule is restricted to the upper levels and rocky slopes where other plants are not able to crowd it out. There is a sharp line of demarcation between the stands of guayule and outwash areas at the foot of the slopes.

Rainfall

Low rainfall is characteristic throughout the area where guayule is native. The yearly rainfall averages from 7 to 15 in., with even less reported in drought years. Cooperrider & Culley (1943) indicated their belief that the requirements of guayule for water might be higher than had previously been considered to be the case. They stated:

> Growth areas—outwashes, fans, cones, etc., including benches on mountain slopes and other run-off fed, naturally irrigated places—indicate that the water requirements of guayule may be greater than might be expected. The water supplied by 10 to 15 inches of rainfall might be raised to 12 or 20 or more inches through natural run-off irrigation. The availability of water is favored also by rocky, highly permeable soils of high infiltration capacity.

Muller (1946) has shown in detail that, under cultivation, guayule roots penetrate deep into the soil (Fig. 3). In nature, on the limestone ridges, etc., to which guayule is restricted, the roots are unable to penetrate deeply but spread out laterally and occupy all of the permeable soil

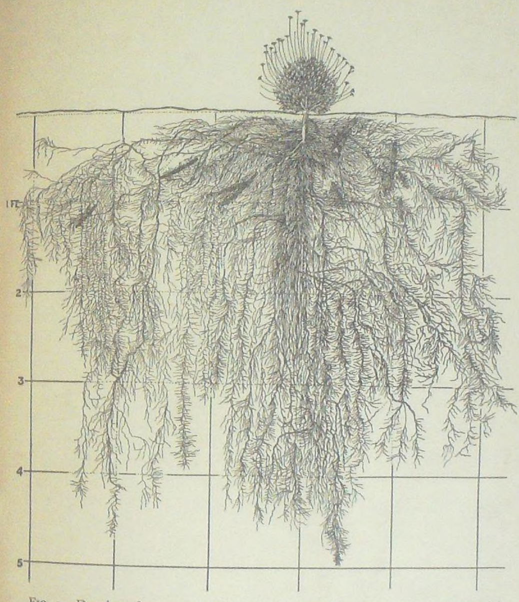


FIG. 3.—Drawing of root system of a guayule plant. The root system was exposed by carefully washing away the soil and making drawings and measurements as the roots were exposed.

in the vicinity of the plant. This characteristic growth-habit permits guayule to take advantage of all available soil moisture and to survive under conditions of drought that are fatal to plants with less well-developed and tenacious root systems. On the other hand, deep rooting is favourable to cultivation, and plants can take full advantage of deep soils, where their roots can penetrate to depths of over 20 ft.—a depth that is not possible in the rocky ridges to which guayule is native.

Temperature

Guayule in nature is subjected to great variations in temperature, both diurnal and seasonal. Muller (1946) states:

> The climatic tolerances of guayule are actually very wide when viewed from the standpoint of its growth in various localities. Its persistence in the wild in districts of Texas where temperatures of −7°F. have been recorded, its tolerance of exceedingly hot and dry summer periods over most of its range, and its luxurious development under irrigation equal to heavy rainfall, cover a wide range of conditions.

Monthly maximum temperatures of about 100°F. are not uncommon during the growing-season in Mexico, and the winter maxima are not much lower. Minimum temperatures seldom go far below freezing in the native range of guayule in Mexico, and night temperatures may be in the forties or fifties even at the height of the growing-season.

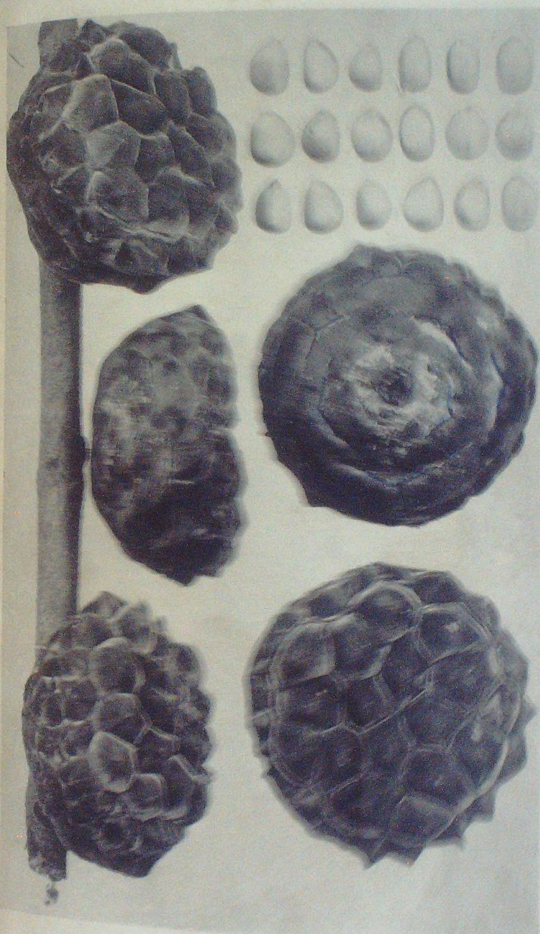
The tolerance of guayule to low temperatures in cultivation is much less than was indicated by Muller. Normal winter temperatures below 15°F. are considered unfavourable for guayule, and extensive winter-killing has been experienced at temperatures of 5°F. As is true of many plants, guayule withstands lower temperatures in colder areas, where the temperatures stay low enough to inhibit growth throughout the winter, than it will stand in areas where the winter resting period is broken by spells of warm weather—especially if the warm weather coincides with rains that encourage new growth. This lush young growth is highly susceptible to damage by succeeding cold weather. Small plantings in northern Texas have survived without serious injury in many instances when similar plantings in the southern part of the state have been destroyed by freezing. The temperature differences were not great, but the hardier nature of the more northerly plants prevented the damage that killed the lusher plantings to the south.

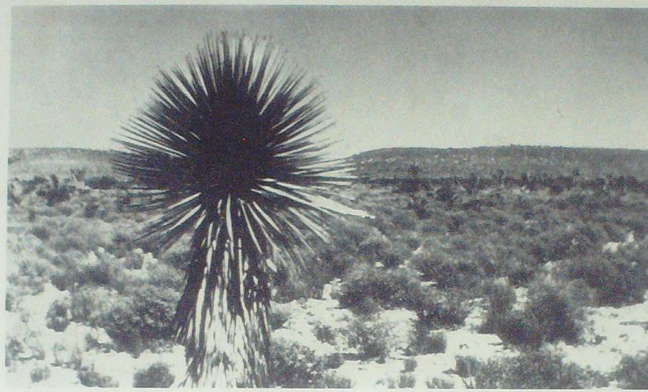
Natural Reproduction

Reproduction of guayule in nature is either by means of seed * or through the development of new plants from root shoots. Because of the high mortality of the seedlings, the limited production of new plants by means of root shoots may be the chief means of reproduction in some areas—particularly in those where the plants have been harvested, leaving the severed roots in the ground.

Guayule seeds abundantly, and mature seeds* picked from the plants while they are still turgid will germinate promptly. However, if the seeds ripen completely on the plant, they enter a period of dormancy that can be interrupted only after storage or by chemical treatment. Under the desert conditions of the native range of guayule, this dormancy is an

* Although the 'seeds' of *Parthenium* and its allies (including those of *Taraxacum*—*see* next chapter) are, technically, fruits, they are colloquially often spoken of as seeds and will in general be so termed in the present work.—Ed.





Photograph by permission of ARS, U.S. Dept. Agric.

Native stand of guayule, *Parthenium argentatum*, with a large plant of lechuguilla, *Agave lechuguilla*, in the foreground.

PLATE 15

important factor in the survival of the species. Normally, the flowering of the guayule plant is started by the onset of the rainy period. Pollination and seed development are prompt, and there is often sufficient moisture for the germination of the seed immediately—but not enough for the establishment of the young plant. Seed dormancy prevents the germination of the seed near the close of the rainy period, forcing it to wait for the beginning of the next rainy period.

A high proportion of the seeds lodge in the shade of the mother plant and others find lodging in vegetable debris near by. At the beginning of the next rainy season, germination is prompt and millions of young guayule plants may be seen. Competition with other plants and even with the mother-plant itself brings about a great mortality of the seedlings, and only in very favourable years is there an appreciable renewal of the stand by the establishment of new seedlings.

Reproduction by seed may be either by amphimixis, which entails the pollination of the ovule, or by apomixis, in which the ovule develops without pollination. Amphimixis involves inheritance from both male and female parents, while apomixis involves only the mother plant. Reproduction in guayule is largely by apomixis. In general, according to Rollins (1950), 36-chromosome plants (diploids) are fully sexual while the polyploid (54-, 72-, and higher-chromosome types) are facultative apomicts. The sexual type is found only in the general area centring on eastern Durango, and it is probable that this area represents the region of origin of the species which would then have spread from there to its present limits. In guayule, fertilization of the endosperm nuclei is required to initiate seed development, but there is no need for fertilization of the ovules in the apomictic polyploid strains. Apomixis is thus facultative and not absolute, and in the commercial strains over 90 per cent of the seeds are the result of apomictic reproduction. Apomixis has resulted in great uniformity in many of the restricted local stands of guayule.

Another factor, both in the survival of the species under extremely adverse conditions and in the development of local uniformity, has been the natural spread of plants by root sprouts. Root sprouts, known locally in Mexico as 'retonos', result from injury to, or exposure of, the root through erosion or any similar circumstance. They are not common in an undisturbed stand of guayule, and are found mostly on slopes where there has been sufficient wash to expose the roots. After guayule is harvested by pulling the plants from the ground, the broken roots remain in the ground to sprout and send up new plants. This is the chief source of retonos. Muller (1946) showed that the broken roots of harvested plants may remain alive for many months if the soil moisture is insufficient for growth, and that they can then start vigorous growth when the rains again replenish the soil moisture. Retonos have a great advantage over seedlings, in having roots of the old plant until their own develop.

TAXONOMY

The Genus

Rollins (1950) has made a detailed study of *Parthenium* and says:

> The name *Parthenium* originated with Linnaeus in the Species Plantarum and was based on plants of two herbaceous species: *P. hysterophorus* from the Island of Jamaica, and *P. integrifolium* from Virginia. The next described species, *P. bipinnatifidum*, from the highlands of Mexico, is a near relative of *P. hysterophorus* and has long been considered conspecific with it. At a relatively early date, *P. bipinnatifidum* was made the basis of two separately described genera: *Villanova* and *Argyrochaeta*.*
>
> Until the discovery and publication of *Parthenium incanum* . . . [in 1820] . . . , the genus was thought to be composed only of herbaceous species. However, during the rapid exploration of Mexico in the decades that followed, several additional shrubby species were discovered. In 1842, Torrey and Gray * placed Nuttall's † *Bolophyta alpina* (1840) in *Parthenium*, thus modifying the generic concept to include a monocephalous plant of very dwarfed habit. By this time, representatives of the four sections of the genus had been discovered and the full range of habital differences was known. These differences are one of the remarkable features of *Parthenium*. One extreme is represented by the ephemeral annual plants of *P. bipinnatifidum*, which complete their life-cycle from seed to seed in eight weeks. Among the herbaceous perennials, *P. ligulatum* and *P. alpinum* are so dwarfed that they hardly project above the gypsum-impregnated soil of their native habitat, from which they are scarcely distinguishable at a glance. Other species represent a series which culminates in the very ligneous types represented by *P. tomentosum*. These may become large shrubs or small trees of over 15 ft. in height. In view of this great range in habit of growth, it is remarkable that such uniformity is present in the floral and reproductive structures of members of the entire genus.

All of the species are confined to the Western Hemisphere except guayule, which has been planted in the Eastern Hemisphere as a possible source of rubber, and *P. hysterophorus*, which has become a weed and as such has been spread to temperate regions of the Eastern Hemisphere. The species are described in detail by Rollins (1950).

Morphological Comparison of the Species

The following discussion of the morphological characteristics of the species of *Parthenium* is abstracted from the material published by Rollins (1950).

Roots. Reference has already been made to Muller's study (1946) of the root system of guayule. He showed that in cultivated plants the roots may penetrate as much as 20 ft. into the soil, although under natural conditions in Texas, guayule forms a much shallower root system—rarely

* J. Torrey & A. Gray—Ed. † T. Nuttall—Ed.

more than 2 ft. deep, but with a much greater tendency to spread laterally than in the cultivated plants.

In plants of the Section *Bolophytum*, including *P. ligulatum* and *P. alpinum*, the root is somewhat expanded at the crown, upon which the persistent leaves are borne. The stem is so telescoped as to be merely an expanded terminal portion of the main root, from which it is not separated by any distinguishable marking.

The roots of the plants in Section *Partheniastrum*, including *Parthenium hispidum* and *P. integrifolium*, are distinctive because they are often much enlarged. In the latter species, especially, the root is usually swollen, producing a tuber-like structure. There is a creeping tendency in the roots of *P. hispidum*, and they are most often without a tuber-like swollen portion, although some specimens have distinct swollen portions.

Stems. One of the outstanding features of *Parthenium* is the extreme range of variation of stem-types which it exhibits. Species of Section *Bolophytum* have a condensed stem, with no clear separation between stem and root. The stem structure is non-woody and the nodes are close together, with the leaves crowded. The older plants of both *P. alpinum* and *P. ligulatum* have numerous suckers and form low, dense clumps of various sizes. Although these sucker clumps seldom project more than a centimetre or two above the ground, they may persist for many years.

Elongated herbaceous stems are found in plants of Section *Partheniastrum* and *Argyrochaeta*, the latter consisting of *P. confertum*, *P. densipilum*, *P. hysterophorus*, *P. bipinnatifidum*, and *P. glomeratum*, in the classification given by Rollins (1950). The members of Section *Partheniastrum* are perennials and the stems die back to the ground at the end of each growing-season. New stems arise each year from adventitious buds on the root-crowns. In the annual species of Section *Argyrochaeta*, such as *P. bipinnatifidum* and *P. hysterophorus*, the stems are softly herbaceous and usually persist through only a single season. However, the roots will continue to produce new shoots for at least three years, if the plants are continually cut back.

All of the species of Section *Parthenichaeta*, consisting of *P. tomentosum*, *P. fruticosum*, *P. cineraceum*, *P. schottii*, *P. lozanianum*, *P. incanum* and *P. argentatum*, in Rollins's classification, are woody and range from low shrubs to small trees. An interesting feature of this group is that they usually produce flowers while the stems are still relatively herbaceous in their first year of growth. The lignification of the stems extends from the first year onwards. Sprouting is rather general in this group, and if an older plant is injured by frost, or in some minor way, new shoots often arise near the ground-level.

Leaves. The range in leaf types in *Parthenium* is almost as great as that in stem types. At an extreme are the undifferentiated, reduced and slightly flattened leaves of Section *Bolophytum*, in which it is difficult to distinguish between petiole and blade. The leaves are borne in dense clusters interspersed with tufts of long whitish trichomes. Perhaps the most highly differentiated leaves are found in the species of Sections *Partheniastrum* and *Argyrochaeta*. In these groups, the basal leaves are sharply differentiated into blade and long petiole, while those on the upper stem tend to be sessile. There is a gradual change from the basal leaves to the upper ones. Entire leaves characterize *P. integrifolium* and some forms of *P. hispidum*, while highly divided leaves are found in *P. hysterophorus*, *P. bipinnatifidum*, and closely allied species.

Trichomes. All species of *Parthenium* are at least partially covered with trichomes, and some species, such as *P. argentatum*, *P. incanum*, and *P. tomentosum*, have a very dense indument. There are a number of different types of trichomes in the genus. The commonest type is nearly straight and pointed, with the largest cell at the base and cell size diminishing toward the tip. Trichomes of the floral parts often follow the same pattern, except that the terminal cell is likely to be larger than the others. In the ontogeny of the leaf of *P. argentatum*, the trichomes are fully differentiated at a very early stage, and the content of the mature trichome has usually disappeared by the time the leaf is fully expanded. Though the trichomes of the genus are varied as to type, it should be noted that none are unicellular.

Flowers and Fruit. The uniformity of most of the floral parts throughout *Parthenium* is as remarkable as is the great diversity of the stems, leaves, and other structures. In each head, there are five fertile ray florets, each with two attached and sub-adjacent, seed-sterile disk florets. These two disk florets do not differ structurally from others of the disk portion of the head—except for their attachment at the base of the achene. There is an actual fusion of tissues at the base of the achene, involving the lateral ribs of the achene itself, the base of the two disk florets, and the subtending bract. All of these structures remain attached to the achene when it is shed. The corolla of the ray floret is persistent and is also a part of the achene complex.

The ray florets are completely unisexual, having no visible remnants of stamens present. The disk florets, on the other hand, do possess an abortive pistil together with the fertile stamens. The stigmas of the two types of florets are very different. Those of the ray floret are deeply cleft, with pollen-receptive tissue extending from the tip down the inner surface of each lobe; the lobes may be erect or spreading, depending upon the species. The stigmas of the disk florets, on the other hand, are capitate, with numerous well-developed glandular cells extending from the apex over the swollen portion.

In *P. argentatum*, the stigmas of the ray florets are receptive as soon as the lobes begin to separate. The newly expanded stigma-lobes are turgid and whitish. When pollination has taken place, the stigma-lobes usually begin to turn brownish within twenty-four hours, ultimately becoming quite dark. Where pollination is not effected, the stigma remains whitish and turgid for several days.

Variation in Chromosome Number within the Species

The chromosomes of *Parthenium* are small, relatively uniform, and numerous. The different species, particularly *Parthenium argentatum* and *P. incanum*, have both diploid plants and plants that are normally polyploid. The value of cytology in the breeding of superior types of guayule will be discussed later. Interspecific hybridization has been successful to a limited degree and offers hope for the future, particularly in the way of increasing both disease resistance and greater tolerance to cold.

The great variation encountered in the chromosome numbers found in the different species has made it difficult to determine the normal diploid number of some of the species. Rollins (1950) states:

> It is now evident that there are at least two groups of species in the genus with respect to their basic chromosome-number. In section Argyrochaeta, *P. hysterophorus* with $2n = 34$ and *P. confertum* var. *lyratum* with $2n = 34$ and 68 fit one pattern, while all of the species so far investigated in the other sections are either $2n = 36$ or derivatives of that number. If, as seems probable, $2n = 36$ is the diploid number for *P. argentatum*, *P. tomentosum* and its var. *stramonium*, *P. fruticosum*, *P. ligulatum*, and *P. alpinum*, it appears that $x = 18$ is the fundamental or basic number of sections Bolophytum, Partheniastrum, and Parthenichaeta. The basic number of section Argyrochaeta would seem to be $x = 17$, but this leaves the $2n = 24$ of *P. bipinnatifidum* not properly accounted for. The latter is the lowest number so far found in the genus. However, the total evidence points away from $x = 9$ as the basic number for the polyploid series of guayule and its closest relative *P. incanum*, as suggested by Stebbins and Kodani (1944), and supports $x = 18$ as accepted by Bergner (1946).

Variation in Guayule within its Natural Range

Restriction in Total Range

The natural occurrence of guayule as described by Lloyd (1911) comprises roughly a rectangular strip of country in south-west Texas and north-central Mexico north of the Tropic of Cancer and between the 100th and 105th meridians (cf. pp. 107–8 and Fig. 1). The rectangle has a maximum width of some 250 miles and a length of, roughly, 450 miles. From its northern limits in the United States it ranges slightly east of south, approaching in the east the 100th meridian only at the southern limit of its range, but approaching in the west the 105th meridian both in the most southerly part of Texas and again at about 25° north. Only one collection has been reported from south of the Tropic of Cancer.

Restriction within Total Range

In common with many other non-competitive species, guayule has been restricted in nature to limited areas within its natural range, and to specialized conditions that are too severe for plants that crowd out guayule where soil and climate are more favourable for plant growth. Guayule is not found where conditions are most favourable for it, but occurs instead where conditions are unfavourable for competitors. This is most aptly illustrated by the relatively rapid growth of guayule under cultivation, when the potentially competing vegetation is kept under control. However, a young planting of guayule will be rapidly overgrown if the intensity of cultivation is reduced; and, even after the guayule tops meet both within and between the rows, grasses and aggressive shrubs soon overtop the guayule in neglected fields.

Natural Stands and Plant Competition

Guayule is thus definitely restricted both in total range and, within its natural range, to mere spotty occurrence. It is found on less than 10 per cent of the land within its natural range, and there is considerable variation in the density of guayule plants within the areas in which it is the dominant species. Lloyd (1911) made careful counts of the guayule at a number of selected stations, and found a count of from 30 to 685 guayule plants per 100 square metres. In the area where guayule plants were counted at a density of 685 plants per 100 square metres, Lloyd found the following competing species:

Scientific Name	*Common Name*	*Number of Plants* *
Parthenium argentatum	Guayule	685
Agave lecheguilla	Lechuguilla	25
Covillea mexicana	Gobernadora	3
Samuella carnerosa	Palma samandoca	2
Dasylirion cedrosana	Sotol	1†
Acacia farnesiana	Huisache	4‡
Jatropha spatulata	Sangre de drago	Scattered all over
Zexmenia brevifolia		3
Lophophora williamsii	Peyote	About 10
Opuntia megalartha	Rastrero	23¶

In an area where there were only 186 guayule plants per 100 square metres, Lloyd found:

Scientific Name	*Common Name*	*Number of Plants*
Parthenium argentatum	Guayule	186
Parthenium incanum	Mariola	14
Opuntia stenopetala	Nopal Colorado	5
Opuntia microdasys	Segador	7
Covillea mexicana	Gobernadora	8
Opuntia imbricata	Gardenche	1
Salvia chamaedryoides	Engorda cabra	3
Dasylirion cedrosanum	Sotol	1
	Cacti (other)	Several small inconspicuous plants
Samuella carnerosa	Palma samandoca	Less than 1 per 100 square metres
Agave asperrima	Maguey	Less than 1 per 100 square metres

* Count reported for 200 square metres. Published figures divided by 2 for this table.
† Count for 200 square metres was 1. ‡ Count for 200 square metres was 7.
¶ Count for 200 square metres was 45.

Guayule represented about 90 per cent of the total plant population both where there were 685 guayule plants per 100 square metres and where there were only 186 guayule plants per 100 square metres. In the dense stand, small plants of *Jatropha spatulata* were scattered throughout the area, but these were not counted and could not be considered in calculating the percentage of guayule in the stands. In the lower stand there were several Cacti that were not counted. It is apparent that, with the advantage of the limestone ridge to handicap its rivals, guayule becomes the aggressor and dominates. Where the soil is better, guayule is unable to withstand the competition and is at best a minor constituent of the natural stand of plants; generally it is lacking where other vegetation flourishes.

Relation of Spotty Distribution to Propagation

In many areas, the limestone ridges that typify the natural occurrence of guayule are sufficiently close together for the interchange of pollen by wind or by means of insects to be expected. As there is a significant portion of guayule seed production that is entirely sexual, the interchange of germ-plasm has naturally acted towards reducing the chances of individual populations varying materially from the norm for the species. A high rate of variability is normal to guayule, and this variability can be preserved only through the sexual propagation of plants.

The predominating seed propagation in guayule is through apomixis, which involves essentially the vegetative propagation of the mother-plant by means of seed. As this process of propagation is dominant in all varieties of guayule that have been studied—except possibly some of the highly localized diploid strains in the State of Durango, Mexico—this apomixis has resulted in a high degree of uniformity in isolated populations. This factor was recognized in the period of exploitation of the wild shrub. The percentage of rubber obtained from guayule from different areas varied considerably, and shrubs from certain areas were preferred for milling because of the higher output of rubber and the superior processing qualities of the high-yielding shrubs.

Local Differences in Shrub Quality

The differences in local types of shrub were often obscured by variations in the time required to harvest the shrubs and transport them to the mill. This involved recruiting field-parties to harvest the shrubs, haul them on pack-animals to the baling sites, bale them, and finally haul them in trucks to the railroad sidings where they remained until they could be picked up. Additional delay resulted from the necessity for storing large quantities of shrubs at the mill, to provide the raw material during seasons that might be unfavourable for harvest or when transportation delays interfered with regular receipt of shrubs. In periods of transportation delays, the shrubs might remain at the railroad siding for several months before they were picked up. Periods of up to six months between harvest and milling were not uncommon.

These delays affected adversely the quality of the rubber in the shrubs, for even under the best of conditions, it was never possible to mill wild shrubs in a fresh condition such as was found to be best for cultivated shrubs. The quality of the rubber from wild shrubs suffered not only from deterioration in the rubber itself, but also from the impossibility of obtaining clean separation of the rubber from the thoroughly desiccated shrub material.

Origin of Local Differences in Shrubs

Numerous strain differences have been found in guayule. Some of the outstanding of these differences have been found associated with particular areas where the strains have become established in nature. The semi-isolation, brought about by the discontinuous distribution of guayule in its natural range, has led to strain isolation. Apomixis, self-pollination, and inter-specific hybridization, have each contributed to this. Powers (1942) attributes to mutation a major proportion of the specific changes occurring in guayule in nature. Many of the intergrading characteristics between *Parthenium argentatum* and *P. incanum* are certainly the result of natural hybridization, as are also some of the intergradations between *P. argentatum* and *P. tomentosum* and those between *P. incanum* and *P. tomentosum*.

Cytological Comparison of Local Variations

Owing primarily to the seed-production being predominantly by apomixis, many of the local populations of guayule in nature are remarkably uniform. In the fall of 1942, LeRoy Powers and W. B. McCallum collected seeds of guayule and mariola (*P. incanum*) in Mexico, and Walter T. Federer collected seeds of the same species in Texas. Bergner (1946) made a detailed study of the chromosomes in the seedlings obtained from these collections and reported:

> At Salinas there are 5 diploid collections ($2x = 36 +$) from seeds harvested in a mountainous area southwest of Mapini, Durango, Mexico. There are 5 triploid collections ($3x = 54 \pm$)-1 from an individual plant growing within the population from which the diploid collection 4255 was obtained, and the other 4 from different places near San Bartolo, Durango. Such commercial strains as McCallum's 109, 111, 210, 255, and 258 also are triploid. The majority of the collections at Salinas have $72 \pm$ chromosomes and are therefore tetraploid ($4x = 72 \pm$). The seeds came from both natural stands and McCallum's commercial strains. Only 9 of the collections made by Powers and McCallum in Mexico are tetraploid. They came from the following locations: one from an individual plant growing within the population from which the collection 4255 was obtained; another from seeds collected near San Juan, Nuevo Leon; a third from Catorce, San Luis Potosi; and the remaining 6 from Majoma in northeast Zacatecas. The trans-Pecos area of

Texas is represented by 362 collections. Of these collections cytological work has been done on only 55 and pollen studies on 4 more. All had 72 ± chromosomes. Eleven of the 20 locations in Texas from which seeds were collected have been sampled. Thus far 25 of McCallum's commercial strains have been found to have 72 ± chromosomes. They are Nos. 38H, 49, 130, 402, 404, 406, 406F, 411, 413, 416, 418, 419, 426, 428, 430, 439, 440, 441, 444, 453, 456, 459, 593, and 735-2, and a Mexican strain (42478 in Powers's collections). Thus far no pentaploid or hexaploid natural stands or commercial strains have been found. Higher chromosome numbers have been limited to certain individuals in triploid and tetraploid populations and strains, and to their offspring.

Durango Strains of Guayule

Collections from the State of Durango, Mexico, have consistently been outstanding in vigour and rubber production. Powers's extensive collections had a high proportion of diploid and triploid numbers from this area.

The diploid guayule is fully sexual and amphimixis is its predominating method of seed formation. The triploid guayule is more highly apomictic in general than any other group of guayule; accordingly, this area of Mexico is favoured as a source of superior germ-plasm from the free-breeding diploids that keep developing and distributing variability, and for the highly apomictic triploids that store the accumulated variability.

Records are not available to determine whether the 'charcoal rot' caused by *Sclerotium bataticola* occurs in the State of Durango, Mexico, although certain strains of guayule from that area are highly resistant to the disease. Norton (1953) and Norton & Frank (1953) showed that this disease is a limiting factor in the growth of guayule in Texas, where it is highly parasitic and is prevalent in sandy soil—particularly during periods of drought. Whereas guayule is resistant to drought it is prone to charcoal rot, standard varieties such as 593 being particularly susceptible. However, when strain 593 is crossed with the resistant Durango strains, both the rate of growth and the resistance of charcoal rot are greatly increased in the resulting progeny.

Cytology and Genetics

The Development of the Flower

The 'flower' of guayule (Fig. 4) consists of a head with five ray florets and numerous disk florets. Ten of these disk florets have a special relationship to the ray florets, though they do not differ structurally from others of the disk portion of the head—except for their attachment to the base of the achene. These disk florets remain attached to the achene when it is shed, and form a part of the seed complex. The ray florets are completely unisexual, having no remnants of stamens. The disk florets, however, possess abortive pistils together with fertile stamens.

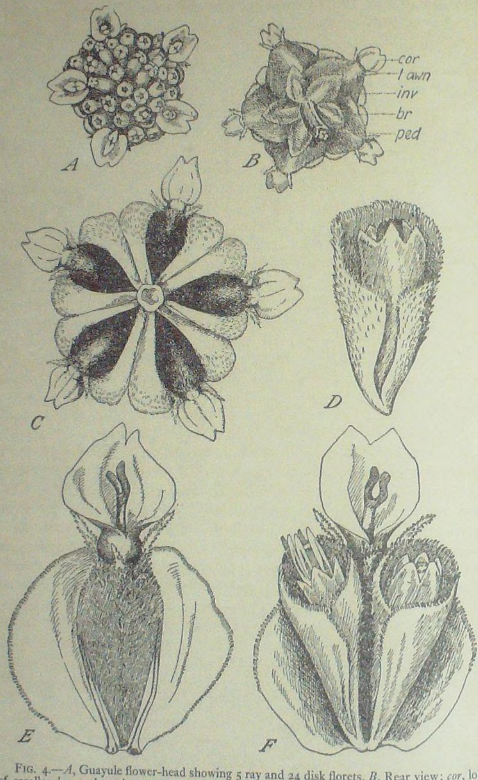


FIG. 4.—*A*, Guayule flower-head showing 5 ray and 24 disk florets. *B*, Rear view; *cor*, lobe of corolla; *l awn*, lateral awn; *inv*, involucral leaf; *br*, bract of ray floret; *ped*, pedicel. *C*, Enlarged rear view with involucral bracts removed to show outline of achenes, sterile florets attached to them, ray corollas, and pappus. *D*, Disk floret with its enclosing bract. *E*, Enlarged view of ray floret without its two attached disk florets. *F*, Enlarged view of ray floret with its two attached disk florets. From *Artschwager* (1943).

The maturation of the flowers starts with the outer disk florets and then proceeds successively inward. The stigmas of the ray florets are receptive as soon as the stigma lobes begin to unfold.

Pollination of Guayule

Gardner (1946, 1947) studied the natural pollination of guayule and found that, in addition to wind pollination, large numbers of insects could be detected carrying pollen. Ladybird beetles and lygus bugs were observed, in particular, as carrying pollen in abundance. A species of fruit-fly was responsible for an increased seed-set in one lot of cages put up to determine the possibility of using insects for controlled pollination. In other cases, none of the insects tried were effective in obtaining a satisfactory set of seed, and Gardner decided that the use of insects to avoid the tedious hand-pollination was not promising.

Controlled pollination in guayule is a slow, tedious operation. The flowers are small and emasculation is slow. As compared with the pollination of *Hevea*, however, the results are rewarding, as a high percentage of success may be expected. In natural diploids, incompatibility of the individual plants to their own pollen obviates the necessity for emasculation, and this same factor can be taken advantage of in other cases where incompatibility has been demonstrated. Otherwise, it is necessary to remove the disk florets in performing the hand pollination.

The Need for Plant Improvement

The breeding of guayule is primarily for the purpose of increasing the yield of rubber per acre. However, in moving toward that end, there are other things that must be considered. The high cost of irrigation in California has forced those interested in the culture of guayule to recognize the necessity for dry-land production. Strains of guayule that accumulate satisfactory percentages of rubber under the cool coastal climate of regions best suited to guayule in California, often do not thrive and accumulate rubber satisfactorily either under irrigation or under dry-land farming in the inland valleys of California or the arid plains of south-west Texas. In some cases, it is inadequate growth that restricts rubber accumulation; in others, growth is adequate but the rate of rubber formation is slow. Some selections show good growth and rubber accumulation in the first year but thereafter the rate of rubber accumulation in them does not keep up with their growth.

Both in California and in Texas, several serious diseases were encountered in nursery plantings as well as in the field. Varietal differences were observed in guayule with regard to its resistance or tolerance to these diseases and, in at least one instance, Gerstel (1950) developed a strong presumption of a relationship between the occurrence of *Verticillium* wilt and the chromosome number of the strain. Gerstel showed that diploids were very susceptible to the disease but that triploids and tetraploids were progressively more resistant.

In general, guayule has a rather narrow range of tolerance to climatic changes. As pointed out previously, it has difficulty in surviving if normal winter temperatures are below some 15°F., and winter killing may occur at temperatures below 5°F. In the Texas area where guayule is native, winter temperatures as low as -7°F. have been recorded, and it is probable that suitable factors can be found in guayule to form a basis for breeding cold-tolerant varieties that might greatly extend the range of adaptability. Cold tolerance in planting material might also be obtained by interspecific hybridization.

The Aims of Plant Improvement

Plant improvement in guayule thus falls into several categories:

1. Improvement in the germination and initial growth of guayule seedlings so as to be able to plant the seeds directly in the field rather than having to plant them in the nursery and then transplant the resultant seedlings in the field. This is already possible where there is adequate irrigation, but has not become a standard practice. It would not be practicable without irrigation.

2. An increase in the yields per acre, both by increasing the size of the plants and by breeding plants with higher concentrations of rubber.

3. An increase in the rate of rubber formation in the early years of growth, in order to decrease the time from planting to harvest.

4. An increase in the rate of rubber formation under hot, arid conditions. Guayule is native to the high plateau of north-central Mexico and produces most rubber under the coastal climatic conditions of California. Yields in Texas have not been satisfactory in some cases, but certain strains do give adequate yields under arid conditions.

5. An increase in the cold tolerance of guayule, so that the limits of the 'guayule belt' can be extended farther north and increased acreage of marginal land can be made to yield a useful crop.

6. An increase in the ability of guayule to produce rubber under somewhat higher rainfall conditions than at present. In the most southerly tip of Texas, the rainfall is greater than it is to the west in the so-called 'guayule belt'. The growth of guayule under the higher rainfall is much better than under drier conditions, but the rate of rubber formation is low and the yields of rubber are unsatisfactory.

7. An increase in the resistance of guayule to diseases that limit the production of nursery stock and seriously interfere with the shipment of nursery stock.

8. An increase in the resistance of guayule to diseases that interfere with the growth of the plants in the field. Strains resistant to charcoal rot, Texas root-rot, and *Verticillium* wilt, have been found. With the high natural variability found in guayule (*see* p. 118), selection having higher resistance to these and to other diseases such as *Diplodia* dieback, southern wilt, etc., may be expected.

Cytogenetics in Plant Improvement

The cytogeneticist is a key man in plant improvement in guayule. All breeding operations are facilitated by recognition and use of the chromosome relationships. Sexuality is a necessity in primary crosses but, even in these crosses, fertilization may not result in pairing of chromosomes but may involve adding of chromosomes to give a combination not previously known to exist. Tysdal (1950) outlined the modes of reproduction possible in a 72-chromosome guayule plant (Table V).

TABLE V

DIFFERENT MODES OF REPRODUCTION OF ONE 72-CHROMOSOME GUAYULE PLANT *

Parent	Number of chromosomes of: Progeny			
	Non-reduction		Reduction	
	Not fertilized	fertilized	Not fertilized	fertilized
72	72	90 (108)	36	54 (72)

* From Tysdal (1950).

All of the types of reproduction outlined above have been found. While the 72-chromosome guayule is highly apomictic, the varieties studied have been found to have from 5 to 20 per cent of what Tysdal terms 'aberrants' that can produce viable seed by the last three methods indicated in the table. A small percentage of unreduced eggs may be fertilized with either 18- or 36-chromosome pollen, depending upon the male parent, giving 90- or 108-chromosome progeny. Such high chromosome derivatives reproduce apomictically and thus breed true. If reduction occurs and the reduced eggs are not fertilized, 36-chromosome offspring result, which are polyhaploids rather than diploids, and whose mode of reproduction is by apomixis, as is characteristic of the other polyploids. If the gamete from the reduction division is fertilized with 18- or 36-chromosome pollen, a hybrid results having 54 or 72 chromosomes. These plants are facultative apomicts. The plant breeder is interested in all the types of reproduction illustrated above, including the reduced 36-chromosome group or polyhaploids.

In the above instance, the 72-chromosome plant was chosen to illustrate the range of variation possible in the cytogenetic complex of guayule and not to indicate any superiority of 72-chromosome plants as the starting point for a breeding programme. The basic building block for the genetic improvement of guayule is the 36-chromosome sexual type, the true diploid. Next in importance is the sexual faction of the 72-chromosome strains. From these two basic types, a great variety of chromosome combinations can be obtained and, when an end-point is reached in any line of breeding, the accumulated characters can be set by introducing known factors for apomixis. Tysdal (1950) states:

> It will be noted that both sexual and apomictic hybrids can be obtained at will; thus, in this species we can practically achieve the goal that was set by Clausen, Keck, & Hiesey (1947) when they wrote, 'It would indeed be of considerable practical and theoretical importance were we able to break the apomictic bond, periodically releasing the variability, and then seal it up again after a period of recombination.' Indeed, while the possibility of such a program is being approached in several species, particularly the grasses, as shown by Nygren (1949) for *Calamagrostis purpurea*, and in *Poa* by the above three workers, the author is unaware of a situation which lends itself so readily to the wishes of the plant breeder.

Inheritance of Apomixis

Gerstel & Mishanec (1950) made a study of the inheritance of apomixis in guayule, using a proved diploid and a proved polyhaploid as parent plants. They summarized their findings as follows:

> 1. In feral guayule the diploids ($2n = 36$) reproduce sexually, but polyploids are facultative apomicts. A fertile polyhaploid with the diploid number of chromosomes, but facultatively apomictic in its reproduction, was crossed with a diploid. If the polyhaploid was used as a female, the following progeny classes resulted: maternals, diploid F_1, triploids, and plants with higher chromosome numbers (doubtful cases).
>
> 2. The reciprocal cross, sexual diploid $\times$ polyhaploid, produced only diploid F_1 plants. Diploid F_1 from both types of crosses were almost entirely sexual; an exceptional unreduced egg was produced in one instance. Production of F_2 and B_1 generations was impaired by incompatibility (not sterility) among F_1 sibs and between them and their recessive parent.
>
> 3. Triploids from the cross apomictic polyhaploid $\times$ sexual diploid were facultative apomicts.
>
> 4. Tetraploids produced by artificially doubling the chromosome number of diploids reproduced sexually on the whole—one exceptional maternal plant in the progeny may have arisen either by selfing or by apomixis.
>
> 5. It is concluded that the genes for apomixis are recessive but that dominance is reversed where two apomictic genomes combine with one sexual one. While apomixis, on the whole, is determined by the genotype, chromosome numbers may have modifying quantitative effects.

Interspecific Hybridization

Interspecific hybridization has assumed increasing importance in the improvement of guayule. The most important of the interspecific hybrids are those between *Parthenium argentatum* and *P. tomentosum* var. *stramonium* (Plate 16(*a*)). This hybrid was reported on by Tysdal (1950) and by Tysdal & Rands (1953). These authors cited the non-guayule parent as *P. stramonium*, but Rollins (1950) described it as a variant of *P. tomentosum*. The guayule-*stramonium* hybrids are extremely vigorous and have also shown a degree of resistance to disease. The rubber percentage, however, has been somewhat lower than that of the better guayule selections. The calculated yields are higher than those of the better guayule strains, but the larger quantity of shrub material that must be handled to obtain an equal amount of rubber is a distinct disadvantage in processing.

Powers & Rollins (1945) and Rollins (1945) studied the hybridization of *P. argentatum* and *P. incanum*, and Rollins (1946) reported on hybridization studies using *P. argentatum*, *P. incanum*, *P. tomentosum*, and *P. hysterophorus*. The success of interspecific hybridization has been demonstrated as a means of obtaining genes for vigour and for disease resistance. These and other characters, such as cold tolerance, might well be greatly increased through more extensive hybridization.

The Tysdal Classification of Breeding Lines

The introduction of *stramonium* blood-lines into the guayule breeding programme gave the resulting plants both vigour and a high degree of resistance to certain of the diseases that limit the growth of guayule. It was necessary to intensify both characters and at the same time recapture the high level of rubber concentration of the high-yielding guayule parentage. The wealth of variation available in guayule, and in the closely related species of *Parthenium* that hybridize readily with guayule, presents a highly encouraging picture for eventual success. There are a myriad criss-crossing paths to be followed, if all possibilities are to be explored. To systematize the breeding operations and orientate the most promising lines within the total possible lines, Tysdal, as reported by Tysdal & Rands (1953), developed a code for the classification of guayule crosses. His code involved, first, the classification of the possible crosses as follows:

A. Guayule crosses, all types involving only guayule.
B. F_1 interspecific hybrids.
C. F_2 interspecific hybrids.
D. $F_1 \times F_1$ (both interspecific crosses; i.e. $B \times B$).
E. BC_1 (interspecific—species $\times$ F_1 and its reciprocal $F_1 \times$ species).
F. BC_2 (interspecific—species $\times$ BC_1 and reciprocal $BC_1 \times$ species).
G. $BC_1 \times F_1$ (interspecific).
H. $BC_2 \times F_1$ (interspecific).
I. $BC_1 \times BC_1$ (interspecific).
J. $BC_2 \times BC_1$ (interspecific).
L. Guayule $\times$ $(F_1 \times F_1)$ (interspecific).
M. $BC_1 \times (F_1 \times F_1)$ (interspecific).
N. $F_1 \times (F_1 \times F_1)$ (interspecific).
R. Crosses involving three or more species.
S. Miscellaneous (any pairing not ascribable to another specified classification).
T. $BC_1 \times$ species (BC_1 crossed to non-recurring parent).

Tysdal set up a series of sub-groups under each of the above classifications. These sub-groups were based on separating the plants in each category into types based on chromosome number and dominant method of reproduction (sexual or apomict). The first series of sub-groups were based on the designation of crosses between four types of plants, sexual 36-chromosome plants and apomictic 54-, 72-, and 90-chromosome plants, in all possible pairings. Thus sub-groups 1 to 4 designated crosses of each of the above types (in the same respective order) with 36-chromosome sexual plants. Sub-groups 5 to 8 designated crosses of each of the four types with 54-chromosome apomicts. Sub-groups 9 to 12 designated crosses of each of the four types with 72-chromosome plants, and sub-groups 13 to 16 designated crosses of each of the four types of plants with 90-chromosome apomicts. Sub-groups 17 to 20 were to designate crosses between each of the four types of plants (in the same order) when crossed with 36-chromosome apomicts. Sub-group 21 was for 36-chromosome apomicts crossed with 36-chromosome apomicts. Sub-group 22 designated crosses involving 54-chromosome sexual plants; and sub-group 23 designated crosses involving 74-chromosome sexual plants. Not all, nor even a large percentage of these possible pairings, could be accomplished in any particular breeding project; but the main classification and sub-grouping were designed to aid in determining the most fruitful lines of breeding.

Population Size in Breeding Guayule

If all of the crosses outlined above were made, a single series would involve a minimum of 736 different types of crosses. Combinations between the different classifications would provide an almost unlimited number of crosses. In a comprehensive breeding programme, it would be necessary to explore the full range of possible combinations to attain the maximum concentration of superior qualities in the available germ-plasm of guayule. However, Tysdal's investigations of crosses already made with respect to their place in the over-all classification, brought the rather surprising discovery that the number of progeny studied was more important in many cases than the class of hybridization involved, and that it was more important to make and study large populations than to create a large number of diverse lines.

The Status of Guayule Breeding

Important steps were taken during the war in the improvement of guayule, the basic principles of guayule breeding being worked out under the leadership of LeRoy Powers. Since the war, the work has been continued on a greatly reduced scale. Substantial advances have been made, though the best general-purpose strain is still No. 593, which had been developed by selection from wild strains by Wm. B. McCallum of the Intercontinental Rubber Company before the United States Government took over the work in 1942. Tysdal's findings would tend to indicate that the cream of the initial improvement has not yet been obtained.

Biology and Autecology

The Root System of the Cultivated Plant

The root system of guayule has been described in connection with the discussion of the plant in nature. Muller (1946) has shown that the root of cultivated guayule may penetrate as far as 20 ft. into the soil. Guayule grows particularly well following a deep-rooted plant such as alfalfa, and many crops show exceptional response when following guayule. The leaves of guayule, being rich in nitrogen, may be responsible for some increase in fertility, and indeed have been used advantageously as fertilizer. It is highly probable that the deep rooting of guayule is primarily responsible for the favourable response of subsequent crops.

In nature, guayule is resticted to the shallow soil of the limestone ridges, and the outstanding root development under these conditions is lateral and such that all the surrounding soil will be occupied by the guayule. Under cultivation, the competition of other plants is kept to a minimum and guayule does best on soils that permit deep penetration. Lateral spread of the roots is limited by the guayule plants in the same or adjacent rows of the planting. The root profiles found by Muller are thus largely straight down—except where clay or hard-pan layers force lateral development.

Rate of Root Growth in Seedlings

Root development in young seedlings is quite rapid. By the time the seedlings form their first true leaves and shed their cotyledons, about the third week after germination, the young roots will have penetrated as much as 8 in. into the soil. At that time, the roots have begun to branch and send out feeder roots, and during the next few weeks the roots branch and increase in size and number without lengthening materially. They develop greatly, both in length and amount, as the aerial portion of the plant starts to grow. Two-month-old seedlings may have pushed their roots down as much as 18 in. to 3 ft. Within the second month, the dominant tap-root of the seedling gives way to a branched, fibrous mass. This is an important fact, as it is apparent that the root shortening and pruning necessitated in transplanting seedlings to the field does not result in a materially different root-structure than that of the seedling itself. Surprisingly, Muller's illustrations show a longer survival of the tap-root in transplanted seedlings than in the seedling plantings that were not transplanted.

Root Growth of Transplanted Seedlings

Root development of a transplant is relatively greater and more rapid than that of the untransplanted seedling. Within two months after transplanting, the plant develops a heavy mass of fibrous roots and a much larger aerial part than that of a comparable undisturbed seedling. At that time, the transplant may be starting to flower if conditions are favourable.

Soil Profile in Relation to Root Growth

Root development after the first couple of months depends to a large extent on the character of the underlying soil. Muller (1946) shows roots that penetrated to a depth of over 8 ft. in twenty-eight weeks at Salinas, California, irrigated plants that had penetrated 5 ft. in two years, and plants adjacent to the latter but grown without irrigation that had penetrated only 3 ft. (though a scattering of roots had penetrated to 4 ft.).

The greatest hazard to root penetration is the presence of clay or other dense layers in the soil. When the root reaches one of these layers, elongation is retarded or stopped and the root spreads laterally. The extent of this horizontal growth is related directly to the character of the obstructing layer. The roots occupy the entire soil structure above a thick, heavy layer that prevents further penetration of the roots, and it is as though the plant were pot-bound. In deep sand the roots are inclined to penetrate deeply and even the laterals grow vertically, often not leaving the root-mass but growing close together to form a long, heavy, rope-like structure.

Plant Competition in Relation to Root Growth

Lateral spread of the roots of guayule is controlled largely by competition. In cultivation, this competition comes largely from guayule plants in a well-tended field. Furthermore, grasses and other weeds may seriously affect the growth of the guayule roots and also control their type of growth, and it is often difficult to make a succession of guayule plantings in a single plot because of the lateral spread of the roots from the planted rows into the rows reserved for later planting (Plate 16(*b*)). If there is an appreciable time between plantings, the succeeding plantings may be seriously retarded by the root-competition of the prior planting.

In nature, guayule is unable to compete with other plants for the deeper soil and is thus confined to areas where other plants cannot survive. In these areas, the established guayule itself is the chief restricting force against further increase in the guayule population. At seeding time, thousands of tiny seeds lodge in the accumulated humus at the base of the mother-plant. When the rains come, this protected spot catches the rain and the seeds are able to germinate. The mother-plant, however, has already occupied all of the available soil within reach of its roots. Though hundreds of young plants have been observed around the bases of old plants, not a single one survives to become established until after the death of the parent plant.

Growth-rate of Aerial Portion

The growth-rate of the root is relatively rapid during the early stage of development of the seedling. Throughout this period, the aerial portion of the plant develops very slowly. In the nursery or under cultivation in the field, the growth of the young plant can be forced; but the normal development depends on the establishment of a substantial root system before the aerial portion of the plant initiates active elongation. In nature or under dryland culture, the active growth of the plant is limited to a short period after rains when there is adequate ground moisture, yet growth can continue for considerable periods when the moisture level is substandard for many crops.

Under dryland cultivation, it takes from three to five years for a guayule plant to attain a sufficient size for harvest. By the end of the third growing-season, guayule plants in 28 in. rows will usually have closed in to present a solid planting. Thereafter, damage occurs when the plants are cultivated and, by the end of five years in the field, the plants should have reached an adequate size for harvest. After that time, plant growth is slowed down somewhat; but the accumulation of rubber continues for several years, and unharvested guayule can be left in the field for up to twenty or more years with no decrease in rubber.

Growth-rate in Relation to Temperature

The native habitat of guayule is a comparatively high plateau region with a wide diurnal fluctuation in temperature. In the growing-season, the day-time temperatures range from 70° to 100°F. and the night temperatures vary from 40° to 65°F. Temperatures down to freezing may occur after the start of the growing-season in late February and near the close of the growing-season in November.

Under cultivation in the United States, guayule thrives both under the cool coastal climate and in the hot inland valleys of California and southwest Texas. Extremes of heat during the growing-season, or of drops in temperature during cool nights, have not seriously affected growth of guayule, which has shown a very wide tolerance to variations in temperature. Growth is suspended when freezing night temperatures begin, and continues suspended until day temperatures in excess of some 70°F. are again the rule, though active growth is dependent on adequate rains or accumulated soil moisture. In the absence of adequate soil moisture, the plants remain dormant and can resist long drought periods without injury. Warm periods during the winter in Texas may encourage new growth that may then suffer in subsequent freezes. Guayule's quick response to warm weather in the presence of adequate ground moisture makes it particularly subject to winter damage under such conditions.

Growth-rate in Relation to Moisture

Guayule is adapted to survival under desert conditions with a minimum of rainfall. Records of precipitation in the natural range of guayule are scattered and not reliable. They indicate that, in many areas, annual rainfall rates of less than ten inches are not uncommon. However, uniformly cool nights and moist air from the Cordilleras make for heavy dews during the growing-season, and these may effectively increase the available moisture without registering in the rain-gauges.

Under cultivation, guayule responds to differences in moisture more quickly than to any other influence, and the growth that is expected under dryland conditions in five years can be obtained in three years under irrigation. Harvest can be hastened even more, but two-year harvest is definitely at the expense of the yield of rubber. Without irrigation, guayule gives adequate growth in areas with from 15 to 20 in. of rainfall, but gives even better growth where the rate of rainfall is from 20 to 30 in. In the latter case, however, the extra growth is obtained at the expense of rubber accumulation. With higher rates of rainfall, disease enters the picture to restrict the growth of guayule. Under irrigation, it is possible to balance growth-rate and rubber accumulation, but such control has not been possible in areas where the increased moisture is obtained from rainfall.

Growth-rate and Flowering

Guayule flowers at an early age and can be expected to produce seed in the first season of growth. Seed production in the first year is very small, amounting usually to less than 10 lb. per acre even under the best of care.

In the second and subsequent years, yields of from 30 to 50 lb. of seed per acre can be obtained if growth is forced. Seed production is related directly to the size of the plant and its conditions of growth. The larger the plant, the more seed-heads are formed and the higher the yield of seed. Seeds produced on nursery or first-year plants are usually normal and viable, though under poor conditions of growth there may be an excessive proportion of undeveloped seeds and thus the germination rate may be reduced.

Flowering in Relation to Temperature and Moisture

Variations in temperature, within the general range of temperatures usually experienced in the growing-season, have relatively little effect on the growth-rate of guayule. Moisture, on the other hand, is a controlling factor. As the flowering of guayule is directly related to the rate of growth, the rate of flowering and seed production can be controlled by irrigation to force the growth of the plants. At Salinas, California, it was possible by controlled irrigation to force three separate flowering-cycles of guayule in a single growing-season. After an early irrigation, water was withheld until flowers had formed and seeding and seed harvest were over. The guayule plants were then given a second irrigation, which forced a second flowering and seeding. The seeds were harvested and a third heavy irrigation was then followed by a third seed-crop. This régime of irrigation was based on the withholding of the water for seed ripening and harvest, and thus differed from a normal régime of irrigation to force maximum growth of the plants.

Rubber Accumulation in Relation to Growth-rate

The rubber content of a guayule plant is a function of the size of the plant and of the percentage of rubber in the plant's tissues. It is necessary to produce large plants with high percentages of rubber to obtain maximum yields, although, unlike flowering and seed production, rubber accumulation does not proceed rapidly when the plant's growth is most rapid.

In this context, it is necessary to differentiate between rubber formation and rubber accumulation. The rubber content is a measure of the total rubber in a plant at any given time, being a measure of the amount of rubber that the plant has accumulated. If rubber is a stable end-product that is not thereafter broken down into simpler products to be re-used by the plant, the terms 'rubber formation' and 'rubber accumulation' are synonymous. There is strong evidence that this is true but there is still a reasonable degree of doubt about the matter.

Spence & McCallum (1935) reported that the amount of rubber in a guayule plant decreased during a period of active growth in pure-sand culture without nutrients, and they concluded that the rubber had been used as a food reserve. In carefully controlled tests, Traub (1946) and Benedict (1949) demonstrated that, under great stress, the carbohydrate reserves of guayule were depleted, but that there was no reduction in the rubber content. Both these later authors concluded that rubber did not serve as a food reserve in guayule.

Benedict (1950) attempted to determine, under controlled conditions in the greenhouse, the environmental factors that affect the formation of rubber in guayule. His tests involved variations in light-intensity, temperature, soil moisture, and available nitrogen. He found that low light-intensity invariably resulted in a low rate of rubber formation. Of the other factors he stated:

> With one or two notable exceptions, any variation in soil moisture, available nitrogen, and temperature which resulted in lower dry-weight also resulted in higher percentage composition of levulins, resins, and rubber. . . . One notable exception to the general observation that plants with lower dry-weights had a higher percentage than those with the great dry-weights was found in the sand-culture series. Plants grown at 60°F. had a lower weight than those grown at 75°F., but they also had a lower resin and rubber content. In other words, the plants on high temperature showed both a greater dry-weight and a greater percentage of rubber than those grown at the low level.

In another test, performed under field conditions at Salinas, California, Benedict (1948) removed the flower-heads from guayule plants as they started to form. He found that the rate of rubber formation in the plants that were not allowed to fruit was much greater than in those that were allowed to flower and fruit normally.

It is apparent that the general relationship between growth-rate and the rate of rubber accumulation holds true under most field conditions. Benedict has demonstrated rather clearly that growth and rubber accumulation are not intrinsically opposed. No method of cultural control has been devised to take advantage of this fact.

Rhythm in Rubber Production

It has been demonstrated that the growth-rate of guayule can be increased by the controlled use of irrigation. Added nutrients and other good cultural practices can also be used to increase the growth-rate. During the period of active growth, the rate of rubber accumulation is at a minimum. When the active growth of the plant is slowed by drought, cold weather, or other stress conditions, the rate of accumulation of rubber is greatly increased. From this, it has been argued that a rhythmic régime of rubber production could be developed under which the plant would be forced into active growth to form the rubber storage cells. Then the growth would be brought to a halt by suitable cultural adjustments to encourage the formation of rubber in the newly-formed phloem cells, and the plant would later be forced into active growth again for the formation of additional storage cells.

Benedict *et al.* (1947) studied the response of guayule to alternating periods of low and high moisture-stress under greenhouse conditions. They compared rubber accumulation in (*a*) plants grown continuously with abundant water (low moisture-stress), (*b*) plants grown with two-month alternations of low and high moisture-stress, (*c*) plants grown with four-month alternations of low and high moisture-stress, and (*d*) plants grown for ten months under low moisture-stress and four months under high moisture-stress. The experiment was designed for sixteen months but had to be terminated at the end of fourteen months. Under the conditions of the experiment, the four-month alternation produced the highest concentration of rubber. The two-month alternation was too short. The guayule that was given ten months of low moisture-stress followed by four months of high moisture-stress accumulated only a little more rubber than that grown with low moisture-stress throughout. Unforeseen seasonal factors and the premature termination of the test complicated the interpretation of the results, but the possibility of the control of rubber formation by differential irrigation was demonstrated.

Morphology and Anatomy in Relation to Rubber Formation

Origin and Storage of Rubber

The occurrence of rubber and its centres of distribution in the various plant organs of guayule have been described in detail by Ross (1908), Lloyd (1911), and Artschwager (1943). Rubber is found in all parts of the plant, but only the stem and root have sufficient quantities to be of economic interest. In these parts, the guayule plant is, with but one or two known exceptions, the most efficient natural stockpiler of rubber in the plant kingdom. Only *Hevea* has been shown to be more efficient in time (annual basis), and *Hevea* needs help from the tapper in that it must have the rubber removed before it will make more. Only the tau-saghyz rubber plant, *Scorzonera tau-saghyz*, has been reported to rival guayule in richness of rubber accumulation; but the storage space in tau-saghyz is extremely limited compared with that of guayule.

The rubber is found principally in the bark of the roots and stems of guayule. Artschwager says:

> Generally speaking, in plants of harvest size the vascular rays of the phloem and, to a lesser extent, those of the xylem contain by far the largest amount of rubber. Smaller quantities are found in jacketing cells of the resin canals, and rather insignificant quantities in the pith, primary cortex, and xylem parenchyma. The active sieve-tube tissue contains practically no rubber. The latter, though perhaps of some debatable significance in the economy of the plant, would have no value as stored rubber since the active phloem becomes in part obliterated, and in part displaced, by sclerenchymatous tissue.

Artschwager states that, in young plants, the most rubber is found in the primary cortex, pith, and vascular rays as well as in the parenchymatous jacket of the primary resin-canals. In young, actively growing stems, rubber appears first in the epithelial cells of the primary cortical and pith canals, but is much more conspicuous in the secreting layer of the newly-formed secondary canals. In old roots and stems that are composed mostly of secondary tissues, rubber secretion is related to the age of the cells from their formation by the cambium. As rubber normally appears first in older cells, except for the epithelium of the resin canals, the direction of rubber appearance is towards the centre of the stem in the phloem, and outwards in the vascular rays of the wood. The younger cells close to the growing axis of the plant contain less rubber than the basal cells.

O. F. Curtis (1947) divided guayule plants of various ages into separate parts and analysed samples to find which parts of the plants contained significant quantities of rubber. Table VI has been compiled from his data with the object of comparing the rubber content of various parts of one-, two-, three-, and nine-year-old plants. In general, both the percentage of rubber and the weight of rubber in the various parts of the guayule plant increase with the age of the plant. It will be noted that, in the stems from the current year's growth (second year stems in two-year-old plants, third year stems in three-year-old plants, and ninth year stems in nine-year-old plants), the percentage of rubber is not significantly different in the different age-groups, but that the amount of rubber stored during the current year is materially less in the oldest plants. The average total dry-weight of the ninth year stems on the nine-year-old plants was only 18·5 gm., as compared with 74·4 gm. for the second year stems of two-year-old plants and 56·0 gm. for the third year stems of three-year-old plants.

TABLE VI

DISTRIBUTION OF RUBBER IN PERCENTAGE OF DRY-WEIGHT OF PLANT TISSUE AND IN WEIGHT OF RUBBER IN PORTIONS OF GUAYULE PLANTS OF VARIOUS AGES *

Part of plant	Average rubber content of plants with ages of:							
	1 year		2 years		3 years		9 years	
	per cent	gm.	per cent	gm.	per cent	gm.	per cent	gm.
Branch roots			6·94	0·78	7·02	1·14	10·15	5·88
Root	5·25	0·82	5·96	1·81	6·24	4·06	8·76	10·03
Crown			8·78	1·95	9·80	4·26	13·27	14·57
Root bark	10·86	0·74						
Root wood	0·92	0·08						
Stems and crowns	6·04	4·06						
1st-year stems			9·60	5·82	10·90	10·82	15·86	18·33
2nd-year stems			9·14	6·41	11·08	14·74	15·55	17·03
3rd-year stems					10·30	5·66		
3rd- and 4th-year stems							15·32	13·54
5th- and 6th-year stems							14·90	8·91
7th- and 8th-year stems							13·54	12·32
9th-year stems							9·88	1·83
Entire plant	5·89	4·88						

* Compiled from Tables I, II, III, IV, V, and VII of O. F. Curtis (1947).

Anatomical Structure in Relation to Environment

Lloyd (1911) and Artschwager (1943) have pointed out that the rate of growth determines the relative increment of xylem and phloem. Lloyd made a study of the relative amounts of bark produced under irrigation and by dry-land plants. He found that the proportion of bark tissue, which is the chief source of rubber in guayule, was higher in the dry-land plants than in the irrigated plants. Since that time, many studies have been made of the rubber content of plants grown under various conditions and with differential cultural treatments.

O. F. Curtis (1947) made a comparison of the percentage of rubber and the rubber content of plants from blocks of three-year-old guayule plants that had been given differential irrigation. One lot had been irrigated only in the first year of growth, but the other had been given an additional irrigation in September of the third year. Both plots were harvested the following April. Information has been taken from Curtis's Tables III and IV to compile Table VII, and the plants were divided into various parts as indicated in that table. The increased growth resulting from the additional irrigation in September of the third year led to a lowered percentage of rubber in all parts of the plants.

Traub (1946) and Benedict (1949) have shown that the rubber in guayule is not depleted during stress periods, but Curtis's evidence may indicate that the amount of rubber in older tissue is reduced during periods of active growth. The evidence is clear with respect to the youngest tissue (branch roots and third-year stems) that the irrigation resulted in the production of increased plant tissue with a lower percentage of rubber than that produced in the non-irrigated plants during the same period. The greater volume of new tissue in the irrigated plants was responsible for a higher content of rubber than in the richer, but lesser, tissues of the non-irrigated plants.

TABLE VII

DISTRIBUTION OF RUBBER IN PERCENTAGE OF DRY-WEIGHT OF TISSUE AND IN WEIGHT OF RUBBER IN INDICATED PORTIONS OF THREE-YEAR-OLD GUAYULE PLANTS OF STRAIN 130. THE 'NON-IRRIGATED' LOT WAS IRRIGATED IN THE FIRST YEAR ONLY. THE 'IRRIGATED' LOT WAS IRRIGATED IN SEPTEMBER OF THE THIRD YEAR AS WELL AS DURING THE FIRST YEAR.*

Part of plant	Average amount of rubber in: Irrigated plants		Non-irrigated (except initially) plants	
	per cent	gm.	per cent	gm.
Branch roots......	6·41	1·21	7·62	1·07
Roots............	5·68	3·87	6·80	4·23
Crown...........	9·13	4·20	10·47	4·32
1st-year stems.....	10·20	9·83	11·61	11·82
2nd-year stems....	10·18	13·12	11·99	16·35
3rd-year stems.....	9·43	6·29	11·16	5·06

* Compiled from Tables III and IV of O. F. Curtis (1947).

Anatomical Structure in Relation to Variety

In discussing anatomical differences that had been attributed to the effect of irrigation, Artschwager (1943) stated:

> Varieties differ. These differences may be qualitative as well as quantitative. The relative size of cortex and wood appears to be a varietal characteristic that may not be affected by environment, although the total growth increment would be in direct relation to the amount of available water. Vessel size, as seen in cross-section, also is apt to be a varietal characteristic and not an expression of the available water. In one instance the larger-size vessels were related to high rubber content, perhaps an accidental correlation, but in this case not a response of rate of growth to differences in water supply.

In his comparisons of the distribution of rubber in various tissues of the guayule plant, O. F. Curtis (1947) gave data regarding two-year-old plants of strains 593 and 406. Information has been taken from his Tables

I and II to compile Table VIII. The interesting point of this comparison is that the vigorous strain 406 had a lower *percentage* of rubber than strain 593, in all parts of the plants. It, nevertheless, had nearly as much *total* rubber as its richer competitor and, in the youngest portions of the plants (branch roots and second-year stems), had greater *amounts* of rubber.

TABLE VIII

DISTRIBUTION OF RUBBER IN PERCENTAGE OF DRY TISSUE AND IN WEIGHT OF RUBBER IN TWO-YEAR-OLD GUAYULE PLANTS OF STRAINS 593 AND 406.*

Part of plant	Average amount of rubber in plants of strain			
	593		406	
	per cent	gm.	per cent	gm.
Branch roots......	8·96	0·44	4·91	1·12
Root.............	8·01	2·11	3·90	1·51
Crown...........	11·43	2·09	6·11	1·81
1st-year stems.....	12·07	6·07	7·13	5·57
2nd-year stems....	11·05	6·00	7·22	6·82

* Compiled from Tables I and II of O. F. Curtis (1947).

Artschwager (1943) states:

> . . . it is necessary to know the varieties anatomically before attempting to interpret the effect of environment on structure. Since rubber storage appears to be related to structure, varieties with a greater storage space for rubber would furnish better raw material for selective breeding than would varieties in which the secondary cortex is thin, even though both varieties might test high in percentage of rubber. The relative growth increments of xylem and phloem may also differ with different varieties. Only selections in which phloem development is favored over xylem should be afforded a future in a breeding program.

VII

BOTANY OF TARAXACUM

Introduction

The Dandelions

THE dandelions are known throughout Europe, Asia, and North America—principally because of the common dandelion, *Taraxacum officinale* Weber,* which is widespread in meadows and lawns, and in cultivated or disturbed areas. In spite of its attractive flowers that make an early spring show, and the foliage that finds some use as a vegetable, the plant is regarded as a weed to be eliminated wherever found. A few selections have been put into cultivation, and its use as a food crop has attained minor importance in some areas.

The Russian names for the rubber-bearing species of dandelion relate directly to the rubber that results from chewing the roots of the plants. The best-known Russian rubber-bearing dandelion is kok-saghyz (Plate 17). The 'saghyz' refers to the chewy nature of the rubber. Ulmann (1951) translates kok-saghyz into 'grunes kaumittel' or 'green masticatory'. Brandes (1942) states that 'kok' means root in the Kazak language. The 'krim' in krim-saghyz (*Taraxacum megalorhizon* Hand.-Mzt.), a second Russian rubber-bearing dandelion, refers to its origin, in Russia, on the Crimean Peninsula.

The Rubber-bearing Dandelions

The genus *Taraxacum* includes two important rubber-bearing species. These species are similar to one another and to the other dandelions, but are quite dissimilar in their manner of reproduction, their native occurrence, and their cultural requirements. Kok-saghyz (*Taraxacum kok-saghyz* Rodin) is a short-season dandelion. In nature, it is found in high mountain regions where severe winter temperatures and dense snow are usual, and where the summer growing-season is short. The other rubber-bearing dandelion, krim-saghyz (*T. megalorhizon* Hand.-Mzt.), is a long-season dandelion with a much greater adaptability to warm winters than even the common dandelion.

* Actually, the vast majority of plants that are so referred probably belong to one or another of the numerous allied microspecies, many of which, however, appear to be of doubtful taxonomic worth.—Ed.

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NATURAL DISTRIBUTION

Kok-saghyz

Geographical Distribution. Kok-saghyz is native to a restricted district in the Kazakh Republic near Alma Ata, where it is found in the valleys and highlands of the Tian Shan Mountains (cf. Fig. 1). Russian estimates have been reported that the area comprises some 10,000 square km. and that the native population of kok-saghyz amounts to some 600 million plants. Kok-saghyz is found in association with many other species of plants, including several other species of *Taraxacum*, and occurs in what Koroleva (1940) designates as 'thickets'.

Altitude. The natural stands of kok-saghyz are found at the mid-elevations of the offshoots of the Tian Shan Mountains at elevations varying from 5,900 to 6,300 ft. above sea-level. The cool spring weather at these high northern elevations is favourable for the germination and initial growth of the young plants. During this initial growth-period, the aerial portions of the newly-germinated seedlings develop slowly, while the roots elongate comparatively rapidly.

Climate. The climate of the native range of kok-saghyz results from its high elevation. Winter temperatures from November through February are constantly below freezing, the ground is covered with snow, and there is no thawing. In the spring and summer, there is a high diurnal variation in temperature. Summer temperatures may vary from 32° to 40°F. at night, up to 86° to 122°F. in daytime. Monthly mean temperatures from March to October, as given by Ulmann (1951), are shown in Table IX.

TABLE IX

MEAN MONTHLY TEMPERATURES REPORTED FOR THE NATIVE RANGE OF *Taraxacum kok-saghyz* IN THE TIAN SHAN MOUNTAINS OF THE KAZAKH S.S.R.*

Month	Temperature	Month	Temperature
March	6°F.	July	61°F.
April	40°F.	August	60°F.
May	45°F.	September	52°F.
June	56°F.	October	39°F.

* From data published by Ulmann (1951).

A generally cool, mountain climate thus characterizes the native range of kok-saghyz. The soil temperatures seldom exceed 60°F., even at the height of the growing-season. The summers are almost without rain. The major portion of some 10 to 12 in. of annual precipitation comes during the winter period. The atmospheric humidity is high, ranging around 80 per cent and never dropping below about 50 per cent.

Soil. The best natural stands of kok-saghyz are found on light, loamy meadow-soils that are rich in humus. The upper horizons of the best soils are low in chlorides. The ground-water is fresh and, where the growth of kok-saghyz is best, the soil is continually moist, particularly in the upper levels.

Growth-cycles. Kok-saghyz is thus adapted to withstand the rigours of its native habitat—both the severe winters and the summer drought. During the spring period of root growth, and during the flowering and seeding season, its requirements for water are very high. The natural moisture of the better soils, together with continued high relative humidity of the air, serve to satisfy this need.

In dry summers, when the soil-moisture decreases after the seeding season, kok-saghyz goes into a resting period in which the aerial portions of the plant die back to the crown. The normal sequence of growth phases of a second-year plant in nature is: the flower buds form in May, and the plants are in full bloom by the early part of June, whilst the development of the seed takes place from mid-June to the first part of July. By mid-July, seeding is complete, and, by mid-August, if the normal summer drought is unbroken by rain, the plant has gone into a condition of complete rest. Early rains may prevent the plants from going into the rest period, and rains that come after the plant has dropped its leaves may cause it to resume growth and form a new rosette of leaves.

Response to Photoperiod. Kok-saghyz is a typical long-day plant. Borthwick *et al.* (1943) studied the effects of photoperiod and temperature on the growth and development of kok-saghyz. They found that it is sensitive to changes in temperature, light-intensity, and photoperiod, but that it has wide adaptability to all but the shortest photoperiods and highest temperatures.

Krim-saghyz

Geographical Distribution. In comparison with the restricted natural range of kok-saghyz, krim-saghyz, the Crimean or autumn dandelion, is widespread throughout the Mediterranean region. It is found in the dry coastal areas of Spain, Italy, Greece, and Yugoslavia, and also in Asia Minor and in Syria. In Russia, it is found only in the southern coastal region of the Crimea, from Eupatoria to Sudak.

Altitude. Krim-saghyz is seldom found above an altitude of some 300 to 400 metres. Through most of its range, this confines it to a rather narrow coastal strip, mainly on the Mediterranean, Adriatic, Aegean, and Black Seas.

Climate. The areas in which krim-saghyz is found vary from 35° to 45° north of the Equator. This northerly location is tempered by the fact that krim-saghyz is found only along the sea coast, where it enjoys an equable maritime climate. In the coastal regions of the Crimea, annual maximum temperatures occur in July and August, and the recorded maxima vary from 96°F. in Yalta to 104°F. in Simferopol. The lowest temperatures recorded were in February and varied from 7°F. in Sevastopol to −22°F. in Simferopol. This southern portion of the Crimea has a relatively long frost-free period extending from late March to late November.

The native habitat of krim-saghyz is sunny and arid, though the annual precipitation is somewhat higher than that of the native habitat of kok-saghyz. In the Crimea, the rainfall varies from 11·7 in. (296 mm.) at Sudak to 21·3 in. (540 mm.) at Yalta. Seasonal variation in rainfall is not great, substantially equal amounts coming in spring, summer, autumn, and winter.

Soil. Krim-saghyz is less selective than kok-saghyz in its soil requirements, and it also shows more tolerance to shade and other unfavourable environmental factors. In general, the soils of its native habitat are dark brown, with a heavy or coarse structure. It withstands a rather high concentration of salt in the upper levels, providing fresh water is available within 2 or 3 ft. of the surface. The long, slowly tapering, sparsely branched roots penetrate several feet into the soil and a fairly deep soil is favourable for growth and survival.

Growth-cycle of Krim-saghyz. The growth-cycle of krim-saghyz is quite different from that of kok-saghyz. The point of greatest similarity lies in the summer resting period that is common to both species. The spring growth of krim-saghyz is entirely vegetative, and no flower-buds are formed even in second-year plants. The onset of summer, with higher air and ground temperatures, brings the growth of the plant to a halt. The leaves wither and die, and the plant goes into a phase of dormancy that may last for from two to more than four months. Dormancy is complete during July and August, but it is possible for plants to enter dormancy as early as May and to continue dormant until late September.

The end of the resting period is marked by bud formation and flowering of krim-saghyz. Flowering takes place prior to the formation of new leaves to replace those lost at the start of dormancy. Because of this characteristic flowering habit, krim-saghyz is commonly known as the autumn dandelion. New leaves are not formed until towards the end of the growing-season, in November, so the plants remain leafless for up to six months during the period of high soil temperatures.

TAXONOMY

Taraxacum

The dandelions belong to the genus *Taraxacum* of the great family Compositae. They are native particularly to the northern parts of Europe and Asia as acaulescent annuals, biennials, or perennials with long taproots. The leaves vary from entire to pinnatisect. The flowers are mostly bright yellow, but white, cream-coloured, and even pinkish dandelions have been described.

The common dandelion, *Taraxacum officinale* Weber, has been introduced into North America and is now a weed in gardens and lawns throughout the temperate zone of northern America. Its leaves are bitter and tonic and are often eaten as a vegetable. The flowers are used to make wine. The roots have been used as a substitute for coffee and, in medicine, as a diuretic, stomachic, and cholagogue.

There are numerous species of *Taraxacum* but, from the standpoint of rubber production, only two, *Taraxacum kok-saghyz* Rodin, commonly known as kok-saghyz, and *T. megalorhizon*, commonly known as krim-saghyz, are of any direct interest. In nature, however, kok-saghyz is found in company with several other species of *Taraxacum* and hybridizes with at least two of them. Krim-saghyz is not so commonly associated with other species of *Taraxacum* in nature; moreover it is wholly apomictic and consequently incapable of hybridization. Its association with other species of *Taraxacum* is relatively unimportant, as there is no intermingling of germ-plasm.

Kok-saghyz

Taraxacum kok-saghyz Rodin is a perennial herb with a vertical root that is often twisted, and in cultivation may be highly divided, with all the main branches growing vertically. The tap-root may be up to 70 to 75 cm. long. The leaves are in a rosette, mostly decumbent but occasionally ascending. They are quite variable in size and shape, mostly narrowly obovate or broadly lanceolate, and entire to sinuate-dentate or incised-runcinate. The individual plant bears from three to eight hollow flower-stalks. These are purplish at the base and generally glabrous, but may sometimes be slightly pubescent on the upper part just below the head, which is commonly 25 to 30 mm. in diameter. The involucre is biseriate, with the outer bracts slightly spreading. These bracts are ovate or lanceolate, more or less pointed at the apex, 5·5 to 6·5 mm. long, 3 to 3·8 mm. wide, and provided with a large, more or less hook-curved, scarcely declining, horn from 2·5 to 4 mm. (sometimes up to 5 mm.) long. The inner bracts are erect (at flowering-time slightly deflexed at the apex), 9 to 12 mm. long, 1·1 to 1·2 mm. wide, and narrowly hyaline-margined, whilst the horn is 2 to 2·5 mm. long and slightly declined. The horns are persistent until the beginning of the fruiting stage, although they may become somewhat dried-up shortly before. The horns of the inner bracts, and sometimes those of the outer bracts, are somewhat purplish at the apex. The ligules are bright yellow, the marginal ones being 2 to 2·3 mm. wide and 10 to 12 mm. long. The inner ones are smaller. The anthers are a dull yellow and exserted up to half their length, and the style is pale yellow—including the bifid stigma which is always a little shorter than the ligule.

The achenes are of a dull straw-colour, quadrangular or rhomboid in transverse section, with from fifteen to seventeen ribs (four of these, opposite to each other, are notably enlarged), the ribs all having upwardly-directed teeth, those on the larger ribs (i.e. the ones on the angles) being conspicuously larger than the others and extending along two-thirds to three-quarters of the length of the achene. The achenes, excluding the column and the beak, are 2·3 to 2·9 mm. long and 0·7 to 0·8 mm. in diameter. The column is 0·8 to 1·1 mm. long, the beak is 4·5 to 5·2 mm. long, and the pappus is white.

Pollination of Kok-saghyz

Pollination of kok-saghyz is performed mainly by bees. Wind pollination plays but a minor role, as the pollen is sticky and gathers together into balls that are carried not more than a few feet. Koroleva (1940) placed glass slides covered with glycerine in a planting of kok-saghyz. The pollen collected was invariably of the form described, and the conclusion was reached that if any wind-pollination took place it would have to be only at the peak of the flowering season.

Species of 'Taraxacum' Associated with Kok-saghyz

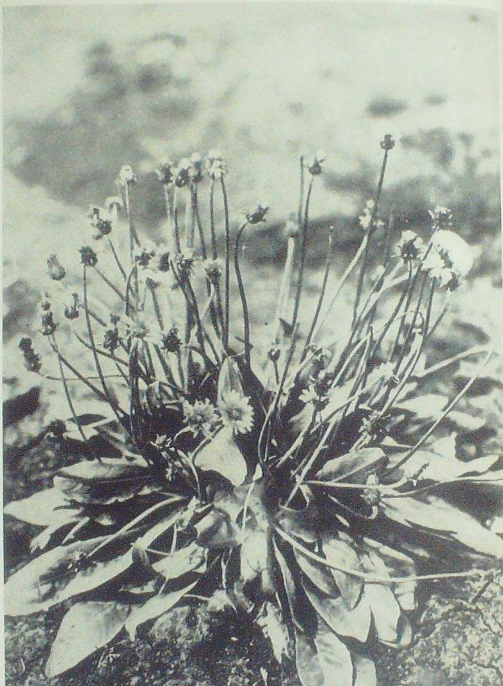
Both in nature and in cultivation, a number of other species of *Taraxacum* have been found associated with kok-saghyz. In some plantings, these other species have predominated over the kok-saghyz itself. None of these others species of *Taraxacum* is important for rubber production. The diploid types hybridize readily with kok-saghyz, but no interspecific hybrid has been found or developed that is of value for rubber production. All intermixtures must, from the standpoint of rubber production, be considered deleterious. The possibility remains that interspecific crossing may be useful in developing new types with increased vigour. Unfortunately, there is a high degree of sterility in these interspecific hybrids. 1
Back-crossing to kok-saghyz is possible and, though the rate of seed-set is low, it is possible that the rubber-content of vigorous interspecific hybrid lines can be increased through back-crossing to the kok-saghyz parent.

Koroleva (1940) made a study of the species of *Taraxacum* associated with kok-saghyz in Russia, and reported the following species either in plantations or associated with kok-saghyz in the natural stands: *Taraxacum multiscaposum* Schischk., which has thinner and darker leaves than kok-saghyz; *T. calcareum* Koroleva, a white-flowered dandelion; *T. bessarabicum* Hand.-Mzt., a dandelion with larger and denser rosettes than kok-saghyz; *T. brevicorniculatum* Koroleva, characterized by the presence of horn-like appendages on the tips of the bracts of the involucre, though these appendages are shorter and thicker than those on kok-saghyz; *T. officinale* Weber, the common dandelion; *T. microspermum* Schischk., with thin, green leaves having a slightly violet shade; *T. magnum* Koroleva, one of the largest of the dandelions and having thin, dark-green leaves with reddish, thick midribs; *T. schischkini* Koroleva, a dandelion with a large rosette of thin leaves having a slightly yellowish shade; and *T.*

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) A large plant of *Parthenium tomentosum* var. *stramonium*. On the left a knee-high plant of guayule has been set in the ground to indicate the relative size.

(*b*) One-year-old planting of guayule adjacent to a five-year-old planting. Note that the first row of the new planting has been almost entirely suppressed by competition from the roots of the older



Photograph by permission of ARS, U.S. Dept. Agric.

A plant of kok-saghyz, *Taraxacum kok-saghyz*, the Russian rubber-bearing dandelion.

PLATE 17

tionschanicum Schischk., with thin, and deeply divided, almost split leaves, and purple flower-stalks that are pubescent for their entire length.

Krim-saghyz

Taraxacum megalorhizon Hand.-Mzt. is commonly known as 'krim-saghyz', the Crimean or autumn dandelion, or, in the Crimea, 'mastikana'. The concepts *T. hybernum* Stev., and at least part of *T. gymnanthum* DC., are included. The name *T. hybernum* dates from 1856 and is preferred in Russia. However, the concept *T. gymnanthum* DC. preceded (1838) the description of *T. hybernum* and included this latter dandelion. H. Handel-Mazzetti prepared a monograph of the genus in 1907 and described this particular concept as *T. megalorhizon*.

Krim-saghyz is perennial and fully apomictic. It has a long, sparsely-branched root that usually is 0·5 to 1·5 cm. thick, but that may be 3 cm. thick and 2 metres long. The leaf-rosette consists of from five to thirty-five leaves, which are thick and glabrous (or lightly pubescent, particularly in young plants). The leaves are slender or lanceolate. They are seldom notched, and then only at the lower end; or they may be divided into various shapes throughout the entire margin. Up to twenty-five thin flower-stalks arise from the rosettes in late summer. At first they are covered with long hairs, but these do not persist. At the time of flowering, the stalk has a length of about 6 to 7 cm. and this length may double during the ripening of the seed. Each flower-stalk has a small flower-head with citron-yellow flowers. When open, the flower-head has a diameter of some 3·5 to 4 cm. Up to the time of flowering, the flower-stalk is upright. As flowering ends, the stalk reclines; but it regains its upright position at the time of the ripening and discharge of the seed. The seeds * are grey-brown or brown in colour and have a white or brownish-white pappus.

The Morphology and Anatomy of Kok-saghyz

Kok-saghyz differs from both guayule and *Hevea* in the relation of its physical structure to the production and accumulation of rubber. In *Hevea*, the important consideration is the rate of formation of rubber and the efficiency of the conducting system for transporting the rubber-containing latex to the tapping cut. Rubber accumulation is unimportant except in so far as it may limit the amount that can be withdrawn at a single tapping. After tapping has been started, the period of accumulation varies from a single day in alternate-day tapping to periods of a month in alternate-month tapping. Both in guayule and kok-saghyz, rubber accumulation is relatively more important than rubber formation, since the entire harvest takes place at one time—at the end of a single season in the case of kok-saghyz and after two to many seasons in the

* *See* footnote on p. 110.

case of guayule. In addition to the shorter period of accumulation in kok-saghyz, there are also differences in the available storage space that limits the total accumulation of rubber in each species.

It has been shown that guayule stores its rubber in the form of latex—but in separate cells, so that it is not possible to obtain the latex by tapping the plant. In kok-saghyz, the rubber is accumulated in the form of latex, as it is in both guayule and *Hevea*, but the storage system in kok-saghyz resembles that of *Hevea* rather than that of guayule. When a *Hevea* tree is being tapped, the latex vessels become conduits and there is a significant flow of latex. Kok-saghyz plants, on the other hand, are too small for individual tapping and the latex vessels, so far as rubber yield is concerned, serve only as storage units. The size, shape, number, and relation of the latex vessels to other tissues of the plant are therefore much more directly related to yield in kok-saghyz than has been found to be the case in *Hevea*.

Rudenskaya (1938) and Artschwager & McGuire (1943) have studied the relationship of the anatomical structure of kok-saghyz to production of rubber. Rudenskaya reported a primary relationship between the storage capacity of the roots of the plant and its ability to accumulate rubber. Artschwager & McGuire recognized this relationship but pointed out that other anatomical features might also be important. They were particularly impressed by the possible role of the sieve tubes, and stated: 'The intimate association of sieve tubes with latex cells in kok-saghyz and the role of sieve tubes in translocation suggest, however, that performance and relative development of the sieve-tube apparatus are closely linked.'

Seedling Structure

As kok-saghyz seeds germinate, the primary root emerges from the base of the achene and grows rapidly downwards. The elongating hypocotyl carries the cotyledons, with the partially enveloping remains of the achene, upwards. Lateral roots are initiated very early, the first ones appearing at the junction of the hypocotyl and root. Although a strong root system develops early in the life of the seedling, the leaf rosette expands slowly and the individual leaves remain minute in size for two months or longer.

The primary root of kok-saghyz rapidly differentiates into growth zones, and the first appearance of latex tubes takes place in the pericycle shortly after germination. Thereafter the formation of additional latex vessels is quite rapid, but is confined in the early stages to the pericycle. Subsequent growth is outward rather than inward, and the development of bark tissue is much greater than that of the stele. The formation of new phloem tissue is in close proximity to the cambial area and, as new phloem is formed, it forces the older tissue outward, exerting increasing pressure on the endodermis and primary cortex. The cells of the endodermis enlarge greatly, both tangentially and radially, but the cells of the cortex rupture and collapse, and the entire structure, including the epidermis, is finally sloughed off.

Structure of the Root

The tap-root of kok-saghyz consists of a relatively small stele surrounded by concentric rings consisting of alternate layers of phloem and parenchyma. The latex vessels are mostly in the phloem layers and thus occur in a series of concentric rings. Considerable variation has been found in the number and size of the vessels in the different rings. Rudenskaya (1938) found in one instance 88 latex tubes in the peripheral ring and 268 tubes in the much shorter seventh ring from the outside, attributing the difference to an intensified differentiation of latex tubes during the period of most rapid growth. As in *Hevea*, the latex vessels are articulated, forming continuous passages by the resorption of the end-walls of the cells. Also, as in *Hevea*, the vessels within any given ring anastomose; but, unlike *Hevea*, no connections have been observed between the latex vessels of adjacent rings.

Cross-sections of mature roots often show, especially in the peripheral rings, latex tubes running longitudinally, i.e. in the plane of the section. This results from the separation of the tubes of the outer rings by the outward growth of the root, and the readjustment of the anastomosing connections. In *Hevea*, such connections are often disrupted by the pressures engendered by this lateral spread that results from increasing growth.

The sieve tubes that are closely associated with the latex vessels in the phloem reach their full size soon after they are formed by cambial action. Their unit cell is some 100 microns long and 10 microns wide. The latex vessels continue to grow for some time after they are formed. The largest vessels have a diameter of around 20 microns and are found in the middle range of the latex-vessel rings. The latex vessels in the outer rings are smaller, as are also those in the inner rings that have not reached their full size.

Bark Sloughing in the Second-year Kok-saghyz

Kok-saghyz is a perennial plant but it does not, as guayule, necessarily continue to accumulate rubber. In nature, it has been claimed that the roots can be left in the ground and that they will continue to increase in rubber content; however, this is not possible under cultivation. During the wintering period, after the first year of growth, the plant develops a parenchymatous layer that becomes corky and continues to grow out from the cambium. This corky layer intercepts the outer layers of the cortex and, when growth is resumed in the spring, a gradual dying of this outer tissue takes place. By the time the active growing period is under way, the outer bark of the root has completely sloughed off and can be seen as a lacy elastic covering over the young root. This covering has been variously designated as a 'sheath', a 'glove', or, from the Russian, a 'tschechol'. Up to 75 per cent of the rubber in plants harvested in April has been estimated by Rudenskaja (1934) to be in the sheath. If the roots are not harvested at that time, the sheath is further disrupted by the growing root and is completely lost in the soil. That not all of the rubber is included in the sheath would indicate that new latex vessels have been formed under the corky separation layer, and that new growth has taken place prior to the April harvest. Ulmann (1951) quotes Mashtakov (1940) as showing the development of this separation layer in four stages, starting with the autumn of the first year, and with the process complete and the sheath discarded by the summer of the second year.

Cytology

Kok-saghyz

Warmke (1943) studied the fertilization and early embryology of kok-saghyz and concluded:

1. The chromosome number in *Taraxacum kok-saghyz* is n = 8, 2n = 16, placing this species among the basic diploids of the genus.
2. Macrogametophyte formation follows the usual sexual pattern: the macrospore mother-cell undergoes two regular meiotic divisions to form a linear series of four reduced macrospores, the chalazal one of which usually becomes functional. As the result of three successive meiotic divisions followed by union of the two polar nuclei and cell-wall formation, the classic 7-celled macrogametophyte is formed.
3. Thirty minutes after pollination, the pollen-tubes are seen to enter the macrogametophyte. Fertilization follows the normal pattern, one male nucleus uniting with the egg and the other uniting with the primary endosperm nucleus. Supernumerary male nuclei are frequently observed in the embryo sac but usually are not functional.
4. The first division in the endosperm occurs about 6 hours after pollination, and the first division of the egg follows about one hour later.
5. Embryonic development follows the aster type, characteristic of the Compositae.
6. Chromosome counts verify the reality of the sexual processes by showing the developing embryo to be diploid, with 16 chromosomes, and the endosperm to be triploid, with 24 chromosomes.
7. During the summer *T. kok-saghyz* is highly self-sterile but cross-fertile. In the late fall and winter it may exhibit considerable end-season self-fertility.

Tetraploid Kok-saghyz

Navashin & Gerassimova (1941) produced tetraploid kok-saghyz by treating the roots with colchicine and propagating the plants by root cuttings. The plants so produced differed from normal kok-saghyz in having larger and more fleshy leaves, larger roots, and seeds that were almost double the weight of normal kok-saghyz seed (7 to 10 mg., compared with 3 to 5 mg. for normal kok-saghyz).

These investigators also reported that, in addition to the larger size of the roots, the individual latex vessels were enlarged so that the storage capacity for rubber in the tetraploid population was much greater than in a comparable population of diploids. An additional merit of the tetraploids was that they reseeded themselves. Diploid kok-saghyz does not reseed itself and must be replanted after harvesting each crop. The tetraploid seedlings were reported as more vigorous than diploid seedlings, and are thus highly competitive at a time when normal kok-saghyz is unable to match the aerial growth of competing vegetation.

Taraxacum

Warmke (1943) states:

> Chromosome numbers of n = 8 and 2n = 16 place *T. kok-saghyz*, along with six or eight other species, as basic diploids in the genus. The great majority of the genus, however, is polyploid. Species with sporophytic chromosome numbers of 24, 32, and 40, representing triploid, tetraploid, and pentaploid forms, respectively, are known. It is of interest that the diploid species, including kok-saghyz, are sexually reproducing, while the polyploids are apomictic.

Krim-saghyz has 24 chromosomes and is thus a triploid. The common dandelion, *T. officinale*, is also a triploid. The other species of *Taraxacum* that are associated with kok-saghyz are mostly triploids, but with three exceptions: *T. multiscaposum* and *T. bessarabicum* are diploids, and hybridize readily with *T. kok-saghyz*, while the white dandelion, *T. calcareum*, is a tetraploid.

Koroleva (1940) pollinated flowers of kok-saghyz with pollen of the triploid dandelions *Taraxacum brevicorniculatum*, *T. officinale*, *T. magnum*, *T. schischkini*, *T. microspermum*, and *T. tionschanicum*. Seed-set was very infrequent and the progeny almost invariably resembled the mother parent, exhibiting the reduced vigour characteristic of inbred plants. However, seven plants were found among the progeny of kok-saghyz from flowers pollinated with pollen of *T. brevicorniculatum*, that exhibited characteristics of the male parent, and that must accordingly have been hybrids.

Selection and Breeding of Kok-saghyz

So far, attempted plant improvement of krim-saghyz has proved futile. Artificially created polyploids of kok-saghyz failed to hybridize with krim-saghyz, and no polyploid types of any species have been found that will hybridize. With kok-saghyz, however, plant improvement by selection and crossing the better lines offers bright prospects of successfully raising the level of yields materially, and of producing plants with greater ability to compete with other vegetation—particularly in the way of developing plants with more active aerial development in the early stages of spring growth.

Intermixture of Non-rubber-bearing Dandelions

The collection of seed from wild stands of kok-saghyz constituted a major source of seed at one time. Koroleva (1940) reported that seed harvested on the farms was contaminated with the seed of the non-rubber-bearing dandelions that had been introduced with the kok-saghyz seed from the 'natural thickets'.

Experimental cultivation of kok-saghyz in the United States was initiated with seed furnished by the Soviet Government. The first shipment consisted of 187 lb. received by air from Kuibyshev in May 1942. Several thousand pounds of seed were furnished later by boat, and this seed was planted throughout the United States and carefully observed for growth and type. It was apparent at once that there was a large number (in some instances predominating) of off-type plants. It was found that, unless a continuing rigid rogueing operation was conducted, the vigour and rapid reproduction of the off-type dandelions soon led to their dominance in fields that had not been rogued.

First- or Second-year Flowering

Normally, only a small proportion of kok-saghyz plants flower and fruit in their first year. It was believed in Russia that types blooming first in the second year were superior for rubber production. The proportion of plants that flower in the first year, however, can be increased considerably by providing better cultural conditions. Over 90 per cent of the plants in a single planting have thus been induced to flower in the first year, whereas, under other conditions, only 20 per cent of the plants flowered in the first year. Mashtakow *et al.* (1940) studied the relationship of first-year flowering to root growth and rubber-content, and found that the yield of rubber at the end of the first season, on 27 September, was greater from plants that had flowered than it was from plants that failed to flower. The percentage of rubber was higher in the roots of the plants that did not flower, but the plants that flowered had larger roots and contained more total rubber.

Leaf Shape

The extremes of variation in leaf shape in kok-saghyz have been classified into three categories—entire, notched, and feathery—for general comparison. Every gradation exists, although it has not been possible to separate strains of kok-saghyz on the basis of leaf shape, as this is not a fixed character but is greatly affected by environment. It is neither a reliable basis of classification for use in separating strains, nor a good index of yield or root size. Minbaev (1940) demonstrated the effect of environment on leaf shape. His test plants were propagated vegetatively to avoid any possibility of strain differences complicating the interpretation of the results. By varying the amount and type of nutrients, he was able to produce extreme variation in leaf shape and rubber production in vegetatively propagated plants with identical genetic constitution.

That leaf shape and flowering habit (first- or second-year flowering) cannot be neglected completely as a basis of selection of superior types of kok-saghyz, is demonstrated by an experiment reported by Kupzow (1941). This author gathered data on the relationship of root size, as measured by the diameter of the root at the crown, to flowering habit and leaf shape in plants having entire, notched, and feathery leaves. The root size of the plants with feathery leaves was the largest, irrespective of the flowering habit, and the plants with entire leaves had the smallest roots. In general, the plants that did not flower in the first year had the larger roots, irrespective of the shape of the leaves. Over-all, the root size varied progressively from small to large as follows: entire, flowering; entire, non-flowering; notched, flowering; notched, non-flowering; feathery, flowering; feathery, non-flowering.

Root Size

As the size of the root is a measure of the tissue available for the extraction of rubber, it is an important factor in yield of rubber. Filippov (1941) found an inverse correlation between root size and the percentage of rubber, indicating that the concentration of rubber is higher in small roots than in large. No one, however, has found a direct relation between root size and rubber-content. Thus the large roots may have a relatively high content of rubber despite their lower concentration of rubber compared with that of the smaller roots. Relationships have been show between flowering behaviour and root size, and between leaf shape and root size. Rudenskaya (1938) showed an inverse correlation between the number of latex vessels per square millimetre and the cross-section area of kok-saghyz roots, a direct correlation between the number of latex vessels per square millimetre and the percentage of rubber in the root, and a significant correlation of 0·65 between the percentage of rubber and the total cross-section area of the latex vessels. Root size and rubber-concentration appear to be independent of each other, and should be capable of being handled separately in a breeding programme and then combined by hybridization.

Polycross Breeding

Small differences in nutrition and other environmental conditions make for major differences in the morphological response of kok-saghyz. While it is possible to carry on a breeding programme on the basis of individual plants, the final results must be determined on the basis of comparisons of large populations. Kok-saghyz is a fully sexual diploid but is largely self-sterile, and this factor is of considerable advantage in mass 'field' crossing of particular selections. Tysdal & Rands (1953) reviewed work done in the United States involving field-blocks planted with selections to be crossed by random 'open' pollination. They showed that prospective yields had been doubled in comparison with yields from check plantings of the original strain, both percentage of rubber and size of roots being increased. Table X has been taken from their report, to summarize the result of this breeding programme.

Swedish and Spanish Investigations

During World War II, research scientists in both Sweden and Spain initiated tests of kok-saghyz as a possible rubber crop for their countries, and in both made progress in adapting the crop to the conditions obtaining locally. The programme of developing new high-yielding strains has been particularly successful in Sweden, whence selected strains have given uniformly high yields in all tests in which they have been compared with local strains (in both the United States and Spain).

Pure-line Selection

Self-sterility in kok-saghyz has been the chief obstacle to the development of pure lines by inbreeding. Warmke (1944) found that at the end of the flowering season there was a period in which the self-sterility of the kok-saghyz plants was interrupted, and that the late seeds might result from self-pollination. The utility of this observation has not been

TABLE X

COMPARATIVE YIELDS OF GROUPS OF SELECTIONS FOR HIGHER RUBBER PRODUCTION IN *Taraxacum kok-saghyz*

Grouping by rubber yield	Selections	Mean proportion of rubber in dry material	Mean dry-weight per plant	Mean weight rubber per plant
mg.	number	per cent	gm.	mg.
200–299	16	9·33	2·94	272
300–399	30	10·28	3·39	344
400–499	12	11·33	3·91	438
Over 500	1	11·20	4·58	517*
Checks: Turkish strain		7·35	2·78	208
Checks: Swedish strain		11·40	3·02	344
Checks: Original variety		7·84	2·71	213
L.S.D. at 5 per cent level†		2·32	1·20	127

* Represents approximately 130 lb. of rubber per acre at normal planting densities.
† Least Significant Difference, the smallest difference between two means that would be considered significant at the five per cent level, i.e. a sufficient difference that the probability of its being due to chance is less than one in twenty (5 per cent).

determined adequately in breeding work, but it indicates the possibility that seed-set might be expected in isolated blocks of individual selections.

Reference to the report of Tysdal & Rands (1953), as summarized in Table X, would indicate that further intensification of rubber concentration is possible. This increase might be expected to double the present rubber-content, involving an increase in the percentage of rubber from the present range of 7·84 to 11·40, as given in the table, to a new level with a range of from 15 to 25 per cent of dry-weight.

F*

VIII

BOTANY OF OTHER RUBBER-BEARING PLANTS

CRYPTOSTEGIA

RUBBER from *Cryptostegia* 'vines' growing in Madagascar and India first appeared on the market early in the nineteenth century; following this, production from wild vines continued for more than three-quarters of a century. *Cryptostegia* rubber is of excellent quality, but no efficient method of bleeding the plants has ever been developed. Most of the rubber has been produced by bleeding the stems of the plants, and the cost of collection was excessive in comparison with that of producing rubber from other sources.

Geographical Distribution

Although the earliest records of rubber production from *Cryptostegia* are based on collections in India, most Indian botanists are agreed that *Cryptostegia* is not native to that country. It is probable that both species, *Cryptostegia grandiflora* R.Br. and *C. madagascariensis* Boj., were originally native only to the Island of Madagascar, and that they were spread by man from there to Africa and India.

The dissemination of the two species was rapid during the nineteenth and twentieth centuries and, by 1943, according to Jenkins (1943), one or the other had been reported from the following areas:

Africa. In British East Africa, Egypt, Mauritius, Réunion, and Madagascar.

Australia. In Queensland.

Asia. In India, Ceylon, Malaya, Java, Formosa, the Philippine Islands, and Hawaii.

North America. In Mexico and the United States.

Central America. In British Honduras, Nicaragua, El Salvador, Honduras, Costa Rica, and Panama.

South America. In Venezuela, British Guiana, Brazil, and Colombia.

West Indies. In the Bahamas, Cuba, Jamaica, Haiti, the Dominican Republic, Puerto Rico, the Virgin Islands, the Leeward Islands, the Windward Islands, Tobago, Trinidad, Curaçao, Aruba, and Bonaire.

Thus, *Cryptostegia* was spread widely throughout the tropical and subtropical portions of the world during the latter part of the nineteenth

Photograph by permission of ARS, U.S. Dept. Ag

A plant of *Cryptostegia grandiflora* forming an arch over a gateway in Florida.

PLATE 18

VIII

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Photograph by permission of ARS, U.S. Dept. Agric.

A plant of *Cryptostegia grandiflora* forming an arch over a gateway in Florida.

PLATE 18

Photograph by permission of ARS, U.S. Dept. Agric.

A vigorous plant of *Cryptostegia grandiflora* completely covering a hedge of succulent *Euphorbia* near Gonaives, Haiti century and the first part of the twentieth century. During this period its value as a possible source of rubber may have had some influence on its geographical dissemination, but the chief influence was its attractiveness as an ornamental (Plate 18). Its first appearance in Mexico was when a German sea captain presented seeds of *C. grandiflora* to friends in Mazatlan as a garden ornamental. First as an ornamental and then as an 'escape', *C. grandiflora* spread across Mexico from west to east, being in many places so aggressive that it even encroached on the highways and byroads. Its first importation into the West Indies must have occurred around the middle of the nineteenth century, as it was reported to be established in Jamaica in 1864.

Dissemination as a Possible Source of Rubber

The first dissemination of *Cryptostegia grandiflora* within the Western Hemisphere primarily as a source of rubber was by Charles S. Dolley (1911, 1925, 1927), who took a lively interest in the plant in the early part of the twentieth century and was instrumental in having plantings made in Mexico in the States of Coahuila, Moreles, and Chiapas, and in Jamaica, the Bahamas, Florida, British Honduras, and British Guiana.

'Cryptostegia madagascariensis' in the Western Hemisphere

The second species, *Cryptostegia madagascariensis*, also was introduced into the Americas as an ornamental and, particularly in Florida, Central America, and the Dominican Republic, was more common than *C. grandiflora*. *C. madagascariensis* was first introduced into Florida as *C. grandiflora*, and persisted under that name for more than twenty years. Not until the real *C. grandiflora* was introduced into Florida by the United States Department of Agriculture in 1923 and 1924, was the true identity of the original introduction recognized. *C. madagascariensis* is commonly known as the 'purple allamanda'. It is a highly-valued ornamental, but has never received particular attention as a source of rubber, though some quantities of 'lombiro' rubber from this species were formerly reported to be exported from Madagascar. The rubber from the base of the plant is similar to that from *C. grandiflora*, but the rubber from the branch tips is inferior, containing as it does a high proportion of non-rubber constituents.

Taxonomy

Only these two species of *Cryptostegia* are recognized. The basic differences between them were first pointed out by Miquel (1863) on the basis of studies of plants of both species at the Botanical Garden in Buitenzorg, Java. Polhamus *et al.* (1934) made a detailed study of the two species at the United States Plant Introduction Garden at Coconut Grove, Florida, and published a comparison of them and of a hybrid that was discovered in the plantings at the Plant Introduction Garden.

'Cryptostegia grandiflora'

Cryptostegia grandiflora R.Br. was first described by Roxburgh (1832) as *Nerium grandiflorum*. This description thus assigned the new species to the family Apocynaceae. Robert Brown in 1819 observed that the plant possessed specialized floral parts for the transfer of the pollen from the anthers to the stigma. These organs, the translators, are generally spoon-shaped, with a sticky disk at the narrow end that becomes attached to visiting insects and is thus carried from one flower to another. The translators alternate in the flower with the stamens, and each one receives pollen from the two adjacent anther-halves. The presence of translators is a constant characteristic of the Asclepiadaceae but does not occur in the Apocynaceae. The recognition of these organs required that the plant be removed from *Nerium* in the Apocynaceae and assigned to a new genus in the Asclepiadaceae, which Brown called *Cryptostegia*.

Cryptostegia grandiflora is a large climbing shrub (Plate 19) which sends out long, whip-like branches that support themselves on any available structure or tree and have been reported to reach the tops of trees 50 or 60 ft. in height. The flowers are large, showy, and bell-shaped. They appear in groups of two or three, and have a purplish colour. The leaves are entire, opposite, and glossy, with a purplish cast to the midribs and petioles.

'Cryptostegia madagascariensis'

Cryptostegia madagascariensis Boj. has less tendency to climb than has *C. grandiflora*. It has thicker, smaller, and more glossy leaves, which lack the purplish coloration that is typical of the midribs and petioles of the leaves of *C. grandiflora*. The flowers of *C. madagascariensis* are smaller than those of *C. grandiflora*, and have a deeper purplish colour. This species is said to have been used as a source of rubber in Madagascar. The latex from the younger portions of the plant has a higher proportion of non-rubber constituents than has that from *C. grandiflora*. The latex from the bark of the basal portions of old stems of *C. madagascariensis* is normally as rich in rubber as that from *C. grandiflora*.

'Cryptostegia' Hybrid

A hybrid of two species of *Cryptostegia* was discovered by Alfred M. Keys in Florida in 1927 and was studied by Polhamus *et al.* (1934). Other hybrids have been discovered elsewhere since then, but this Florida hybrid has been studied in great detail and a knowledge of its performance and characteristics contributes to a recognition of the basic differences between the two species.

In all essential respects the hybrid was intermediate between the two species, and a study of the F_2 generation and successive progenies demonstrated beyond doubt the essential factors that differentiate the two species. Of particular note are the organs termed corolla appendages, which are invariable in the two species and are so characteristic as to be of prime diagnostic value in determining the identity of flowering specimens. The intermediate nature of the F_1 hybrid, in which the appendages are approximately one-half-cleft, is emphasized by the corolla appendages of the flowers of the F_2 and succeeding generations, which show all gradations of cleavage from the single, uncleft appendage of *C. madagascariensis* to the deeply cleft appendage of *C. grandiflora*.

Climatic Requirements

Rainfall. Cryptostegia * grows under widely varied conditions—from arid desert to humid tropics. Under cultivation, the best growth has been obtained either with natural rainfall amounting to 70 to 80 in. annually, or with supplemental irrigation in drier areas. However, *Cryptostegia* has established itself in areas of Madagascar, Mexico, and the West Indies where the rainfall is quite low.

Temperature. Cryptostegia has a wide adaptability to variations in temperature. Beckett *et al.* (1934) stated:

> *C. grandiflora* plants proved well adapted to the extreme weather conditions at Bard, California. Seedlings and rooted cuttings set out in the spring months developed rapidly, reaching the flowering stage in the late summer and continuing throughout the winter, producing and maturing many pods, unless checked by frost. Plants subjected to freezing temperatures were seldom killed below the ground, and new growth was produced in the spring from the root stalks.

They also stated:

> The plants were killed to the ground in December by frost and the dead material was pruned off in the spring before new growth started. Although these plants were subjected to killing frosts of various degrees every winter, very few died.

Minimum temperatures were as low as 18°F. at Bard, California, where Beckett *et al.* grew *Cryptostegia*, and summer temperatures were as high as 120°F. These temperatures represent the extremes for *Cryptostegia*, and the winter temperatures were too low for optimum growth as the plants were killed to the ground annually.

Nath (1943) reported that, although most Indian botanists do not consider *Cryptostegia* as a native of India, it was to be found throughout the length and breadth of that country. It was growing wild in the Punjab and the United Provinces, where extremes of temperature occur; under desert conditions in the Rajputana States; and in Bombay, Madras, and the Central Provinces, where the winters are comparatively mild. The plants are often found scattered, but in some places more or less extensive stands have been located. Nath notes that the annual mean temperature does

* In this and the succeeding discussion, the term *Cryptostegia* is used for the usual rubber-bearing plant, *C. grandiflora*, unless specifically broadened to include *C. madagascariensis* or the hybrid *Cryptostegia*.

not appear to be of importance, but that the maximum and minimum temperatures and relative humidity influence growth-rate and development of *C. grandiflora*.

Light. *Cryptostegia* is intolerant of shade, and the total annual light is doubtless a leading factor in the survival and growth of the plants. Beckett *et al.* (1934) compared plants grown in lath houses with those grown in the open under the hot, dry, semi-desert conditions of Bard, California. Even under these extreme conditions, the plants in the open were often superior to those in the shaded houses. In less extreme climates any shading of the plants slows down growth. Under natural conditions, *Cryptostegia* is limited to the margins of forested areas and to situations where there is abundant light.

Soil. *Cryptostegia* thrives on a wide variety of soils, growing in both highly alkaline and highly acid soils. It has even been found in brackish tidal swamps, sometimes with the leaves encrusted with salt. Apparently thriving best in dry situations with a high water-table, it grows well in soil with a coarse texture or on alluvial soils, but does not thrive on shallow soil with solid rock or other impervious layers near the surface. Of some 45,000 acres of *Cryptostegia* planted in Haiti during World War II, the major portion failed because of the choice of shallow soils underlain with solid limestone. On the deeper soils, the *Cryptostegia* thrived without regard to other soil variations.

Morphology and Anatomy

Much of the rubber of commerce that originated from *Cryptostegia* in India and Madagascar was obtained by making incisions into the bark of the stems and catching the latex in suitable containers. When it became desirable to obtain rubber from *Cryptostegia* on a large scale during World War II, new and more efficient methods of obtaining the rubber were sought. A basic need was to study the origin and occurrence of the rubber-forming tissues, and the method of rubber regeneration to replace that removed in tapping.

Rubber-bearing Tissue in 'Cryptostegia'

Rubber occurs in the form of latex in all parts of the *Cryptostegia* plant. In the leaves, it is found both associated with the chloroplasts in the individual cells and in latex vessels in the veins and midribs. Latex vessels are found in the leaf petioles and throughout the bark of the twigs, stems, and roots. They are found also in the pith, and this is an important source of the rubber obtained from the tips of the shoots. J. T. Curtis *et al.* (1946) reported the presence of rubber in secondary parenchyma cells in both wood and bark. These rubber globules varied from 1 to 10 per cell and ranged from 1 to 12 microns in diameter, though the majority measured 3 microns or less. Similar globules were found in xylem parenchyma cells of the root.

Origin and Occurrence of Latex Vessels

Artschwager (1946) made a comprehensive study of the anatomical structure of *Cryptostegia grandiflora*. He traced the development of the latex-vessel system from its first initiation in the developing embryo to its ramification throughout the plant. Unlike those in *Hevea*, the latex vessels of *Cryptostegia* are not articulated but are spread throughout the stems and leaves by elongation and profuse branching. They are not confined primarily to vertical growth as in *Hevea*, but may grow horizontally from the pith to the cortex and then again assume a vertical growth. In the course of such growth, the latex vessels penetrate the cambial area but have no particular affinity for that area, since the cambium is not the source of the new latex vessels as it is in *Hevea*.

Artschwager (1946) likens the growth of the latex vessels in *Cryptostegia*, as they penetrate between the cells, to the development of the hypha of a fungus. At first, the diameter of the latex cell is small and its walls are greatly scalloped. The bore of the latex cell increases rapidly, however, and the cell-walls straighten, though they increase very little in thickness. Numerous nuclei are evident, especially in the young part of what remains a single cell, and these at first do not differ greatly either in size or staining reaction from those of the surrounding cells. Soon, however, they begin to retain the safranin stain tenaciously and to appear a brilliant red when so stained, whereas the nuclei of the surrounding cells are coloured blue by safranin. The red staining indicates the presence of rubber, and its appearance marks the first formation of rubber in the latex vessels.

Latex cells are very numerous in the shoot apex—especially in the nodal region, where they run obliquely, and for a short distance even horizontally, to accompany the leaf-trace into the leaf. A few of the latex cells terminate in the growing-points of the axis, and these furnish initials for the latex system of the entire aerial part of the plant. As the latter grows, each initial develops into a branching system ramifying throughout the entire plant body.

'*Cryptostegia*' *Latex*

The latex of *Cryptostegia*, particularly that of *Cryptostegia grandiflora*, has been studied by Mercier & Balansard (1932), Trumbull (1942), Nath (1943), Rhines & McGavack (1943), Hendricks *et al.* (1944), W. S. Stewart & Hummer (1945), and Blondeau & Curtis (1946).

Blondeau & Curtis give the following measurements of the rubber particles in the latex of the two species and of the hybrid:

C. grandiflora.

Whip latex—0·4 microns, only a narrow range in sizes.

Trunk latex—0·8 microns, range from 0·6 microns to 1·4 microns.

C. madagascariensis.

Whip latex—0·2 microns and 1·1 microns; two distinct sizes.

Trunk latex—0·4 microns, only a narrow range.

F_1 Hybrid.

Whip latex—0·2 microns and 1·1 microns; same as *C. madagascariensis.*

Hendricks *et al.* reported a diameter of 1 micron for the particles from whip latex. Trumbull reported sizes of 0·2 to 1·5 microns, with an average of 0·6 to 0·7 microns.

Blondeau & Curtis reported the pH of *Cryptostegia* latex as 5·2 to 5·6, with a definite diurnal fluctuation showing a high in the morning, a low about midday, and a return to the high during the afternoon and evening. They also reported that *Cryptostegia* latex could be stabilized by the addition of formic, acetic, or hydrochloric acid sufficient to reduce the pH to 2·0 to 2·5. It could also be stabilized by the rapid addition of sufficient NaOH solution to bring the latex to a pH of 11.

The coagulation of *Cryptostegia* latex is quite different from that of *Hevea* latex, which actually is a good coagulant for the former. Blondeau & Curtis (1946) reported that *Cryptostegia* latex could be coagulated by the proper use of any of the following agents: anionic and cationic synthetic detergents, hexylresorcinol, natural gums from certain leguminous trees, colloidal resins such as gum guiac or sodium resinate, alkalis, heavy-metal salts, acetone, formaldehyde, sodium chloride, and *Hevea* latex. Trumbull (1942) found dilution with water effective, and also reported that a 0·5 per cent solution of sodium soap was a good coagulant.

Cryptostegia latex differs from that of *Hevea* principally in the diverse nature of the non-rubber constituents. Mercier & Balansard (1932) reported the isolation from it of two substances of glucosidal nature, one being a saponin and the other alkaloidal and somewhat toxic. Nath (1943) reported the purification from *Cryptostegia* latex of nitrogenous needle crystals with a melting point of 236° to 237°C. and having a bitter taste. W. S. Stewart & Hummer (1945) found a bi-refringent material that was inversely correlated with rubber in *Cryptostegia* latex, while Rhines & McGavack (1943) studied the inorganic elements in the serum and reported that Na, K, Mg, P, and Li were most plentiful and that there were traces of Fe, Si, B, and faint traces of Cu and Mn. They also suggested the presence of phenols. Hendricks & Wildman (1946) isolated a triterpene ester from the latex of *Cryptostegia madagascariensis* and of the interspecific hybrid.

The Physiology of Rubber Production

For mass-production of rubber from *Cryptostegia*, any thought of tapping the stems individually was discarded. Tests were conducted to determine the possibility of extracting the latex by passing the stems between rollers, such as those used to extract sugar-containing juice from sugar cane, and comprehensive tests were conducted by Harry & Lober (1943) in Australia to determine the possibility of extracting the rubber by ball milling or by the use of solvents. Chief reliance, however, for obtaining rubber from *Cryptostegia* was placed on tip-bleeding by cutting off the ends of the stems. Artschwager (1946) showed that this method resulted in obtaining rubber primarily from the latex vessels of the pith, which predominate in tissue of that age.

Rubber Regeneration. W. S. Stewart *et al.* (1948) reported on experiments on the bleeding of *Cryptostegia* and the regeneration of rubber following bleeding. They reported that there is a rapid reduction in the dry-weight (total solids or crude rubber) of latex following the initiation of bleeding by cutting off the tip of a shoot. The latex that flows out during the first ten seconds had a dry-weight of 28·7 per cent of the fresh weight of the latex. The latex coming during the second ten seconds had a concentration of 17·5 per cent. The latex obtained from twenty-one to fifty seconds after making the cut had a solids concentration of 15·6 per cent, and that obtained in the next fifty seconds had a concentration of only 13·9 per cent of solids.

After the flow had stopped, there was a small increase in the concentration of solids in the latex that was demonstrated by reopening the latex vessels by cutting the stem 1 in. from the first cut. The slight gain in concentration was apparent immediately, and there was no further gain in concentration by waiting twenty-four hours to reopen the cut.

Bleeding Schedules. A study was also made of the best schedules of successive bleedings to obtain maximum yields. It was found that the best yields, as measured by the weight of the crude rubber obtained by coagulating the latex with an excess of alcohol, resulted from making the first cut in the third to sixth internode from the end of the shoot, removing 1 to 1½ in. of the shoot at each subsequent bleeding, and allowing forty-eight to seventy-two hours between bleedings. Almost as much rubber was obtained by making four bleedings per internode, with four- to seven-day intervals between successive bleedings. These comparisons, based on total yield per whip before exhaustion, show that *Cryptostegia*, unlike *Hevea*, requires a long period to reconcentrate the latex.

Location and Importance of Nuclei in Latex Vessels. It is of considerable importance that the nuclei which Artschwager (1946) reported in the latex vessels of *Cryptostegia* were found only in the tips of the tubes—the portions of the vessels that are removed first in bleeding the shoots. Rebranching of the latex vessels follows the bleeding but, if the nuclei are involved in rubber synthesis, as appears to be the case, there could be no regeneration of rubber at the point of bleeding until fresh nuclei were formed. *Hevea*, having a latex-vessel system composed of a network of articulated cells, has no lack of local nuclei, and the regeneration of the rubber proceeds without interruption when the latex is withdrawn.

Length of Stem Involved in Latex Flow. W. S. Stewart *et al.* (1948) also studied the distance that the latex flowed following bleeding of *Cryptostegia*. It has been shown that in *Hevea* an appreciable area below the cut contributes latex, and that latex also comes from the sides of the tree and even, around the ends of the cut, from above. Tracing the flow of latex in whips such as those of *Cryptostegia* is simpler than studying the flow of latex in a tree such as *Hevea*. An ingenious method of determining the area of flow was used by W. S. Stewart *et al.*, who delimited the area of possible flow by freezing the shoots at predetermined distances from the cut by applying blocks of solid carbon-dioxide (dry-ice). This effectively cut off the flow of latex and made it possible to determine, with great accuracy, the length of stem involved in the flow of latex following the opening of the cut.

It was found that 11·6 in. of stem were normally involved in movement of latex in the first ten seconds after the cut was opened. In the next ten seconds, the flow was detected at a distance of 14·2 in. from the cut. Within forty seconds, flow was detected at 24·2 in. from the cut, and within sixty seconds there was flow at a distance of 26·8 in. from the cut. These authors found only a slight diminution of flow when the total area of possible flow was limited by freezing the shoot at 40 in. from the cut.

Diurnal Variation in Latex. W. S. Stewart *et al.* (1948) also studied the diurnal variation in rubber-content of the latex. For this purpose they gathered latex from groups of shoots bled at 6·15 in the morning and compared it with latex from groups of shoots bled at 3 o'clock in the afternoon. They noted that the evidence from this and two earlier experiments indicated that latex obtained after the night, or dark, period is higher in its percentage of rubber hydrocarbon and lower in insolubles (non-rubber materials insoluble in water) than is latex obtained after the day, or light, period. These authors pointed out that their results were from percentages rather than dry-weights, and that they could not be taken to mean that insolubles are formed during the night and rubber hydrocarbon during the day. In this experiment, there was a steady reduction in the percentage of rubber throughout the first three days of the test. As the analytical procedures separated the total solids only into rubber and insolubles, the reduction in the percentage of rubber was balanced by an increase in that of insolubles. In the second three-day period, there was no constant trend in rubber-content, but there was considerable fluctuation which was balanced by contrary fluctuation in the percentage of insolubles.

Influence of Time of Day on Latex Flow. Curtis & Blondeau (1946) studied the influence of the time of day of bleeding on the yield and composition of the latex. They concluded:

> Minimum yields of latex and rubber were obtained in all cases during midday hours. Yields of rubber from the bark of old trunks and from young fruits continued low throughout the afternoon whereas yields from the whip-like vegetative branches returned in the late afternoon to a point equalling or exceeding that of early morning.
>
> The time of minimum yield was correlated with the time of greatest atmospheric evaporating power as measured by the vapor pressure deficit. Latex composition changed considerably throughout the day, the rubber

fraction of the total solids varying from 50 per cent in the early morning to nearly 65 per cent at noon in the case of whip latex. Latex acidity also varied, being most acid in the midday hours and least acid in the early morning and late afternoon. Only minor diurnal differences in quality of the rubber obtained by latex coagulation were found.

From the standpoint of plantation practice, it appeared that only morning tapping should be used for trunk latex collection, but that whip latex and fruit latex could be collected throughout the day, with provision for a relatively long noon-time rest period.

Origin of Rubber in 'Cryptostegia'. W. S. Stewart *et al.* (1948) studied the effect on the formation of rubber of removing the leaves from *Cryptostegia.* They found that in the first bleedings, defoliated plants produced more rubber than plants with all their leaves, but that with repeated bleedings the plants with their leaves left on consistently produced more rubber. Further tests showed that the leaves of the individual shoot being bled were the most important in rubber production from that shoot, and that the leaves on other shoots of the same plant did not affect the bled shoot's rubber production directly.

These authors also tested the importance of the root on rubber production by the shoot, by comparing yields of grafted plants. For this study, three types of planting material were available—*Cryptostegia grandiflora*, *C. madagascariensis*, and plants of the hybrid discovered earlier in Florida. Plants of each species and of the hybrid were used as rootstocks, and each of the three was used as a scion on each type of rootstock. Samples of latex were obtained from shoots from the scions and from ungrafted suckers from the rootstocks. The rubber-content of the total solids from the latex obtained from shoots of *C. madagascariensis* varied from 0.7 to 2·0 per cent, and there was no effect shown by any of the stocks in comparison with ungrafted plants. Ungrafted suckers and scions of *C. grandiflora* yielded total solids with rubber-contents varying from 45·9 to 56·0 per cent. The rubber-content of the solids from the latex obtained from hybrid scions and ungrafted suckers varied from 27·9 to 38·0 per cent—except for one sample, from a scion on a *C. madagascariensis* rootstock, which had a rubber-content of 45·6 per cent.

It is clear that the root of a *Cryptostegia* plant has little or no direct effect on the rubber-content of the latex. The slowness of regeneration of rubber following bleeding would indicate that the seat of rubber formation is not close to the cut tip. The proof that active leaf functioning is necessary to a high yield of latex would indicate that there is a direct connection between leaf activity and the formation of rubber—also that rubber, or an essential precursor, is produced in the leaves and must be transported to the stems before further rubber can be obtained from them.

Propagation of 'Cryptostegia'

Propagation by Seed. The propagation of both *Cryptostegia grandiflora* and *C. madagascariensis* is easily and effectively accomplished by direct seeding. In some circumstances, it has been found desirable to plant the seed in nurseries and transplant the young seedlings to the field after they have grown several leaves. In most cases this is not necessary, as the germination rate is high, the seeds are comparatively large, and machine planting is feasible—together with thinning and cross-ploughing to obtain an even stand. Hybrid plants, however, do not come true to type from seed and must be propagated vegetatively.

Rooting of 'Cryptostegia' Cuttings. Loomis & Heuer (1944) studied the rooting of *Cryptostegia* cuttings and reported that the best rooting was obtained in a propagating box with bottom heat maintained at from 85° to 90°F. and with the tops of the cuttings kept at a materially lower temperature. They found air-layering or marcottage * satisfactory but slow (Plate 20(*a*)). However, they were able to increase both percentage and rapidity of rooting by ringing the parent plants before making cuttings. This resulted in the formation of a heavy band of callus tissue. Girdling the shoot from one to ten days before cutting did not materially increase the root formation, and it was found best to wait several months between girdling and cutting the stems for rooting. The use of Rootone (indole-butyric acid) increased root formation and speeded root growth. Rooted cuttings of *Cryptostegia* are shown in (Plate 20(*b*)).

Harvesting Methods

During World War II, because of the fact that it was found to be adapted to such a wide range of soils and climates, *Cryptostegia* assumed an importance far beyond that of many other rubber-bearing plants. Small-scale tests were conducted in the United States, Mexico, and Central America. More comprehensive tests were conducted in Australia (Harry & Lober, 1943) and India (Bhatnagar *et al.*, 1945). The Government of the United States authorized and financed a production programme in Haiti which resulted in the planting of some 45,000 acres of *Cryptostegia*. Several tons of rubber were produced and tested, but no commercial quantities of rubber were forthcoming from this source. The chief difficulty encountered was in developing a satisfactory method of obtaining the rubber from the plants.

Tip Bleeding. Hans G. Sorensen, of the United States Department of Agriculture, devised a method of tip bleeding that involved repeated clipping of the tips of the long, whip-like shoots and catching the exuding latex in a suitable receptacle. After the Government of the United States had contracted with a quasi-governmental agency in Haiti to plant up to

* Air-layering (or marcottage) was accomplished in this instance by ringing the bark of a stem of a *Cryptostegia* plant at one or more heights above the ground and tying a suitable rooting medium, moist sphagnum moss, around each point that had been ringed. A special moisture-proof marcot box or other water-proof covering was used to confine the rooting medium and slow down the loss of moisture. The rooting medium was kept moist until each ringed area had become well rooted. The stem was then severed at the points where it had been ringed and the cuttings were established in soil.

100,000 acres of *Cryptostegia*, that agency, the Société Haitiano-Americaine de Développement Agricole, more commonly known as SHADA, established an efficient research organization under the leadership of J. T. Curtis. This group improved and simplified the clipping method originated by Sorensen and developed a process by which numerous stems could be tied into a bundle and bled as a single unit, thus greatly facilitating and speeding the operation.

Plug Collection. McGavack (1944) obtained an American patent for a method of bleeding *Cryptostegia* that was developed at an experimental farm established by the United States Rubber Company at Yuma, Arizona. This method involved a combination of clipping and mechanical extraction of the rubber from the clippings. It was found that appreciable amounts of rubber could be obtained by gathering the clippings to recover the rubber that had coagulated on the ends in the form of small plugs. This amounted to more than the total rubber obtained as latex when the plant was clipped.

Mechanical and Chemical Treatment of Leaves. Harry & Lober (1943) reported on the results of experiments on the mechanical extraction of rubber from the leaves of *Cryptostegia* in Australia. They compared the results of ball milling of fresh material, ball milling of acid-digested material, ball milling in the presence of acids or solvents, acid digestion after ball milling, and various other methods of mechanical or chemical extraction, of rubber from the leaves. In Central America, Reif & Trafton (1946), of the United Fruit Company, developed a chemical digestion method of extracting the rubber from *Cryptostegia*.

Other Methods. Several other methods that were tested in the hope of finding a rapid and cheap means of collection are worthy of mention. A sled-drag method was originated by Percy Heath at the United States Plant Introduction Garden at Coconut Grove, Florida. This method consisted in using a linoleum-covered sled on the ground, to catch latex resulting from bleeding the plants. As one group of plants stopped bleeding the sled was pulled to an adjacent group. Bleeding was started by cutting with pruning shears, and the latex and coagulate caught on the linoleum were treated chemically to complete the coagulation, being thereafter washed and sheeted.

A top-drag method was developed at a co-operative research station of the Governments of Mexico and the United States at Llera, near Ciudad Victoria, Tamaulipas, Mexico. This method consisted in trimming the row of plants to a given height and drawing an oilcloth upside down over the freshly cut tips of the plants. The droplets of latex adhered to the oilcloth and coagulated to form a thickening coat of rubber that could be stripped off and washed.

A staked-leader method was developed by Howard E. Gentry, of the United States Department of Agriculture, who was stationed at Sinaloa, Sin., Mexico. This method involved tying the shoots to stakes, initiating bleeding by the use of hedge clippers, and allowing the latex to drop into receptacles fastened to the stakes.

Ing. Eduardo Chavez of Tamaulipas, Tamps., Mexico, developed a machine to cut the stems and collect the tips and latex in one operation. Hand-labour was required to suspend a light board with perforations through which the shoots were placed for cutting. The machine made the cut, gathered the tips in a sack, and collected the latex in a trough behind the cutting blade.

For field studies, a method of collecting the latex in small bottles placed on the ends of the shoots at the time of clipping was developed at Ciudad Victoria, Tamps., Mexico. The bottle was held by a grommet consisting of a thin sheet of rubber with a small hole in the centre for inserting the end of the shoot. While this method was not considered as a possible commercial system of gathering the latex, it was effective in speeding up the taking of yield data, as the operator employing it could drain many shoots in the time that otherwise might have been spent in bleeding a single shoot.

'Cryptostegia' as a Source of Rubber

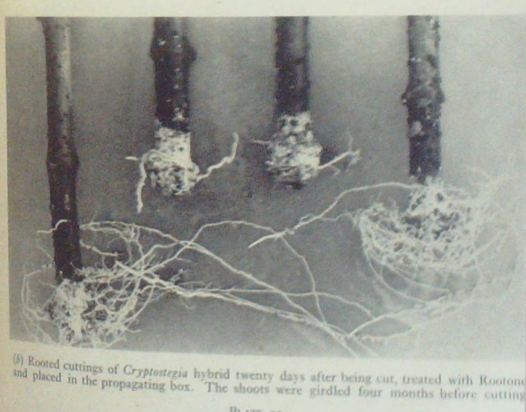
No method of harvesting the rubber from *Cryptostegia* was devised that was superior to the clipping and tip-bleeding method perfected by the research department of SHADA in Haiti. There is no record that that organization attempted to superimpose the plug-collection method on their clipping method, and it is possible that some decrease in the cost of production could have been effected in this manner. The best estimates were that some three man-days of labour were required for harvesting each pound of rubber. Even under comparatively low labour rates, this made the cost of the rubber prohibitive as long as other sources of rubber were available. The planting of 45,000 acres of *Cryptostegia* in Haiti was a monumental task in efficient organization of seed collection, land acquisition, research accomplishment, and planting. It was accomplished under war-time pressures, and its failure to provide significant supplies of rubber resulted only from the lack of an efficient method of obtaining the rubber that was available.

GOLDENROD

Goldenrod became of interest as a possible source of rubber solely as a result of the efforts of Thomas A. Edison. Prior to the time that he took an interest in domestic sources of rubber, no thought had been given to goldenrod as a possible source and little attention to any plant that did not have latex. Guayule, of course, did not have evident latex but had been a source of rubber for hundreds of years. Some attention had been given to another group of plants, called rabbit brush (*Chrysothamnus* spp.), that also does not evidence latex. Yet on the whole, the presence of evident latex was considered the mark of a rubber-bearing plant.

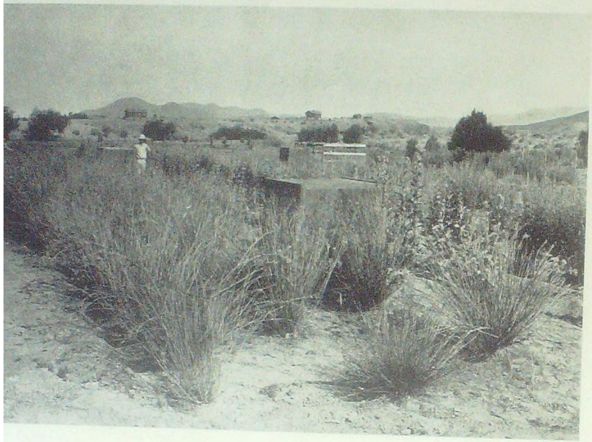
Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) A field of hybrid *Cryptostegia* plants propagated by marcotting.

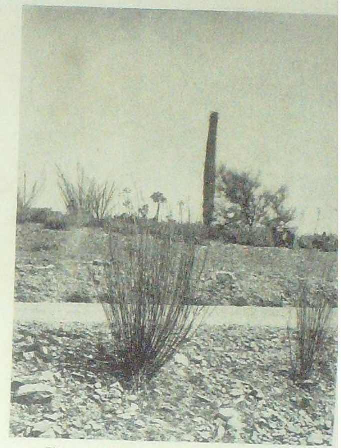


(*b*) Rooted cuttings of *Cryptostegia* hybrid twenty days after being cut, treated with Rootone and placed in the propagating box. The shoots were girdled four months before cutting

PLATE 20



(*a*) Experimental planting of the desert milkweed, *Asclepias subulata*.



Photographs by permission of ARS, U.S. Dept. Agric.

(*b*) A wild plant of *Asclepias subulata* on a barren hill-slope. The stems are 2 to 5 ft. high.

PLATE 21

Edison's Search for Rubber Plants

Edison's particular interest was in finding plants that might be cultivated in the United States for rubber production. He solicited the help of the United States Department of Agriculture in propagating material of plants from outside the United States that might be suitable for domestic cultivation, but his own search was confined principally to the United States, though some collections were made in Mexico. To locate new sources of rubber, Edison organized collecting parties to obtain samples of all types of native plants for chemical tests of their rubber-content. Some of the groups organized for this purpose collected plant samples for more than three years, and over 17,000 samples were collected and analyzed.

At the time of collection, botanical specimens were obtained and preserved for identification. Careful records were kept of the place of collection and of the nature of the plant. In addition to the collections made by his own parties, Edison appealed to executives of the Union Pacific Railroad, who ordered their section-men to gather plants growing along the right-of-way. This resulted in the submission of thousands of plants. As the collectors in this case were not trained in the preservation of plant specimens, the selection and preservation of specimens for botanical identification were not done at the time of field collection. The plants had to be identified on the basis of botanical specimens taken from the individual lots after their arrival at the Edison laboratories in West Orange, New Jersey. Many of the samples did not contain flowers, fruit, and other parts necessary for botanical identification. Many arrived at the laboratory in poor condition owing to inadequate preparation of the plant for shipment, that resulted in putrefaction *en route*. Precise identification of these collections was often difficult and sometimes impossible, though all the determinations that could be made of plants in the Edison collections were later re-checked by S. F. Blake of the United States Department of Agriculture.

Laboratory and Field Tests. Edison first classified the thousands of plants that were being collected and analyzed in his laboratories on the basis of his own visual examination of the rubber, which was extracted by benzol after a preliminary elimination of resins by treatment with acetone of the ground plant samples. All samples were labelled in his handwriting to indicate his estimate of the amount and quality of the extract, whilst his next classification was to segregate species that showed more than 2 per cent of rubber. He quickly became aware that the goldenrods were giving consistently higher results than other groups of plants.

Edison next initiated plantings of the outstanding species as determined by the chemical analyses. The careful notes kept of the original collections made it possible to make seed and plant collections, for purposes of propagation, in the precise areas in which the original collection had been made. Almost a dozen species of goldenrods were included in

Edison's initial plantings, but his further tests tended to eliminate most of the species and, at the time of his death in 1934, the species of chief interest was *Solidago leavenworthii* Torr. & Gray.

The Edison Botanic Corporation. After the death of Edison, the Edison Botanic Corporation was formed to carry on his work with rubber-bearing plants. However, when it became apparent that these activities were not commercially remunerative and had no immediate prospect of becoming so, the executors of the Edison estate decided that they should be given no further support. Arrangements were accordingly made to turn all planting materials and records over to the United States Department of Agriculture.

Rubber in Goldenrod

Rubber is found in goldenrod principally in the leaves. Only negligible quantities have been found in the stems and roots. Polhamus (1933) reported on the analysis of thirty-nine species of goldenrods, all of which contained rubber. Up to 6·70 per cent of rubber (dry-weight) was found in the leaves, but the highest percentage of rubber found in the stems was only 0·40 and in the roots 0·12. From the standpoint of rubber production, therefore, only the leaves are important.

The results of microscopical examination of the leaves of goldenrod were reported by M. L. Rollins *et al.* (1945), who showed that the rubber is contained in isolated globules floating among the plastids in the protoplasm of both palisade and spongy parenchyma cells. Usually these globules occur singly, and they average about two microns in diameter. Occasionally as many as five can be found in a single cell, but in those cases they are much smaller than usual. There is hardly any rubber-bearing tissue in the stems. Near the green end of the stem there are many small resin ducts associated with the fibro-vascular bundles, and each of these ducts is surrounded by a single layer of cells containing rubber globules. However, the amount of rubber extractable from the stem is negligible.

Seasonal Variation in Rubber Accumulation. Very little rubber is formed in goldenrod during the season of active growth. The rate of rubber formation and accumulation increases as the growth-rate decreases in the late summer and autumn. The rubber accumulates first in the lower leaves, and accumulation progresses upwards as the upper leaves reach full maturity. Maximum rubber-content and full maturity of the leaf occur at approximately the same time, and the leaves are normally shed soon after that time. This shedding process also works progressively from the base of the plant, starting soon after flowering commences and becoming more rapid as cold weather sets in. The entire remaining complement of leaves is dropped soon after the first frost. High winds, drought, heavy rains, and other adverse weather conditions in the autumn, encourage early loss of leaves by goldenrod.

Time of Harvest. It is necessary to delay the harvesting of goldenrod leaves as long as possible in order to permit the accumulation of rubber in the upper leaves, though to avoid overbalancing the increase in the top leaves by the loss of the high-rubber-content lower leaves is also important. A partial harvest of the lower leaves at the time of their maximum rubber-content would be desirable, but would require excessive hand labour.

Effect of Light on Rubber in Goldenrod Leaves. Presley (1936) showed that the rubber in goldenrod leaves is quickly lost in sunlight after they die, either on the plant or after being shed, whereas in darkness the extractable amount of rubber may actually increase. The wave-length of the light affected the rate of disappearance of the rubber. When goldenrod leaves were exposed in envelopes made of coloured cellophane, the disappearance of the rubber from leaves stored in clear, red, green, blue, and black (light-proof) envelopes decreased in that order, the greatest and quickest disappearance being in the clear envelopes and no decrease in rubber being found in the leaves in the light-proof envelopes, which instead showed a slight but consistent and significant gain.

From these experiments, it is evident that the leaves should not be left exposed to light, whether on the plant after the death of the leaves or in the process of harvesting. A period of several weeks is normal for the processes of dying, desiccation, and shedding of goldenrod leaves. They are shed gradually and there is no accumulation on the ground of leaves that might be harvested conveniently.

Propagation of Goldenrod

Propagation by Seed. The 'seeds' of goldenrod are very fine and difficult to handle for field propagation. In laboratory or greenhouse tests, however, no particular difficulty is experienced in growing seedlings, though seed germination percentage is usually low. A convenient method of planting the seeds in the greenhouse at Savannah, Georgia, was in large pots or small greenhouse 'flats'. The seeds were planted on the surface of the soil and covered either with a thin layer of sand or with a single layer of thin paper tissue. The tissue selected was not resistant to water but protected the seeds from the force of the fine spray used carefully in watering the germination beds. The seedlings were allowed to continue in the germination bed until they had formed two or three true leaves. They were then transplanted to flats and set out at a distance of 2 × 3 in. for growth to a height of 4 to 6 in., which was considered suitable for transplanting to the field.

Propagation by Stolon Shoots. Propagation of goldenrod by seed was confined to breeding operations. For field propagation, the shoots that come up during the winter and early spring of the second and succeeding years of a planting are used. Edison was the first to use these shoots for propagating goldenrod for rubber production. He termed them 'pups', because they clustered so thickly around the base of the mother plant.

Many species of goldenrod are characterized by the production of large numbers of underground stolons. Stolon production is quite variable in the goldenrods, some species producing them profusely, and others only sparsely or not at all. Among the species studied as possible sources of rubber, *Solidago sempervirens* does not produce stolons but can be propagated vegetatively by division of the crown. The presence of stolons in a plant that might otherwise be identified as *S. sempervirens* is taken as proof of its hybrid origin—a common occurrence, as this species is often closely associated with *S. fistulosa*, which is a heavy producer of stolons. The two species are very dissimilar but hybridize readily.

Most of the species, and especially *S. leavenworthii*, the most promising for rubber production, bear stolons profusely. It is possible that, in nature, the spread of some species of goldenrod is more by stolons than by seed. However, the ability of goldenrod to spread to newly cleared land, and the frequent occurrence of hybrid plants, indicate that natural propagation by seed is far from rare.

The underground stolons of goldenrod may be from as little as an inch to several feet in length. Each stolon is segmented and may send up a shoot at any or all of its nodes, or it may have only a single shoot at the end of the stolon. There is great variability in the number of shoots produced, some species being much more prolific than others. Individual plants of *Solidago leavenworthii* normally produce from ten to thirty stolon shoots each. A considerable increase can be made in the rate of vegetative reproduction by digging up the entire stolon and rooting cuttings from those sections that have failed to send up shoots. The stolons may be cut into short sections (with at least three nodes each) and these may be rooted to supplement the stolon shoots. Up to fifty shoots and polynode cuttings can thus be obtained from an individual plant.

Propagation by Stolon Cuttings. Hamner & Marth (1943) studied the use of growth-promoting substances in the rooting of stolon and stem cuttings of goldenrod. Stolon cuttings of goldenrod, soaked in aqueous solutions of several growth substances at concentrations of from ten to one hundred parts per million, for eighteen hours, were inhibited in top growth. Soaking of stolon cuttings for three hours in indolebutyric acid solution at ten or fifty parts per million gave some increase in rooting over those not so treated. Cuttings dusted with indolebutyric, naphthaleneacetic, or naphthoxyacetic acids, or with naphthalene acetamide, or with a mixture of these four, in all cases dispersed in powdered talc, produced more roots than did those without such treatment—except when the concentrations were above parts per million.

The greatest number of roots were formed when the temperature of the substrate was maintained at 70° to 80°F. Regardless of treatment, stolons cut into 3-in. pieces produced many roots and heavy top-growth, whilst those cut into ½-in. pieces produced few roots and only 50 per cent of the pieces rooted.

These investigators also studied the rooting of stems. They found that young stems rooted best, and that cuttings from near the tips of the stems were better in this respect than those from lower on the stem. Only a small percentage of the cuttings from old, mature, leafless stems formed roots. Stem cuttings soaked in aqeous solutions of indolebutyric acid at twenty-five, fifty, or one hundred parts per million, for three hours, produced more roots than did untreated controls.

Breeding and Genetics in 'Solidago'. The Compositae, to which goldenrod (*Solidago*) belongs, is the largest family of flowering plants. From the standpoint of rubber, the most illustrious member of the family is guayule, which has been an important source of commercial rubber, the Russian rubber-bearing species of *Taraxacum* and *Scorzonera* being next in importance. No other member of the family has ever served as an important source of rubber; yet Polhamus (1957) reported that, of 568 analyses of some 131 species of Compositae, only seven failed to show rubber. Though only a small proportion of the numerous species belonging to the Compositae have been analysed for rubber, it is a fairly safe assumption that all members of this family synthesize rubber under suitable circumstances.

Variation in Goldenrod. The goldenrods are perennial herbs occurring mostly in North America, but with a few reported from South America, Eurasia, and one from the Azores. Fernald (1950) states: '*Solidago*, like *Aster*, is one of our most difficult genera. Natural hybridization frequently occurs and the species are also highly plastic. For proper study FULL SPECIMENS showing subterranean parts and basal leaves, as well as the whole flowering stem, are essential.'

Goodwin (1945) has made detailed studies of *Solidago sempervirens* and has compared this species as it occurs in the northern part of its range in New England with material from the southern part of its range in Florida. In hybridization studies, he has attempted to determine the genes differentiating the various morphological forms. For purposes of comparison he also included *S. rugosa* and hybrids between the two species and between the geographical variants of *S. sempervirens*. He found that a large number of genes were involved in the differentiation between the two species, but that a comparatively small number of genes could account for the differences in the geographical variants of the one species.

Plant Improvement in 'Solidago leavenworthii'. Solidago leavenworthii is the principal species of goldenrod that has been studied as a possible source of rubber. It is a species of limited distribution in Florida, and shows much less variability than the more widely distributed species. In cultivation at Beltsville, Maryland, its growth was only fair, and it did not over-winter well. At this place, its yield of leaves and rubber-content were inferior to those of more widely distributed species with which it was compared. Its growth in South Carolina, Georgia, Mississippi, Louisiana, New Mexico, and Southern California was good. In all respects it is characterized as a southern plant not adapted to survive severe winter conditions.

In the beginning, the selection of individual seedlings on the basis of comparative performance was relied upon for the development of superior strains of goldenrod. Seedlings were selected on the basis of growth-type, rubber-content, and yield of rubber. Individual plants that had been found to have superior amounts of rubber were propagated by means of stolon shoots and stolon cuttings, and compared in row plantings. Those that proved outstanding were increased and compared in replicated blocks. In re-selecting among the seedling progeny of prior selections, the seedlings were planted in rows alternating with stolon shoots from the mother strain. Only those seedlings were selected for increase whose yield was equal to the mean of the parent strain plus twice its standard error—in other words, seedlings that were significantly better than the mean of the clonal plants of the parent strain.

Continued selection resulted in negligible further improvement after the primary selection had been made and proved. It was not possible to select plants that combined factors for high leaf-yield with those for high rubber-content. A breeding programme was therefore initiated to segregate and purify the characters for leaf-yield and percentage of rubber, and then combine them by hybridization. Interspecific hybridization had not proved of importance in the improvement of yield in goldenrod, and was not considered a promising method of crop improvement.

The Flowers of 'Solidago leavenworthii'. The flower-head of *Solidago leavenworthii* is approximately seven to nine millimetres long and two millimeters wide, and normally contains from ten to twelve disk florets and from fifteen to eighteen ray florets. The ray florets are pistillate and open one or two days ahead of the first disk florets. The disk florets are perfect and open over a period of three or four days at a rate of two to five per day.

At Savannah, Georgia, if weather conditions are normal, the disk florets open at about 9 a.m. As soon as the corolla is open, the style begins to elongate rapidly, and at this stage of development the stigma is surrounded by the anthers which are attached to each other in the form of a sheath or envelope that is closed at the apex. The elongating style carries the anther envelope upwards until both stigma and anthers are extruded considerably beyond the corolla tube. Between 11 a.m. and 12 noon, the apex of the anther envelope opens, and a mass of pollen is pushed out by the continued elongation of the style. As soon as the pollen is shed, the filaments slowly retract and the anthers are partially withdrawn into the corolla tube, leaving the stigma fully exposed.

The stigma lobes gradually spread apart to expose their receptive inner surfaces. For the first day or two, the lobes remain confluent at the extreme apex, while separated below to provide an entrance for the pollen. However, if pollination does not take place promptly, the lobes spread farther apart until they are no longer touching at the apex. No studies were made to determine the optimum stage of receptivity of the stigmas, but these remain turgid and apparently receptive for as long as two weeks if pollination does not occur.

Hand-Pollination. Hand-pollination in goldenrod is slow and tedious, because of the small size of the flowers and the difficulty in emasculation. The manual operations were facilitated, in many cases, by transplanting to pots in the greenhouse, where the operations could be performed more readily and where it was easier to control the spread of unwanted pollen. Here it was possible to provide protective covers consisting of cheesecloth on a wire frame that could be suspended over the plants. These covers, equipped with pulleys and counter-weights could be raised or lowered at will with minimum loss of time during the pollination period which, because of the normal behaviour of the flowers, was limited to about two hours in each day.

The tiny size of the flowers made emasculation prior to opening impossible. The most successful method of emasculation devised was by washing the pollen away with a fine stream of water from a hypodermic needle, appropriately mounted so that water under pressure could be made available by the use of a suitable foot valve, leaving the hands free for manipulating the stream of water and the flower-head. Because of the habit of goldenrod of opening only a few florets per head each day, it was necessary to wash away the pollen daily for up to four days.

Goldenrod as a Source of Rubber

Great difficulty was experienced during World War II in developing methods of harvesting the leaves of goldenrod and extracting the rubber in a condition suitable for commercial utilization. The specific qualities of goldenrod rubber were determined in experimental small-scale tests. A sufficient quantity of the rubber was produced to make it possible to conduct factory-type evaluation studies. Methods of fabrication were worked out, and factory tests were made in a commercial factory utilizing goldenrod rubber furnished by the Southern Regional Research Laboratory of the Bureau of Agricultural and Industrial Engineering (now the Agricultural Utilization Service) of the United States Department of Agriculture.

The impossibility of quickly developing efficient methods of growing goldenrod on a large scale and harvesting the leaves in an acceptable manner, led to the closing out of the goldenrod work before definitive answers were obtained on the production problems. It was demonstrated that rubber of usable quality could be produced from goldenrod, but it appeared that the rubber would be different from that from other botanical sources and would require special processing. The cost of producing this rubber would be much higher than that of producing either *Hevea* or guayule rubber, and there was no prospect that the cost could be reduced enough for peace-time use.

Scorzonera

Rubber-Bearing Species of 'Scorzonera'

The Scorzoneras of mid-Asia are extremely variable in leaf type, growth habit, and annual growth-rhythm but, unlike the species of *Taraxacum*, all these Asian species of *Scorzonera* have appreciable contents of rubber and several are potential sources of rubber. The chief rubber-bearing Scorzoneras are tau-saghyz, usually referred to botanically as *Scorzonera tau-saghyz* Lipsch. & Bosse, and teke-saghyz, *S. acanthoclada* Franch.

Lipshitz (1932) lists a number of Asiatic rubber-bearing species of *Scorzonera*. In addition to *S. tau-saghyz* and *S. acanthoclada*, Lipshitz lists *S. turkestania* Franch. and *S. racemosa* Franch. (grouped together because of their close association in native stands), *S. virgata* DC., *S. divaricata* Turcz., *S. hissaricata* C.Winkl., *S. albicaulis* Bunge, and *S. tragopogonoides* Regel & Schmalh. s.l.

Ulmann (1951) treats tau-saghyz as including several closely allied species of *Scorzonera* and lists the five chief forms as *S. vavilovii* M.Kult., *S. mariae* M.Kult., *S. tau-saghyz* Lipsch. & Bosse, *S. longipes* M.Kult., and *S. karataviensis* M.Kult. In addition, he lists the types 'Macagoni' and 'Zaretzkii' of *S. tau-saghyz*. The specific forms listed he differentiates on the basis of variation in leaves, pedicels, flower-heads, floral envelopes, seeds, pappus, and latex. All of these are known locally as tau-saghyz, and all are restricted to a limited area in the Kara-Tau Mountains in the Tian Shan Range.

Tau-saghyz

Scorzonera tau-saghyz Lipsch. & Bosse is an important Russian rubber-bearing plant belonging to the family Compositae, and may possibly have the ability to accumulate a higher concentration of rubber than any other plant in the world. Certainly only guayule can be compared with tau-saghyz in percentage concentration of rubber, and the reported analyses put tau-saghyz clearly out in front, with percentages of up to 40·76 of rubber reported by Kultiasov (1932).

In many instances, considerable difficulty has been experienced in getting tau-saghyz established, and a period of up to five years is needed for the maximum accumulation of rubber. Both of these factors probably have been important considerations in Russian preference being given to kok-saghyz, which can produce a crop of rubber in a single season and is comparatively easy to establish. The rubber from tau-saghyz is reported to be excellent.

As is true of kok- and krim-saghyz, tau-saghyz is a root crop. The records of high rubber-content are of rubber from the root, since the aerial portions of the plant have only small amounts of rubber. As with the other Russian root-rubber crops, the entire plant must be ploughed up at harvest time and the crop must then be replanted. It has been reported that krim-saghyz will regenerate itself from roots left in the ground if this is not ploughed to a depth of more than some 8 in., although there is no record that similar regeneration can be expected of tau-saghyz after harvest.

Teke-saghyz

Scorzonera acanthoclada Franch. is known as teke-saghyz and has received attention as a possible source of rubber. Like tau-saghyz, it has its highest concentration of rubber in the roots. Teke-saghyz has been exploited as a wild source of rubber but has not been cultivated extensively. It is a poor seeder and, in nature, probably depends more on vegetative spread than on propagation by seed. The rubber of teke-saghyz is similar to that from tau-saghyz and is of high quality. Perhaps no other group of plants has a higher proportion of promising rubber-bearing plants than the Asiatic species of *Scorzonera*, all of which appear to form rubber in appreciable amounts. These species are distributed over a large area in the Ural Mountains region. They present a wide variation in growth and vegetative characteristics that offers hope of a significant improvement, through selecting and recombining the best factors for high yield of roots and high percentage of rubber.

Tau-saghyz in Nature

Tau-saghyz is found in nature at elevations of from 500 to 1,100 metres. The winters of its native habitat are long, and the summer period is short and extremely dry. The annual growing-season is limited to some three months (April, May, and June), and the leaves of the plants may often be nipped by frost as late as in May.

The annual rainfall amounts to some 350 mm., and about half of this comes in the spring months from March to May. The rest of the rainfall comes in the autumn and winter. The month of July is normally rainless and is characterized by high winds and a mean temperature of around 77°F.

Tau-saghyz plants initiate growth in April, normally flower in May, and seed in June. The dry, windy weather of July causes the plants to enter a period of dormancy that is usually not interrupted until the following spring. In cultivation, there is a great variation in the growth response of tau-saghyz plants. Thus under some conditions there is no rest period and the plants may continue growth throughout the year, whereas in other cases the normal summer dormancy is followed by a period of renewed growth in the autumn. To some extent these growth types are related to the climatic conditions encountered in cultivation, but variations in growth-response at a single place have been attributed to differences in the origin of the seed.

Teke-saghyz in Nature

Teke-saghyz is found at elevations of from 2,200 to 3,900 metres, the majority of plants being found at elevations of 2,500 to 3,200 metres. Winter temperatures in its natural habitat range around freezing, and summer temperatures have a mean of only some 68°F. The rainfall amounts to about 400 mm. annually and 80 per cent of this comes in the winter and early spring. Most of the remainder comes towards the end of the summer and in the autumn.

The growth of teke-saghyz normally starts in the middle of June; flowering takes place in July, and seeding occurs in August. Teke-saghyz blooms initially in its second or third year, and natural stands of around 2,000 plants per 100 square metres are considered normal.

Origin and Occurrence of Latex Vessels in Tau-saghyz

Baranova (1935) has furnished detailed information on the origin and occurrence of latex vessels in tau-saghyz. The latex-vessel system is comparable to that of kok-saghyz in that it consists of an articulated system developed by the fusion of adjacent walls of individual cells to form a continuous network. The latex vessels are found primarily in the phloem tissue, and anastomose to form lacy cylinders around the stele of the plant. The new vessels originate in the cambial region, and new networks are formed continuously during the growing-season throughout the life of the plant. The annual sloughing of the root-bark (such as has been reported as characteristic of kok-saghyz) has not been reported for tau-saghyz, and this may account for the higher accumulation of rubber found in tau-saghyz. The plant is perennial and may continue storing rubber for many years, as is the case with guayule.

Asclepias

The Milkweeds

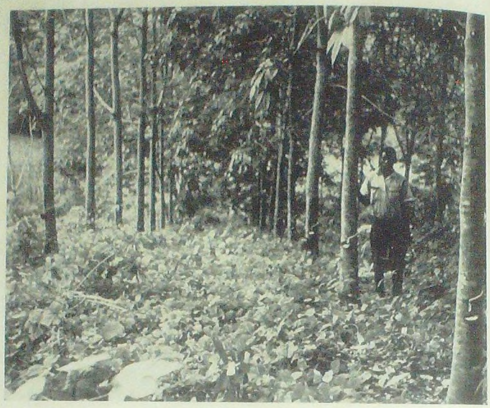
Asclepias is a genus of originally American and African herbs that are now widely scattered throughout the temperate zones of the world. They are found in freshly abandoned fields, in open woods, in swampy areas (both brackish and fresh), on plains and prairies, and in hot, dry, semi-desert situations. The members of this genus are generally known as milkweeds. They belong to the family Asclepiadaceae and thus are closely related botanically to a number of other rubber-bearing plants, chief of which is the *Cryptostegia* rubber vine of Madagascar.

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) General view in a plantation of *Hevea brasiliensis* showing a farm road separating two blocks.

(*b*) Eighteen-year-old 'seedling' planting of *Hevea brasiliensis* in the Panama Canal Zone.

PLATE 22



Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Eight-year-old budded trees of *Hevea brasiliensis.*

(*b*) Protecting nursery plants of *Hevea* from South American leaf-blight by the use of a hand spray.

PLATE 23

The milkweeds are characterized by an abundance of latex that has long been of interest as a possible source of rubber. A 'milkweed', not further identified, was investigated and found to contain rubber in Russia in the eighteenth century. Many individuals in the United States tried to obtain rubber from milkweeds during the nineteenth and twentieth centuries. Whiting (1943) contributed a valuable bibliographical survey of the information available on milkweeds with respect to their possible use for rubber, fibre, and other purposes. From the standpoint of possible rubber production in the United States, the most valuable contributions are those of Fox (1912*a*), Hall & Long (1921), Beckett & Stitt (1935), and Beckett *et al.* (1938).

Milkweed has not become a commercial source of rubber, though the above investigators were able to demonstrate that appreciable amounts of rubber could be produced from it under cultivation. There has also been much interest in milkweed as a possible source of other industrial products such as fibre, cellulose for paper making, and oil. During World War II, considerable quantities of the seed-floss were collected in the United States to replace the unobtainable kapok.

The Desert Milkweeds

Hall & Long (1921) studied the rubber-content of wild plants of the western species of milkweed and found that *Asclepias subulata* Decne. was the most promising. Beckett & Stitt (1935) studied this desert species under cultivation (Plate 21(*a*)) and reported about the same range of rubber-contents in the plants (0·5 to 6·0 per cent) as that reported by Hall & Long (0·8 to 6·5 per cent) for wild plants. Beckett *et al.* (1938) studied the rubber-content of a second desert milkweed, *A. erosa* Torr., in which Hall & Long reported only a low rubber-content of 1·54 per cent in the leaves and 0·48 per cent in the stems. Beckett *et al.* reported rubber-contents in the leaves of *A. erosa* ranging from 2·45 to 13·06 per cent of the dry-weight—the highest reported for any species of milkweed.

'*Asclepias subulata*'

Asclepias subulata Decne. is a perennial herb with numerous rush-like stems arising from a central crown near the surface of the ground (cf. Plate 21 (*a*) and (*b*)). The young stems are dark green, later becoming woody at the base, and acquiring a greyish-white bloom at maturity. The mature stems are from a quarter- to half-an-inch in diameter and from 2 to 5 ft. in height, tapering only slightly from the base to the apex. The leaves, which are short and slender, are produced only on young stems and shoots and are retained for a comparatively short period. The flowers are greenish-yellow and are arranged in umbels at the tips of the stems. The slender, tapering seed-pods are from 4 to 6 in. long and, when ripe, split along one side, allowing the seeds, each of which bears a pappus of stiff, silky hairs, to be scattered by the wind.

Geographical Distribution. The geographical distribution of *Asclepias subulata* extends over a wide area—from southern Nevada in the north to the southern end of Baja California, and Sonora, Mexico, and from southeastern Arizona westwards to the Coastal Range of southern California.

Within its natural range, *A. subulata* is usually confined to dry, stony stream-beds where the water runs after the infrequent rains, and to the depressions on mesas, where the water accumulates and remains for a short period after rains. Occasionally, plants are found on barren hill-slopes (Plate 21(*b*)). In depressions where the soil is fairly fertile, the plants are considerably larger than those on the hill-slopes. The largest continuous stand reported by Beckett & Stitt (1935) started some thirteen miles south of San Luis, Sonora, Mexico, and continued for some 55 miles to the Gulf of California.

The areas in which A. *subulata* grows most abundantly are subject to wide ranges of temperature and rainfall. Winter temperatures below freezing are common, and summer temperatures may exceed 120°F. United States Weather Bureau data, quoted by Beckett & Stitt, show an annual range in temperature at Yuma, Arizona, of from 22° to 120°F., and at Mesa, Arizona, of from 15° to 119°F. These temperatures are typical of those of the natural range of this desert milkweed. The rainfall at Yuma averaged 3·47 in. per year over a period of fifty-four years, and the mean rainfall at Mesa was 8·65 in. over a period of thirty-three years.

'*Asclepias erosa*'

Asclepias erosa Torr. is a perennial herb with stout, upright stems usually from 3 to 4 ft. in height but sometimes reaching 6 ft. The stems are numerous, eight to twenty per plant, and sparsely branched. The leaves are opposite and occur in pairs, being nearly sessile, ovate or lanceolate, and pubescent when young but practically glabrous when mature. The mature leaves are from 6 to 8·5 in. long, and 2·5 to 3·5 in. wide at the base, being very abundant and persistent. The first leaves are usually retained until autumn. The flowers are pale cream-coloured or greenish, and are borne in umbels at the tips of the shoots. The seed-pods are 2·5 to 3 in. long and 1·5 to 1·75 in. wide; they split along one side when ripe, and this permits the seeds to be scattered by the wind. The seeds are flat, about ½ in. long and ⅜ in. wide, with a pappus of silky hairs at the hilum.

Geographical Distribution. The natural distribution of *Asclepias erosa* is limited to the arid regions of the southwestern part of the United States and northwestern Mexico. It extends from Kern to Inyo Counties in California, southwards through the Mohave Desert to San Diego County, eastwards to north-central Sonora, Mexico, and northwards to Utah.

The plants reported by Beckett *et al.* (1938) were confined to dry, gravelly stream-beds, where the water runs for short periods after the infrequent rains, and to borrow-pits along highways and railroads. The plants were usually found in scattered groups of ten or more. In one locality between Parker and Bouse, Arizona, Beckett *et al.* reported several colonies of seventy to eighty plants each, occurring in intermittent groups along washes caused by a periodic flow of flood waters for a distance of 2 or 3 miles on either side of the highway.

Propagation of Milkweeds

The desert milkweeds are propagated by seed. No difficulty is encountered either in gathering the seed or in planting and germination. All species of *Asclepias* are perennial, and there is some spreading through shoots arising from rhizomes. In the desert milkweed, *A. subulata*, growth consists of numerous stems coming from a large crown. As the plant becomes older, more and more stems are produced. Attempts at vegetative propagation, by dividing the crowns of outstanding individuals, were unsuccessful. Dividing the crown also proved unsuccessful in obtaining initial increase of promising wild specimens, though whole plants could be transplanted without undue difficulty.

Rubber in the Milkweeds

All parts of the milkweeds contain rubber in the form of latex contained in vessels that bleed freely when the plant is cut or broken. The common milkweed, *Asclepias syriaca* L., has an abundance of rubber in the leaves, branches, and roots. The highest concentrations reported were in the leaves and fruits. In *A. erosa*, 50 per cent of the aerial bulk of the plant, and a predominant portion of the rubber, are contained in the leaves. In *A. subulata*, the leaves are scarcely more than scales, and are unimportant in the matter of weight of the plant or in their contribution to the quantity of rubber. In this species, the stems are the chief source of rubber.

Seasonal Variation in Rubber-content

The studies of R. E. Beckett and his associates, on the rubber-content of the desert milkweeds, have contributed significantly to a knowledge of the seasonal variation in the rate of rubber accumulation in the milkweeds. As in the case of guayule, the desert milkweeds do not accumulate rubber rapidly during the growing-season; but when the rate of growth is reduced at the end of the active growing-season, the rate of rubber accumulation increases and maximum rubber-content is found after the start of dormancy at the beginning of winter.

Breeding and Selection

Beckett & Stitt (1935) made periodic analyses of fifteen plants of *Asclepias subulata* for four years, the object being to determine the seasonal variation in rubber-content. An examination of the data indicates that there was a high correlation in the performances of the individual plants at various dates. Those plants with comparatively high rubber-content at any given period, tended to maintain a high level at all periods. There was considerable variation, but the possibility of selecting plants of superior yield was demonstrated.

In the sixteen rounds of analyses made of these plants, plant number 7 was highest in rubber content nine times, was second three times, and third, fourth, eighth, and tenth once each. Plant number 6 was first twice, second twice, third three times, fourth three times, fifth four times, sixth once, and seventh once. Plant number 14 was first once, second twice, third six times, fourth once, fifth once, sixth three times, eighth once, and ninth once. There was more variation at the other end of the comparison. Plant number 1 ranked lowest four times and had a highest ranking of fifth. Plant number 3 ranked lowest twice, next to lowest five times, and had a highest ranking of seventh. Plant number 11 ranked lowest four times, but also ranked high once.

Difficulties were experienced in the selection and propagation of superior plants. Vegetative propagation proved impossible. The floral structure of *Asclepias* is complex and difficult to manipulate in emasculation and transfer of pollen from plant to plant. As in other members of the Asclepiadaceae, *Asclepias* produces waxy pollen-masses called pollinia that facilitate cross-pollination by insects. Hand-pollination was accomplished by the use of a long, slender, hooked needle to remove the pollinia from one flower and transfer it to another. Insect pollination was accomplished in screen cages when the tarantula hawk, *Pepsis formosa* Say, a large wasp, was introduced as the insect pollinator.

IX

PRODUCTION OF RUBBER FROM HEVEA

Areas Suitable for Hevea Rubber Plantations

The selection of areas suitable for plantation rubber production (Plate 22(*a*)) depends primarily on the trio of factors that controls large-scale farming operations of all kinds—namely climate, soil, and available labour. Suitable conditions exist in the tropical portions of the Far East, and that area has been the main centre for the development of rubber cultivation. In the last few years, however, there has been an increase in planting and production in tropical Africa. There is a very extensive area of land in tropical America that is ideally suited to rubber growing, but the development of large plantations has been held back in the past by disease, sparsity of labour, and governmental instability.

Climate

The climatic requirements for the cultivation of *Hevea* rubber trees are geographically rigid. By temperature limitations the culture of *Hevea* is restricted to a belt extending some 20° to 25° north and south of the Equator. However, only a small proportion of the land areas included in this broad belt is suitable for rubber cultivation—because of local variations in soil, climate, availability of labour, and transportation facilities.

Temperature. *Hevea* will survive occasional temperatures as low as freezing-point but does not thrive where such low temperatures occur. In general, except for local areas where weather conditions are extremely favourable, temperature restricts the cultivation of *Hevea* to a band less than half the width indicated above and, within this smaller belt, also eliminates desert areas where temperatures are excessive and elevated areas where temperatures are too low.

Rainfall. *Hevea* requires at least 75 to 80 in. of rainfall annually. Double that amount is not excessive, if drainage is good. In portions of the Amazon Valley, the native *Hevea* trees are flooded annually—sometimes for a considerable period of time. Flooding on plantations, however, may seriously affect growth and decrease yields, or may drown out the trees.

Uniform annual distribution of rainfall is favourable to the growth of *Hevea* and the production of latex. The best growth has been found in areas without a decided dry season; but there are glaring exceptions to such a tendency, and high yields have been obtained in Viet-Nam, where a distinct dry season may last for as long as four months.

Diurnal variations in rainfall may be as important in rubber cultivation as seasonal variations. Rain at tapping time in the early morning interferes not only with the physical process of tapping but, by wetting the bark of the trees, causes the tapping channels and the latex cups to overflow, with consequent loss of rubber.

Soils

Hevea has a wide tolerance to different soils. Being a tree crop, the workability of the soil, as by ploughing and cultivation, is of less permanent importance than moisture absorption, moisture-holding capacity, drainage, resistance to flooding, and other factors of soil-moisture relationship. A deep soil is needed to encourage deep penetration of roots. Surface rooting, resulting from shallow soils or bad sub-surface drainage, is a major factor in wind damage.

Labour

From the inception of planting to the harvest of the rubber by the tapping of the trees, the production of rubber is largely a matter of hand labour, although labour-saving equipment has been adopted wherever possible. However, budding and tapping have not been amenable to automation. A resident labour population amounting to an average of one labourer for each four acres of rubber is needed.

Planting

Planting Material

In general, there are three classes of planting materials that have been used in establishing rubber plantings. In the order of their historical use, these are: (1) unselected seeds; (2) budded stumps; and (3) clonal seeds.

Unselected Seeds. Originally, all plantings of *Hevea* were made through the use of seedlings. The seeds originated first in the Amazon Valley (Wickham's collection, *see* p. 25), and were later obtained from plantings in the East. A major portion of over eleven million acres of *Hevea* known to exist in the world consists of trees from unselected seeds (Plate 22(*b*)). On the whole, these plantings are low in yield and extremely variable in growth, bark characteristics, and branching habits. In the present highly competitive market, these 'seedling' trees are being replaced by better planting material that has the potential of more than doubling the yields of rubber.

Budded Stumps. In the second decade of the twentieth century, the first successful vegetative propagation of *Hevea* was made through the rooting of cuttings. The successfully rooted cuttings were from the stems of young 'seedlings', as branch-wood from older trees failed to root. Buds from the branches of the older trees could, however, be implanted in the bark of young 'seedlings' to produce budded plants. The budded progeny from a single bud-mother tree is, horticulturally, a clone.

Clonal plantings are now standard for planting and replanting *Hevea* to obtain the highest yield and best performance (Plate 23(*a*)). Budded trees have growth types that characterize the individual clones and differentiate them from 'seedlings'. The swelling at the bud-union shows that the tree has been budded and makes a point of reference for future measurements of tapping height and tree growth. The stem of the clone has less taper than that of a 'seedling', and the bark is less thick.

Clonal Seeds. Isolated monoclone plantings provide pure seed from individual clones. Hand-pollination also has been used to produce clonal seed, though the seed-set is poor and the output of the pollinators is low. There is considerable variation in the performance of 'seedlings' from different clones, some showing the high-yielding character of the mother clone, whereas others are only slightly better than unselected 'seedling' trees. They are far more uniform than unselected 'seedlings', though somewhat less uniform than clonal plantings. Clonal 'seedlings' do not have the cylindrical trunks that characterize clonal plants, and their bark is more like that of ordinary 'seedlings', though more uniform.

Budwood Nurseries

Budwood gardens, to supply budwood for producing budded stumps, should be planted either contiguous to, or within a reasonable distance of, the rootstock nursery or the field to be planted (if budding is to be done in the field). After the budwood garden has been established, the plants are allowed to develop two to four shoots each. When these shoots are 4 to 5 ft. long, they can be cut back for budwood, which is usually cut in pieces about 1 yd. in length. New shoots are then allowed to develop, to furnish additional budwood.

Rootstock Nurseries

'Seedlings' in the rootstock nursery provide the roots of the budded trees of the planting. Budded stumps from this nursery are transported direct to the field, for transplanting into permanent positions. The nursery should be located as close to the field as is practicable. The nursery site is preferably a level area with deep, fertile, friable soil. Local shade is desirable and, if none is available, a quick-growing shade crop may be useful in the early stages, or artificial shade may be provided until the 'seedlings' are fully established.

Planting distances in the nursery are chosen to grow as many plants as possible per unit of space and, at the same time, to provide convenient access for weeding, budding, and digging. A planting distance of 1 ft. by 1 ft. within beds, with 3 to 4 ft. between beds, has been found satisfactory for base-budding under most conditions where there is no necessity for spraying or dusting for disease protection. Two-row beds 3 ft. apart have been found superior to four-row beds where the base-budded plants are to be over-budded for disease protection. The two-row beds have also been found superior for the production of base-budded stumps in many locations, since less crowding gives more uniform growth and facilitates both budding and digging.

In many cases, it is necessary to protect the plants in the nursery with fungicides. If hand equipment such as that shown in Plate 23(*b*) is employed, the necessity for the use of fungicides need not affect the spacing in the nursery. However, if power equipment such as that shown in Plate 24(*a*) is to be used, sufficiently wide alleys must be left at regular intervals to accommodate the equipment.

Planting the Rootstock Nursery

The rootstock nursery is normally prepared for planting by deep digging and forming into carefully levelled, raised beds of appropriate width. The height of the bed is dictated largely by the local drainage conditions. Any chance of flooding must be avoided, and so must excessive drying that may result from the beds being too high. In many cases, the beds may be planted on the level, as shown in Plate 24(*b*).

Planting may be done with either fresh or pre-germinated seed. Freshly harvested seeds start germination within five days, and germination is complete within a week to ten days. If there is a local source of fresh seed of the quality and type desired, a high rate of germination may be expected. After the seedlings are established, the nursery must be kept free from weeds, and the fertility of the soil must be maintained at a high level by the addition of nutrients. Avoidance of injury to the young seedlings by the tools used in cultivation and weeding is important, as budding will be done in the bark at the base of the seedling, and any injury may complicate or prevent successful budding.

Planting at Stake

Planting is sometimes done 'at stake' by placing from two to several seeds at each permanent planting point in the field. The holes are first prepared by digging, back-filling, and staking. The seeds are planted at each site, and as the seedlings grow the poorer plants are eliminated until only two seedlings remain at each position. The better of the two seedlings is budded and, if the bud takes, the other seedling can be removed at the time the budded seedling is cut back. If the bud fails to take on the first seedling, the second seedling can be budded on the next budding round. This method of planting eliminates the nursery and transplanting but increases field upkeep, and there is greater danger from browsing animals and rodents. Costs of disease protection are greatly increased in such field-budding.

Budding

Nursery seedlings can be bud-grafted after they reach the size of a large pencil. They should be budded before they reach a diameter of ¾ in. at ground level. Bud-grafting at such an early age is more difficult, requiring a higher degree of skill, than grafting later on, when the seedling is larger. A high percentage of success is possible at the early age, however, and the transportation of the budded stumps to the field in transplanting is much easier and less costly than in the case of the larger stumps.

The Budding Operation. The budding operation involves making, in the bark of the seedling, a cut shaped like an inverted, square-shouldered U. This cut is made as near to the ground as possible. An axillary bud from a stick of budwood from the selected clone is then cut (Plate 25(*a*)), the cutting being deep enough to include a thin sliver of wood with the bud. This bud-patch is trimmed to fit the opening in the bark at the base of the seedling that will be made by peeling back the bark that has been cut open. For larger seedlings, the fit may be loose; but in the small seedlings the patch should exactly fit the cut.

The bark on the rootstock is then peeled back, the wood sliver is removed from the bud-patch (Plate 25(*b*)), and the bud-patch is placed against the exposed cambium of the rootstock without sliding and is then held firmly to avoid movement until it can be tied in place. The bark of the rootstock that has been peeled back (the flap) is smoothed back over the inserted bud-patch. It is then tied in place with a convenient binding, such as the paraffined cloth bandage shown in Plate 25(*c*). A banana- or palm-leaf shade may be tied loosely over the patch to shade it from the sun.

Opening. After about three weeks, the bandages are removed and the patch is inspected. A green, 'live' colour of the patch indicates 'take', while a brown, shrivelled appearance indicates failure. The flap of the rootstock can be cut off at this time.

Cutting Back. A week to ten days after opening, a second inspection is made of the bud-patch. The tops of all young budded trees with successful bud-patches can then be cut back to 'force' the new buds to grow, or such trees can be held in the nursery without cutting back until they are ready for planting. Cutting back involves removing the top of the rootstock to within about an inch of the bud-patch (Plate 26). Under favourable conditions, the new bud will begin to swell and start growth within a week to ten days. This is the ideal time for transplanting the budded stump to the field.

Over-budding. In the Americas, a system of over-budding (also known as top- or crown-budding) is used to produce a tree with disease-resistant foliage. Such trees consist of seedling rootstocks, intermediate high-yielding stems for the tapping-panels for rubber production, and disease-resistant tops. Over-budding at a height of 6 to 8 ft. above the lower bud-union can be done in the nursery before the tree is transplanted to the field, or in the field after transplanting. In most cases, it is considered preferable to over-bud in the nursery, as this simplifies fungicidal protection of the high-yielding but disease-susceptible 'panel' clone until its foliage can be replaced with that of the disease-resistant clone.

The over-budding operation (Plates 27(*a*), 27(*b*), and 28(*a*)) is similar to that described for the base-budding, except that the cut in the bark of the high-yielding scion is made in the form of an upright U. The inverted cut employed in the rootstock facilitates inserting the bud from above, while the upright cut made in the top-working operation facilitates insertion of the bud from below—as is necessary in budding above head-level.

Transplanting

The final nursery operation is the digging up of the budded stump or over-budded three-component tree which, in its turn, has been cut back to within a short distance of the top bud (Plate 28(*b*)). In cutting back a top-worked tree, it is often recommended that a stub from 3 to 4 in. long be left above the bud-patch to serve as a support to which the tender new shoot may be tied until it becomes sufficiently sturdy to resist wind damage.

The digging, transplanting, field preparation, and all other details of field establishment, follow practices well known to skilled nurserymen, and are quite similar to methods followed in the establishment of other tree crops.

Operations Required in Planting

A complete lexicon has been developed that categorizes all of the operations of planting and simplifies their orderly arrangement—from budding, opening, cutting back, and digging in the nursery, to clearing, burning, terracing, lining, holing, back-filling, transplanting, pruning, supplying, and slashing in the field. These terms all designate operations that have been worked out to give maximum efficiency in the establishment of a rubber planting.

Local customs vary, and there is some difference in the performance of these tasks. The general terms may be defined as follows:

Budding. The act of implanting a bud from one tree into the bark of another.

Opening. The removal of bindings on the new budding, and first inspection for budding success.

Cutting back. Removal of the top of the rootstock or, in over-budding, of the high-yielding scion to 'force' the newly implanted bud to grow.

Digging. The lifting of nursery plants for transplanting to the field. Plants may be dug individually, or a trench may be dug along an entire row of plants to facilitate lifting. Side roots are pruned to 4 to 6 in. and the tap-root is pruned to about 18 in. in length. Digging is done when the new buds have started to swell but before excessively long sprouts have developed. Such sprouts are tender and easily broken off in handling.

Clearing. The removal of trees and brush before planting. In some cases, particularly in replanting, the roots of the old trees are dug up to avoid early incidence of root disease, and the fallen timber and brush is piled in the alleys of the new planting—either for burning or to be left to decay.

Burning. The destruction of fallen timber and brush by burning. Timber piled between the rows of rubber rots quickly but, in the meantime, is a harbouring place for insects and rodents that attack the rubber trees. Burning, to be effective, must be delayed until towards the end of the dry season, to allow the timber to dry out as much as possible.

Terracing. The construction of terraces for hill-side planting. The terraces vary from shallow contour trenches to elaborately constructed shelves with the outer edges raised to avoid erosion. They slope laterally inwards. The longitudinal slope of the terraces is very gradual, and long terraces are furnished with drainage points and silt pits to control erosion.

Lining. The laying out of planting lines and staking of planting points.

Holing. The digging of planting holes about 1 ft. square and at least 18 in. deep.

Back-filling. Refilling the planting holes with rich top-soil.

Transplanting. Transfer of the dug plant from the nursery, and replanting it at its permanent location in the field. The root-crown should not be lower in the new ground than it was in the nursery, and the soil should be tamped carefully around the root of the stump.

Pruning. Removal of rootstock shoots, excessive scion shoots, and low branches. Care must be taken to ensure that only one shoot develops and that it comes from the scion bud and not from the rootstock. All branches that start below a height of 8 ft. should be removed.

Supplying. Replacing plants that fail to grow after transplanting. From few to many of the budded stumps transplanted to the field fail to grow, while later on there are apt to be further deaths of plants in the field. Until the planting has become fully established, vacant planting positions can be supplied with new budded stumps, and it may be confidently expected that they will get along as well as those successfully established in the first transplanting. After two years, however, it is not possible to replant every position, as the young plants will be unable to compete with the larger plants. In cases where three adjacent planting positions are vacant in such plantings, it is often possible and desirable to replant the middle position. If a sizeable area of mature or nearly mature trees is destroyed by wind or other influence, it is possible to supply a larger number of the vacant positions, though the competition of the older trees around the margin of the area to be supplied must be taken into account.

Slashing. Control of natural or planted covers by cutting them back above ground. Clean-weeding is no longer considered desirable, except in a narrow ring around the tree. This ring may be mulched with dried grass or other vegetable material, which acts not only as a source of humus but also to reduce the reflection of heat that often, particularly with light-coloured soils, causes damage to the bark of the tree on the side towards the sun. Natural cover of spontaneous origin may be allowed to develop, or cover-crops may be planted. It is necessary to make regular rounds to slash these covers and keep them under control. It is also essential to make careful inspection of the trees and to remove any 'vines' that start climbing.

Planting Arrangement

Planting Density. Traditionally, the layout of a rubber plantation is a regular square or triangular pattern, though unequal spacings, with wide alleys between closely spaced trees, are often favoured. These plantings may consist either of single rows of trees, with a planting distance of 10 ft. or less between trees in the row, or a two-row planting such as one having rows 10 ft. apart with trees planted 10 ft apart in the row. Alley widths of from 30 to 90 ft. have been suggested, these wider spaces being used for intercrops.

Advantages of Unequal Spacings. There are many advantages of unequal spacing. The production of catch-crops, intercrops, and cover-crops is facilitated, as is the use of heavy farm equipment. Aeration and sanitation of the plantation is much better. The development of the tree crowns is superior, as the crowns can grow much larger before crowding the broad alleys—in spite of inevitable crowding within the row. Owners of large estates are little interested in the production of catch-crops, and hardly more in the planting of intercrops. Small producers and plantations of moderate size, however, find that catch-crops can repay a significant portion of the planting costs during the several years that such crops can be raised between the rubber trees, prior to the closing in of the alleys. Permanent intercrops such as coffee and cacao are attractive hedges for the one-crop plantation, and these crops benefit from the shade of the rubber trees.

Timing of Operations

Seasonal Change in the Tropics. Planning of agricultural operations in the tropics, where there is only a small seasonal variation in temperature, must take into account primarily the annual total and seasonal variation in rainfall. In rubber planting, two or three rainy seasons are required for the initial planting and propagation of the clonal material, the planting of nurseries, base-budding of the seedlings and, in the case of clones that need to be protected from disease by over-budding, top-working in the nursery before transplanting. The timing of the final operation of transplanting is particularly important in relation to the rainy season.

The Seeding Season. The timing of nursery plantings is dictated by the seeding season that is, in general, from August to October north of the Equator, and in February and March to the south. Locally, this relationship may be reversed, as flowering takes place at the end of the dry season just prior to, or simultaneously with, the regeneration of leaves. Thus, the seeding period is related to the dry season rather than directly to the length of day, as would be assumed if the north–south relationship were invariable. In Florida, where there is a distinct winter during which growth is entirely suspended for an appreciable period, flowering continues throughout the growing-season and, in mild years, seed may be ripening throughout the winter. *Hevea* seeds are short-lived, so that prolonged storage is not possible, and the planting of nurseries is, in general, limited by the availability of fresh seeds.

Plantation Management

Intercrops

The *Bulletin of the Rubber Research Institute of Malaya* for January and March, 1955, gives the following specifications for a good intercrop:

The intercrop should not grow as tall as *Hevea* and should have a different root system.

The intercrop should be tolerant of shade.

The intercrop should not be more susceptible than *Hevea* to the diseases they have in common.

Harvesting the intercrop should not damage the rubber roots, cause soil erosion, or damage the soil structure.

The intercrop should not be slow to mature, or, like coconuts, have a longer economic life than *Hevea*.

Intercrops listed in the above bulletin as useful under suitable conditions include: Liberian coffee, cacao, Manilla hemp, pineapples, tea, oil palms, sisal, pepper, ginger, gambier, derris, and kapok.

Plates 29(*a*), 29(*b*), and 30(*a*) show various crops interplanted with *Hevea*.

Cover-crops

In the beginning of rubber cultivation, clean culture was considered essential. A high rate of erosion resulted, and the use of cover-crops was soon adopted as the most promising method of controlling erosion. Now, the use of cover-crops is standard practice on rubber estates, and Young (1955) has given the following specifications for a good cover-crop:

(*a*) It should be easily multiplied, preferably by seed.

(*b*) The root system should be such that it does not compete with the rubber, yet has good soil-binding properties and does not require high-quality soils.

(*c*) Growth should be rapid and there should be abundant leaf, both in full sunlight and in shade.

(*d*) It should tolerate pruning or slashing.

(*e*) The cover should be resistant to drought, disease, and pests.

(*f*) Should be a good competitor and able to resist and suppress weed growth.

(*g*) Should be easily eradicated when required.

(*h*) Should be suitable for land reclamation and reafforestation.

(*i*) Should not form products which are toxic to the main crop (grasses are noted for this bad characteristic).

A single plant combining all or even a major portion of these qualities will be hard to find. Few plants are tolerant equally of shade and sun and, at the same time, highly competitive with other plants under both conditions, yet easily eradicated when required. It is necessary to content oneself with somewhat less than perfection, or to attain some degree of success by planting two or more covers (not necessarily at the same time) to meet varying conditions. For instance, *Pueraria phaseoloides*, one of the most popular of all cover-crops, is highly tolerant of sun and is particularly valuable as a cover in new plantings (Plate 31(*a*)). It is a vigorous competitor and drags down all competing weeds (Plates 30(*b*) and 31(*b*)) and even trees, including rubber itself if the cover is not controlled. However, *Pueraria* is not tolerant of shade, and must be replaced by a more shade-tolerant plant when the tree crowns come together. Wide alleys provide conditions suitable for *Pueraria* for several years longer than is the case with planting systems giving equal distances within and between rows.

Natural ground-covers such as that shown in Plate 32 are useful if kept under control, but most of the ground-covering plants that have been used are legumes. The power of fixation of nitrogen is considered a desirable character of these latter, and improvement of the soil is next in importance to erosion control. According to Young (1955), the important cover-crops in Ceylon are *Calopogonium mucunoides* (a creeping or climbing legume), *Centrosema pubescens* (a creeper or climber), *Desmodium ovalifolium* (a semi-prostrate legume), *Mimosa inermis* (said to be a thornless variety of *M. invisa*, and having a prostrate habit), *Psonchocarpus palustris* (a creeper or climber), *Pueraria phaseoloides* (a vigorous creeper), *Stylothanthes gracilis* (a semi-erect plant), *Crotalaria anagyroides* (an erect, tall-growing annual), *Flemingia congesta* (an erect, much-branched plant growing to about 6 ft.), and *Tephrosia candida* (a strong-growing, hardy shrub).

Nutrition

Fertilization in the nursery is designed to ensure that as many of the seedlings as possible will reach buddable size rapidly and uniformly, and will have succulent bark that will slip easily in the budding operation. A suitable rate of fertilization per square metre would be: a single application of 200 gm. of rock phosphate (25 to 28 per cent P_2O_5, 40 to 45 per cent CaO), plus two applications of 5 gm. each of ammonium sulphate (20 to 21 per cent N_2), and 5 gm. either of double superphosphate (36 to

42 per cent P_2O_5) or of ammonium phosphate (16·5 per cent N_2, 20 per cent P_2O_5). In the case of soils deficient in potash, 3 gm. of muriate of potash should also be added when the nitrogen fertilizer is applied.

In the field, fertilizer is applied on an individual tree basis. The following rates are characteristic: at 1 month and 6 months after transplanting, 24 gm. of ammonium phosphate each; at 1 and 1½ years, 50 gm. of the same salt; at 2 and 2½ years, 100 gm.; at 3 and 3½ years, 200 gm.; and at 4 and 4½ years, 250 gm. If the soil is deficient in potash, muriate of potash may be added at the following rates: at 1 month and 6 months, 12·5 gm.; at 1 and 1½ years, 25 gm.; at 2 and 2½ years, 50 gm.; at 3 and 3½ years, 100 gm.; and at 4 and 4½ years, 125 gm.

In old plantings, the use of rock phosphate has been recommended for improving the growth of the cover-crops as well as for maintaining the vigour of the rubber trees and promoting the renewal of bark of trees in tap. Fertilizers containing potassium are used where it has been determined that the soil is deficient in potassium.

Disease and Pest Control

The control of diseases and pests is an important function of estate management. Many diseases attack *Hevea*, but the majority of them are of minor importance as they are restricted in spread, lead to little mortality, and require little in the way of control. Several have seriously affected stands of *Hevea* in localized areas, and a few have resulted in epidemics of serious proportions. Pest damage has proved serious in some localities and has required control measures, but has not proved a limiting factor in rubber cultivation. Diseases of the *Hevea* rubber tree, and the chief pests that have been encountered in the Far East, have been described by Petch (1921), Steinmann (1925), and Sharples (1936). Diseases occurring on *Hevea* in its native habitat in Brazil have been described by Weir (1926).

Root Diseases. The important root diseases of cultivated rubber in the East include black root-rot caused by *Xylaria thwaitesii*, brown root-rot caused by *Fomes lamaensis*, *Helicobasidium* rot caused by *Helicobasidium compactum*, red root-rot caused by *Ganoderma pseudoferreum*, rootcollar rot caused by *Ustulina maxima*, smelling foot-rot caused by *Sphaerostilba repens*, and white root-rot caused by *Fomes lignosus*. These diseases are not specific for rubber, and may spread by, or through, other plants. Their control depends largely on the early discovery of centres of infection, destroying the infected plants, and isolation of centres of infection by trenching to avoid further spread. In replanting, the importance is stressed of completely removing the old roots wherever a centre of infection is found.

Diseases of the Stem and Crown. The aerial portions of the *Hevea* tree are attacked by numerous pathogens, mostly of minor importance but some of great significance. In general, it is convenient to divide these afflictions into those of the stem, of branches, of bark, and of leaves. One pathogen, *Phytophthora palmivora*, attacks all of the aerial parts and causes leaf-fall, twig dieback, and bark canker. These symptoms are all the manifestations of a single disease that has been serious in isolated instances in the East, universally present throughout the tropics, but not a major disease of *Hevea*. Manis (1954) reported a severe epidemic of leaf-fall, twig dieback, and bark canker at Los Diamantes, Costa Rica.

The most serious bark diseases are those of the panel, as these diseases affect the yield and commercial life of the tree directly. Black stripe, caused by *Phytophthora palmivora*, and mouldy rot, caused by *Cerastostomella fimbricata*, are the most serious of them. These diseases are highly infectious under suitable conditions, and great care must be exercised to prevent their spread. The infection may be carried either by the tapping knives or by wind-borne spores. Fungicidal-paste treatments are effective, but must be applied in the early stages of infection, or the penetration of the fungus will carry it below the sphere of effective action of the fungicide.

Pink disease, caused by *Corticium salmonicolor*, attacks the bark of branches and requires treatment. Small branches are cut off, while the affected bark of older branches is pared away and the clean wood and bark around the infection treated with a fungicidal paste.

The South American Leaf-Blight. In addition to *Phytophthora omnivorum*, several other fungi are the causes of mild to severe infections of the leaves. South American leaf-blight, caused by *Dothidella ulei*, is potentially the worst disease of *Hevea* rubber trees that is known. Only the fact that this disease is confined to the American tropics, where cultivated rubber is relatively unimportant, makes possible the continuation of the plantation industry of the East as it is today. Fungicidal sprays have proved effective in nurseries and young plantings, but are considered impracticable for use in mature rubber plantings. Planting in the Americas has been possible only by top-working the susceptible, high-yielding clones with disease-resistant selections. None of the planting material used in establishing millions of acres of plantations in the East has any appreciable degree of resistance to the disease.

Leaf-blight of *Hevea* has been studied by Stahel (1917), Rands (1924), and Langford (1943, 1945). Langford developed a satisfactory method of controlling the disease in nurseries, but did not consider the spraying of field plantings to be feasible. In the Americas, there were no high-yielding clones other than the disease-susceptible ones from the East. Overbudding the high-yielding but susceptible clones with disease-resistant selections proved feasible, and this procedure became the basis for planting rubber in the American tropics.

'Oidium' Mildew. Mildew caused by *Oidium heveae* has not proved to be as deadly as leaf-blight, but has been especially serious in Ceylon, where control measures are necessary. When the disease affects the young,

newly developing leaves, the leaflets become discoloured and their margins curl and crack. White velvety patches develop on the undersides of the leaflets, which drop one by one, leaving the petiole still attached. Practical control of the disease has been attained by spraying with Bordeaux mixture or dusting with sulphur. One clone, LCB 870, has proved highly resistant to the disease; but it is inferior in yield and has not proved useful as a top-working clone, being extremely susceptible to wind damage.

Other Leaf Diseases. Species of *Helminthosporium*, *Scoletotrichum*, and *Phyllosticta* cause minor leaf-injury in the East, and species of *Alternaria*, *Pellicularia*, and *Catacauma* in the Americas. Carpenter (1951) showed that *Pellicularia* could be controlled in nurseries by spraying, and that this disease did not appear to be serious in mature trees. In his investigations of the disease, Carpenter found a great many disease-resistant clones.

Pests. Pests include both mammals and insects—the elephant in the East and the lace-bug in Brazil. Elephants, monkeys, deer, wild pigs, porcupines, rats, and Indonesian hares, have been reported as pests in rubber plantings. In Central America, a local rodent, the taltuza, has been the cause of extensive injury in nurseries and even in young field plantings. This rodent attacks the roots of the trees and, in nurseries, may make its way underground along an entire row of seedlings, cutting off each just below the ground-level.

Snails and Slugs. Snails and slugs cause considerable damage in rubber plantings. The giant snail, *Achatina fulica*, has become a particularly bad menace since it reached the rubber-growing areas of the East in 1911. Although these snails feed mostly on leaves and buds, they cause extensive damage to the bark of young rubber trees, often necessitating replanting.

Two species of slugs, *Mariaella dussumieri* and *Paramarion martensi*, cause serious damage in rubber plantings. They feed primarily on the buds—first the terminal and then the side buds—as they develop. Control of snails and slugs is obtained by hand-picking, clean-weeding, and the use of poisons. Use of metaldehyde and rice bran is effective to bring large populations quickly under temporary control. Permanent briquettes, containing metaldehyde and rice bran mixed with lime and cement, are useful for maintaining control.

Insects. Several insects attack *Hevea*. Termites attack the roots, make channels over the tapping panels, and build nests in the crotches of the trees. Bark borers gain entrance to the trees through injuries caused by lightning or disease, and can thus be controlled by adequate inspection and treatment. Leaf-cutting ants attack the leaves, as do also lace-bugs in Brazil. Aphids do damage in the nurseries and other plantings. The control of termites and leaf-cutting ants is difficult, but constant effort in seeking out the nests and applying suitable poisons can keep them in check.

Plant Parasites. Plant pests cause minor damage. Mistletoes such as *Loranthus globosus*, *L. pentandrus* and, less commonly, *Viscum orientale*, are found on rubber trees. The seeds are spread by birds and germinate almost anywhere. On a suitable host, such as *Hevea*, the haustoria of these semi-parasites penetrate to the cambium and young wood. Several non-parasitic epiphytes are found on rubber trees, including ferns, species of *Dischida* (pigeon orchids), and *Ficus annulata* (one of the strangling figs). The chief harm of these vegetable pests is the breakage of the branches by their weight. Control of plant pests is obtained by cutting off branches attacked by mistletoes, and by pushing off the epiphytes with long poles as soon as they are observed.

Replanting

The economic life of a rubber plantation depends not only on the age of the trees but also on their yield, on the cost of rubber production, and on the cost of replanting with superior trees. The replacement of old, low-yielding, unhealthy plantings with high-yielding stock is a matter of simple economics for the owner of a large plantation, but is difficult for the smallholder with no other source of income.

The need for replanting large acreages of uneconomic rubber has been recognized not only as a personal problem of the owners but also nationally of Malaya, Indonesia, and other countries of the Far East that are dependent on revenue from the export of rubber for a significant portion of their national income. Rubber cultivation gives employment to many individuals; and supporting services, such as local shops, and industries catering to the needs of the plantation staff and labour-force, give employment to even more.

Thousands of acres of old rubber trees have reached the stage where it is no longer profitable to harvest the rubber, and many of the existing areas could be replanted with rubber varieties that would yield more than twice the rubber currently obtained. Governmental subsidization of replanting has been adopted as a national policy in Malaya, where it is supported by export taxes on the rubber. This subsidy is paid yearly, and each year's subsidy is based on the progress made in replanting. Thus there is an annual income to repay, partially, the cost of replanting. For the smallholder who does his own replanting, the subsidy serves as a source of income to replace that lost when the old trees are removed.

RUBBER PRODUCTION

The Initiation of Tapping

When the rubber tree has reached a circumference of 18 to 22 in. at about 3 ft. from the ground (or from the bud-union in the case of buddings), it is large enough to be tapped. Not all of the trees in a planting reach the tapping size at the same time, and tapping is usually started when some 50 to 70 per cent of the trees are of the prescribed size, only those trees that have reached tapping size are brought into tap, the remaining trees being added as they become sizeable.

Recommendations of the Rubber Research Institute of Malaya

The Rubber Research Institute of Malaya (RRIM) has recently (1957) reviewed the available information on the opening of young trees for tapping. The following considerations formed the basis for their recommendations for the initial tapping of young rubber trees.

1. Alternate daily tapping of clonal seedlings through a half-spiral cut usually results in a high incidence of brown bast.

2. Tapping towards a junction of bark of different ages leads to a severe drop in yield.

3. Bark of the second renewal is often thin and yield from it is disappointing.

High-yielding trees are more prone to brown bast * than low yielders. The yield capacity of individual trees (be it seed or 'seedlings', clonal or unselected) varies greatly. If brown bast cases occur mainly amongst the highest yielding trees, it follows that the proportion of crop lost through resting the affected trees is higher than the proportion of the trees rested. A brown bast incidence of from 15 to 20 per cent could mean a loss of about 40 per cent of the crop if only the highest yielders are affected.

When clonal seedlings are tapped every third day, the brown bast incidence rarely amounts to more than five per cent. The immediate loss in yield from this system of tapping is known to be from twenty to twenty-five per cent as compared with alternate-day tapping. This loss is thus less than the potential loss due to brown bast incidence with a higher intensity of tapping.

Clones recommended for planting are mostly resistant to brown bast. Tapping every third day instead of on alternate days leads to better growth, and so a reduced rate of tapping in the early years has been advocated. In periods of high prices, 100 per cent tapping (alternate day) would appear best, but when prices are down and the return per tapper is more important than the yield per acre, the tapping cut might be restricted to 67 per cent intensity (every third day).

Based on the above considerations, RRIM has made the following recommendations:

Seedling Trees. A half-spiral cut should be opened about 20 in. above ground-level when 70 per cent of the trees in the area to be tapped have reached a girth of 22 in. at that height. The trees should be tapped every third day.

* Brown bast is a physiological disorder of the bark of the tapping panels of *Hevea* trees that results when the trees are over-tapped. Some trees are quite susceptible to brown bast and become affected even with moderate tapping. Others are resistant to brown bast and remain healthy even with comparatively heavy tapping.

The second and subsequent panels are opened 40 in. above ground-level. Tapping every third day is recommended throughout, but if it is decided to tap on alternate days after some four years of tapping every third day, the trees should be brought back to tapping every third day as soon as more than 10 per cent of the stand shows signs of brown bast. The length of the tapping cut of partially dry trees should be reduced when tapping is on alternate days. Dry trees being tapped every third day should be rested for six months.

Budded Trees. A half-spiral cut should be opened at between 50 and 60 in. from the union when 70 per cent of the trees have reached a girth of 20 in. at the height of opening. Tapping should be on alternate days throughout, except on clone Glenshiel 1 (and other clones suceptible to brown bast) which should be tapped every third day. Subsequent panels should be opened at the same height as the first.

Tapping Equipment

The Tapping Knife. Only very simple equipment is needed for tapping a rubber tree. The most important piece of this equipment is the tapping knife (Plate 33(*a*)), which has a wooden handle about 6 in. long to which the blade is secured with rivets. The knife is adapted from the farrier's knife, used in trimming horses' hoofs, and its V-shaped cutting edge is designed to make a narrow channel in the bark of the tree. This serves both to open the latex vessels and to provide a channel for the latex. For thin-barked budded trees, the V-bend at the end of the knife blade must be quite acute to make it possible to cut a good channel in the bark. A more gradual bend is allowable for tapping 'seedlings' that have thicker bark.

The Spout. At the lower end of the tapping cut, a vertical groove is cut into the bark of the tree to conduct the latex to a spout (Plate 33(*b*)) that empties into the cup. This spout consists of a thin strip of metal with one end rounded and the other squared for driving into the tree, the strip being cupped lengthwise to form a trough for the latex. By pressure from the handle of the tapping knife, it is driven into the bark of the tree far enough to be stable, but without exerting sufficient force either to bend the point of the spout, or to drive it unnecessarily deeply into the tree.

The Latex Cup. The latex cup (Plate 33(*b*)) has a capacity of 300 to 500 cubic cm. and may be of ceramic, glass, metal, or other comparable material. Aluminium is very satisfactory but is often subject to pilferage. Smallholders often use the half-shells of coconuts, the halves of gourds, or similar receptacles that may be available without cost, or at much less cost than aluminium or ceramic cups. Any cup used must be easily kept clean, if a high-grade latex is to be produced.

The Cup Hanger. A wire hanger (Plate 33(*b*)) to hold the latex cups on the tree is made from a short length of heavy galvanized wire. The length of the wire depends on the girth of the tree, for it should extend roughly half-way around the tree. The hanger is formed with a loop at its centre large enough to hold the tapping cup. The ends of the wire are bent, like the jaws of tongs, to grip the tree.

Ammonia. When necessary, particularly in tapping young trees, the tapper is furnished with a bottle of dilute (about 2 per cent) ammonia, and a few drops are added to each cup at the time of tapping—to prevent pre-coagulation of the latex. A stock solution may be made by passing ammonia gas into water very slowly until there is an increase of 10 lb. in weight for each 90 lb. of water. Adding four parts of water to each part of the stock solution gives the desired 2 per cent solution for field use.

Tapping

Rubber is obtained from the tree by a system of tapping that consists of paring off a small amount of bark—just sufficient to open up the ends of the latex vessels. Excessive consumption of the bark is avoided to conserve it for future rubber production, and there is considerable variation with regard to the exact area of the tree under tap at any one time and also in the frequency of tapping. The standard tapping system involves a single cut on a half of the circumference of the tree, which is then reopened on alternate days, a small shaving of bark being pared off each time (*see* below). Sundays, holidays, and morning rains, may interfere with the tapping so that, instead of the 180 tappings annually that would be expected with alternate-day tapping, it is usual to count on 160, or fewer, tappings per year.

The Tapping Task. The acreage to be tapped is subdivided into 'tasks', each representing the area handled by a single tapper in one day. Depending on local customs, planting densities, yields, and distances from the factory, the daily task of each tapper varies from 250 to 400 trees. With alternate-day tapping, each tapper can handle two tasks and, with periodic tapping, such as daily tapping for a month followed by resting the trees for two months, he might handle even more tasks, depending on the relation of the period of tapping to the period of rest.

Laying Out the Tapping Cut. A flexible template is used to mark the limits of the tapping panel on the tree and the desired slope of the tapping cut. It is convenient to mount the template on a rod cut to the length indicating the height of the lower end of the tapping cut. The template extends upwards and to the left when the rod is placed vertically against the tree.

The latex vessels in the bark of *Hevea* do not ascend vertically but have a slight slope to the right. To intercept a maximum number of latex vessels, the tapping cut is sloped upwards to the left at an angle of about 30° above the horizontal (Plate 33(*b*)). The limits of the panel and the location of the cut are indicated, in laying out the panel, by shallow grooves that can conveniently be made with a tapping knife. In some instances, shallow nicks may be made in the groove that marks the left margin of the panel. The grooves show the distance the tapping cut moves down the trees each month.

Starting the Cut. The tapping cut is opened along the mark made in laying out the panel, and a vertical groove is made in the bark at the lower end of the tapping cut. This vertical groove is to direct the latex to the spout that is driven into the bark about 4 in. below the lower end of the tapping cut. The cup hanger is fastened on the tree and the cup mounted to receive latex from the spout.

Some five tapping cuts are required to bring the cut to the correct depth and during this period the yield of latex is low. In the first tappings, the latex may be too thick to run the full length of the cut. The highest concentration of latex vessels in the bark is near the cambium layer, and as many of these vessels as possible must be cut to get maximum yields; but cutting too deeply results in wounding of the cambium. As the optimum depth is reached, it is possible to detect the delicate green of the cambial layer; then, only about a millimetre of uncut bark remains.

Thereafter, tapping involves merely the reopening of the cut, on each tapping day, by paring off a small shaving of bark. This operation results in the bark being gradually removed downwards. The initial cut is made at a height of about 3 ft. from the ground in the case of 'seedlings', or a similar distance above the bud union in the case of budded trees. The tapping cut progresses down the tree at a rate of 8 to 12 in. a year, and thus a period of from three to four years is required to reach ground-level (or the bud union) on the first panel.

The Tapping Operation. The tapper first removes the dried strands of rubber from the spout, vertical channel, and tapping cut of the tree. Standing with his right arm next to the tree, he starts the new cut by pushing upwards with the tapping knife and cutting a thin shaving from the upper end of the tapping cut to start the flow of latex, cutting with the upper edge of the V groove at the end of the knife. He then draws downwards with the knife and, with a series of short, quick strokes, pares off the thinnest possible shavings of bark.

On finishing the cut, the tapper removes any bark shavings that may have fallen onto the spout or into the cup, adds the ammonia (if any is being used) to the cup, and hurries on to the next tree. Tapping is started by 6 in the morning and finished by 9.30 in the morning.

Brown Bast. Overtapping of trees, particularly of 'seedlings', leads to the development of a physiological disease known as 'brown bast'. Reducing the intensity of tapping, either by making fewer tappings or by confining the cut to a smaller fraction of the girth of the tree, reduces the incidence of brown bast. In the selection of clones for propagation and use on plantations, trees that were highly susceptible to brown bast were rejected and the incidence of brown bast in clonal plantings is, therefore, far less than in 'seedling' plantings.

Tapping Systems. Tapping systems vary, both with regard to the proportion of the surface of the tree that is being tapped and the frequency with which the tapping cut is reopened. Single cuts may vary from one-third of the circumference of the tree to a full spiral. Multiple cuts have been used for slaughter-tapping, to obtain the maximum yield from trees that are to be cut down before replanting, and have lately been given consideration as possible for normal tapping operations. Tapping may be conducted daily, alternate daily, every third or fourth day, or may be periodic. In periodic tapping, trees are tapped frequently (usually daily) for a given period and are then rested for an equal, or different, period. There are various merits in the different tapping systems, including ease of supervision or record-keeping, but the chief effort has been to develop a system that will give maximum yield with minimum injury to the tree.

Classification of Tapping Systems. Dijkman (1951) has given a full exposition of the ingenious methods that have been devised in the East [cf. Guest (1939), de Jong (1939), Directeuren der Proefstations (1940)] to designate the various tapping systems and to relate the intensity of any given system to that of alternate-day tapping on a half of the circumference. This standardized nomenclature is essentially a fractional presentation based on (1) the proportion of a full spiral tap; (2) the frequency of tap; and (3) the relative intensity of the tap in relation to a half-spiral on alternate days. This last is considered to constitute the same intensity as a quarter-spiral tapped every day or a full spiral tapped every fourth day. For ease of presentation, the quarter-spiral tapped daily was adopted as the basic unit of intensity. This is a mathematical relationship rather than an expression of yield, as a doubling of the tapping intensity does not necessarily result in a doubling of yield. It does, however, in general represent the relative hardship imposed on the tree over any given period, and it represents the proportion of the surface of the tree involved in the tapping operation during that time.

Stimulation of Yield

Plant improvement through the development of high-yielding clones has been the most successful method of increasing rubber yields and reducing costs on the Eastern rubber plantations. Thus research has paid off in increased supplies of rubber, and may be expected to contribute materially to further increases. Yield increases have been sought also through other means, such as the use of fertilizers, increased tapping intensity, the stimulation of bark activity by various substances applied to the surface of the bark, and the injection of chemicals into the bark.

Increased Tapping Intensity. Tapping intensity has been a subject of great controversy since the beginning of plantation production of rubber, In the very beginning, tapping was very infrequent—being employed at first only to demonstrate the flow of latex. As the increase in flow from repeated tapping was demonstrated, tapping became more and more frequent, first on several cuts in a herringbone pattern, and later on a half-circumference single-cut daily or on alternate days. The increasing intensity caused the appearance of brown bast, however, and there was a swing towards more conservative methods.

Various systems of intensified tapping have been tried in war-time to increase production to the utmost, and in peace-time to drain all possible rubber from trees to be removed for replanting. Some of these tapping systems have given greatly increased yields and, in many cases, greatly intensified tapping schedules have been applied without undue increase in the incidence of brown bast.

'Slaughter-tapping' is the term used to indicate an all-out bleeding schedule to get maximum yields from trees that are to be removed before either replanting or replacement with other crops. It involves the length of cuts, the number of cuts, the frequency of tapping, and sometimes the depth of tapping. It is applied without regard to the welfare of the trees.

Increasing the intensity of tapping to obtain greater yields of rubber in war-time took the form mainly of multiple cuts on a single panel, sometimes known as high-low tapping, or tapping of more than one panel on a tree alternately—the so-called change-over system. A number of different intensities of tapping were tried and it was found that individual clones responded differently to the greater intensity of tapping. Surprisingly, brown bast did not become the problem in this intensified tapping as had been feared.

Increase in the intensity of tapping does not necessarily result in a corresponding increase in the cost of tapping. Increasing the length of cut does not result in a comparative increase in the time devoted to cutting, but in high-low tapping the time involved in making the high cut is greater than that involved in making the low cut, as a ladder must be carried along and used in making the high cuts.

In Viet-Nam, Campaignolle & Bouthillon (1955*a*) reported a method of increased tapping-intensity, instituted just prior to the onset of the dry season, that resulted in an increase in yields far in excess of the relatively small increase in tappings per year. This intensification consisted in tapping every third day (d/3, d/3) instead of on the first and fourth days of a seven-day cycle (d/3, d/4), for a period of three months prior to resting the trees in February and March, and resulted in the trees being tapped eighty-eight times during the year (instead of eighty-five times for the trees kept on the d/3, d/4 system). This change resulted in an increase of only 3·5 per cent in the number of tappings.

The over-all increase in yield attributed to the intensified tapping was reported as 24 per cent on the basis of grams of rubber per tree per tapping, or 40 per cent on the basis of yield of rubber per hectare. Twelve clones were included in the test, and there was a striking difference in the reactions of the various clones. Clones AVROS 152 and BD 5 gave no increase in yield per hectare and decreases of 12 per cent and 10 per cent, respectively, in yield per tree per tapping. Clone DJ 1 gave an increase of 83 per cent in yield per tree per tapping and 105 per cent in yield per hectare. All clones except AVROS 152 and BD 10 gave sizeable increases in yield during the year following this intensified tapping immediately before the rest period.

Injections of Copper Sulphate. There has also been research on the use of chemicals to increase the flow of latex. The use of copper sulphate injections into the bark of rubber trees has been tested extensively in Viet-Nam as reported by Campaignolle & Bouthillon (1956). Significant increases in yields were attributed to these injections. Annual or semi-annual injections of copper sulphate resulted in a continued yield at a rate above that of untreated trees though, in occasional years, a decrease in total yield was noted for the treated trees. Typical of the results was a test using two blocks of trees for which comparative yields were available for a period of four years prior to the initiation of the test. Injections of copper sulphate were made annually in block B in November of each year from 1950 to 1955. The yield records in kilograms of rubber per tree per year for 1947 through 1950, before injections were started, and for 1951 through 1955, after the injections were started, are shown in Table XI.

TABLE XI

COMPARATIVE YIELDS OF RUBBER IN KILOGRAMS OF RUBBER PER TREE PER YEAR BEFORE AND AFTER THE INITIATION OF ANNUAL INJECTIONS OF COPPER SULPHATE

Year	Block A Control Kgm.	Block B Treated Kgm.	Increase Kgm.	Remarks
1947	4·2	4·5	0·3	Production of the two blocks before treatment.
1948	5·4	5·5	0·1	
1949	5·3	5·7	0·4	
1950	5·3	5·8	0·5	
1951	4·9	6·5	1·6	Annual injection of $CuSO_4$ in the trees in Block B.
1952	5·0	6·0	1·0	
1953	4·2	5·6	1·4	
1954	3·3	2·4	− 0·9	
1955	4·1	5·4	1·3	
Total	21·5	25·9	4·4	For period of injections only.

Hormone Pastes. Appreciable increases in yield have followed the application of hormone pastes to the bark of *Hevea* trees, and the use of proprietary stimulants such as 'Stimulex' and 'Eureka' have increased rapidly both in Viet-Nam and in Malaya.

Baptist (1955) pointed out that the use of stimulants to increase the flow of latex is not new. As early as 1912, the practice of scraping the outer layers of bark from below the tapping cut was found effective, and smallholders later applied substances such as cow-dung and termite earth in order to increase both yield and bark renewal. In the third decade of the present century, mixtures such as 'Neubark' and 'Solar Vim' appeared on the market, but without much response from estates. In 1929–30, experiments with bark scraping and the application of nitrate of soda, wood ash, and cow manure were performed on several estates under the guidance of the Rubber Research Institute of Malaya. Yield increases were reported.

Baptist (1955), Baptist & Dejong (1955), and Dejong (1955) made detailed studies of various methods of yield stimulation and found several that led to a considerable increase in yield. In general, however, they found that, under conditions obtaining in Malaya, the stimulation was temporary and the trees soon returned to their former yields or somewhat less. These investigators were extremely cautious in the use of stimulants, except on mature trees and those marked for early replanting. Treatments that were included in the tests reported by the above-mentioned authors included light and heavy scraping of the bark below the tapping cut and above the tapping panel, injections of copper sulphate, bark treatments with oils (particularly palm oil) below the tapping cut and with hormonal growth-regulating materials including 2,4-D (2,4 dichlorophenoxy acetic acid) and 2,4,5-T (2,4,5-trichlorophenoxy acetic acid). The oil and hormone treatments were applied, below the tapping cut, to a narrow band of scraped or unscraped bark situated above the tapping panel, and to a narrow band of renewing bark, just above the tapping panel, which represented the area tapped during the preceding month.

These authors reported significant but temporary increases in yield after light scraping of the bark below the tapping cut, and in response to the treatment with hormones both above and below the tapping cut. Increases following treatment with 2,4,5-T exceed those following treatment with 2,4-D. Significant increases in the rate of bark renewal were noted in several instances, particularly when the bark immediately above the tapping cut was treated with oils or hormones. This increased rate of bark renewal was not always desirable, as it consisted of non-rubber-bearing tissue. Dejong (1955) states:

> A similar but more exaggerated picture is obtained when the yield stimulant is applied above the tapping cut. Under the conditions of our experiments the thickness of one-year-old renewed bark on the treated trees was nearly three times that on control trees, but all of the extra thickness is made up of undifferentiated parenchymatous tissue which, in its outer layers, has become hardened by excessive stone cell formation.

Levandowski (1958) found that in Liberia there was a significant and constant difference in the response of particular clones to bark stimulants.

Collection, Coagulation, and Packaging

Collection

After finishing tapping, the tapper returns to his trees to gather the latex. He carries a large receptacle, which may be a pail expressly designed for carrying latex, or may be made from a kerosene tin or comparable container suitably furnished with a handle to facilitate carrying. Two of these receptacles can be balanced on the ends of a pole for carrying on the shoulders.

In small plantings and where the distance to the factory is not large, the tapper is expected to carry the latex to the factory. On larger estates, a system of collection points is set up to receive the latex from the field and, in at least one instance, trolley wires have been installed to assist in transporting the latex to the collection station. A careful record of yields is kept, for each tapper and for each area, at the collection point. This primary record is the unit for cost accounting for the estate.

In collecting the latex, the tapper empties the contents of the tapping cup into his latex pail and wipes out the tapping cup with his finger, extracting as much of the latex as possible and leaving the cup clean. The cup is then placed upside-down on the cup hanger (cf. Plate 33(*b*)) and the tapper continues on his way. Cleanliness of the utensil is highly desirable, and even though it is not possible to have the cup cleaned thoroughly each day but only periodically, it is necessary to have a special force of cleaners to wash the utensils and remove all accumulated dirt and rubber.

If the latex is delivered at a collection point, it is often necessary to add a small quantity of ammonia to avoid pre-coagulation of the latex—particularly if it is from young trees. Lumps of rubber that form in the latex before it arrives at the factory must be removed and milled separately into off-grade rubber.

Bulking of the Latex

After recording the yields, the bulking of the latex is the first important task of the factory (Plate 34(*a*)). The production of a standard clean rubber is the aim of all estates. The rubber from the various fields and clones is quite variable, and the small producer cannot do as good a job as the large one of producing standard qualities of rubber because he is restricted to the types produced by comparatively few trees. His chances of equalizing the changes attributable to seasonal variation in rubber-content are limited in comparison with the opportunity of the manager of a large estate, who can mix latex from many clones and from different areas of the plantation.

The First Straining

As the latex is assembled, it is strained for the first time. The strainer used has a comparatively coarse screen and is designed to remove the larger particles such as bark shavings, twigs, leaves, or other sizeable objects that find their way into the latex. A suitable screen may be made of aluminium plate with 1/16-in. perforations spaced 1/8-in. from centre to centre.

The Rubber-content of the Latex

Knowledge of the rubber-content of the latex is important to the producer. Task and field records depend upon the yield of rubber rather than of latex. The percentage of rubber in the latex varies from field to field and from day to day. Large errors in the estimation of yield would result from using any standard measure of relationship of rubber to latex.

It is necessary to standardize the preparation of rubber in the factory so that a standard quality is produced. The first requisite in standardizing the factory processing is to dilute the latex to a standard consistency. To do this, it is necessary to know with some accuracy the rubber-content of the latex. Chemical tests requiring trained assistants or much time are undesirable. The addition of ammonia or other preservatives or anti-coagulants at the time of tapping also adds a measure of difficulty in determining the rubber-content of the latex.

Determining the Rubber-content of Latex

The most accurate method of determining the rubber-content of latex is by drying or coagulating a sample and making a chemical analysis of the dried gum. The chemical analysis is involved and time-consuming, and is not suited to day-to-day estate operation.

The simplest determination of rubber concentration that has been developed is to measure the specific gravity of the latex and estimate the rubber-content on the basis of the relative specific gravity of the major constituents. The rubber globules as they occur in latex were reported by de Vries (1926) to have a specific gravity of 0·914, the serum having a specific gravity of 1·020 (1·016–1·025). The specific gravity of the latex varies with the percentage of rubber, the percentage of water, and the percentage of non-rubber constituents. None of these is constant, and variation may be brought about by cultural treatment, seasonal variation in rainfall and temperature, tapping intensity, and many other conditions that affect the flow of latex. These factors do not affect all of the latex constituents in the same manner, serum constituents often being increased by factors that cause a decrease in the rubber-content.

The specific gravity of the latex bears a general relation to the rubber-content of the latex and can be used for making a rough estimate of the rubber-content. Special hydrometers have been developed and marketed under proprietary names such as 'Metrolac', 'Latexometer', etc. Some of these instruments are marked to read in pounds of latex per gallon, whereas some read in per cent of rubber. They are useful and widely used, but they are liable to errors which make their use questionable in estimating yields where a small miscalculation of rubber-content would be magnified into a large one in the estimation of long-term or large-area yields.

Dilution and Second Straining

Following the first bulking and straining of the latex, a reading is taken of the rubber-content of the latex which is then diluted with water to a concentration of from 12 to 15 per cent. After a short wait for the precipitation of heavy particles of sand, the latex is strained a second time—on this occasion through a fine screen (60 mesh) which will catch the small particles of dirt and trash that passed through the coarse screen. The second screen can be made of 26-guage monel metal or other highly-resistant material with No. 0 round perforations. It should not be made of brass or other material having copper as a component, as traces of copper in rubber are deleterious.

Market Types and Grades of Rubber

Natural rubber is marketed in several forms and many grades. Basically, the chief forms are smoked sheet, crepe, and latex. The standard grade for comparisons of price or quality is No. 1 ribbed, smoked sheet (RSS 1). The smoked sheet and crepe are each marketed in several forms or grades, and the production of each is attended by the formation of a certain percentage of scrap that is prepared separately and marketed as lower-grade rubber. Estate scrap and native rubber are often remilled into lower grades of blanket crepe that are marketed in a variety of grades. Whole rubbers prepared by spraying the latex against heated, revolving disks have special properties, as do also the super-grades of smoked sheet and crepe that are prepared with particular emphasis on cleanliness to obtain a small premium in value. Technically classified rubber is tested and marked as to milling quality in the country of origin. Superior processing rubber, developed by the Rubber Research Institute of Malaya, is a new type which is partially vulcanized before coagulation.

Concentrated Latex

Rubber intended for sale as latex is handled in much the same manner as other latex up to the point of dilution. At that point, the latex must be concentrated to reduce shipping costs to overseas markets. Fresh latex has a rubber-content of from 30 to 35 per cent that must be increased to 60 to 70 per cent. This concentration of the latex is accomplished by centrifuging in a modified cream separator, by creaming with alginates or other suitable creaming agents, or by evaporation in the presence of protective colloids.

Coagulation

The bulked, strained, diluted, and re-strained latex that is not to be shipped as latex is measured into coagulation tanks for the separation of the rubber. There is great variation in the methods of coagulation and particularly in the equipment used. Simple coagulation tanks can be made from a kerosene tin by cutting it lengthwise midway between the front and back to give two substantially equal tanks. More elaborate tanks may be constructed of concrete, with a porcelain lining and baffle plates to separate the coagulating latex either into limited slabs or as a continuous slab.

Hevea latex can be coagulated by many chemicals, the most commonly used being acetic and formic acids. Coagulation can be brought about quickly or may be induced to take place overnight. Quickly-coagulated rubber is harder and more difficult to work on the rolls than rubber that has been coagulated more slowly. If ammonia has been added to the latex, it is necessary to add sufficient acid to neutralize the ammonia as well as to coagulate the latex.

In using formic acid to coagulate *Hevea* latex, it is convenient to make up a stock solution of the acid with a concentration of four per cent formic acid. About 1 litre of this stock solution is needed to coagulate 100 litres of latex diluted to 12 per cent rubber-content. If ammonia has been added by the tapper, or at collection points, the amount of acid must be increased. With normal usage of ammonia, about 1·75 litres of the stock solution of the acid are needed to coagulate 100 litres of ammoniated field latex diluted to a 12 per cent rubber-content.

The acid must be added quickly and mixed thoroughly and promptly with the latex. Froth formed on the surface of the latex in this mixing must be skimmed off carefully to avoid its appearing as bubbles on the surface of the coagulated rubber. This froth contains rubber which is collected and coagulated separately for the production of lower-grade rubber.

Every possible sanitary precaution is taken in the coagulation of the latex, to avoid contamination and to keep the latex clean. Any bacterial infection may lead to the formation of bubbles; all 'foreign' objects appear as specks in the finished rubber, and all such defects lead to the downgrading of the rubber when it is marketed.

Sheeting the Rubber

The latex coagulates in a thick curd. If the correct amount of acid has been added, the serum will be clear and nearly free from rubber particles. A milky serum indicates that the acid has not been strong enough to bring about complete coagulation and that a portion of the rubber is being lost. If the acid has been too strong, the coagulum will be hard, brittle, and difficult to sheet.

After coagulation, the rubber must be passed through hand- or power-rolls to reduce the thickness sufficiently to assure adequate drying. The rubber is passed from six to eight times between the rollers, starting with the rolls from six to 8 mm. apart and gradually tightening them until a sheet not more than 2·5 mm. in thickness is obtained. The smallholder with only a single hand-mill must pass the rubber again and again through the one mill. On large estates with batteries of power-driven mills, the sheet is passed successively through the entire battery, coming out of the final rolls with the desired thickness.

The Marking Rolls

The sheet is passed through a marking roll after it has reached its final thickness, and sheeting is done in mills with smooth rolls. The sheet remains smooth, and is kept clean by being washed in water between each two passages between the rolls. The marking rolls are grooved to give a corrugated surface to the sheet. This rough surface facilitates the drying of the sheet, and many estates also have special groovings on the rolls to trade-mark their rubber.

Smoking the Rubber Sheet

Sheeted rubber is dried in a smoke-house (Plate 34(*b*)). There is a slight preservative action of the smoke that prevents deterioration of the rubber during the drying period of a few days to a week. The sheets of rubber are hung on poles in the smaller smoke-houses, or may be hung on racks on small trolleys for passage through the larger smoke-houses. It is desirable to keep the smoking to a minimum, to avoid having the rubber in the direct line of entrance of smoke into the smoke-house, and to prevent the tars from the smoke condensing on the ceiling of the smoke-house and dripping onto the rubber.

The temperature of the smoke-house is maintained below 50°C. and the smoke-house is well ventilated. The fire is kept low and not allowed to burn with a detectable flame. Sheet rolled to a thickness of 2·5 mm. should dry under these conditions within four days. A sheet 5 mm. in thickness requires almost four times as long to dry. The rubber is clear, without opaque spots, and translucent when it has reached the correct degree of dryness. It can then be withdrawn from the smoke-house and is ready for grading and packing for shipment.

Crepe Rubber

Rubber is prepared in the form of crepe by running the sheeting rolls at unequal speeds to impart a tearing action. The crepy texture of this rubber facilitates drying without the need for smoke. Small quantities of a bleaching solution, such as sodium sulphite, may be added to the latex in making crepe. These help to keep the crepe light in colour and so increase its desirability for use in coloured goods.

The crepe is not dried in the smoke-house but in special houses that have controlled heat and no smoke. Because of its texture, crepe rubber of any given thickness dries more quickly than smoked sheet of the same thickness. Crepes of greater thickness, such as those used for shoe soles, are made by rolling together several thicknesses of the thinner crepe.

Off-type Rubbers

Slabs and other off-type rubbers produced by smallholders through the use of alum as a coagulant, or by natural coagulation, are normally sold to remillers who work the rubber on washing rolls to eliminate the dirt and trash and clean up the rubber as much as possible. The resulting rubber is sheeted out in the form of blanket crepe varying from light to dark brown. The rubber is sold in competition with the plantation off-grades such as 'tree lace' gathered daily from the tapping cuts, the ground scrap from the base of the tree, and the pre-coagulated rubber strained from the latex on its arrival at the factory. Even in these off-grades, the better grades of clean pre-coagulum are kept separate from the dirty bark crepe.

Grading Smoked Sheet

Before packing for shipment, the rubber is inspected carefully for defects or blemishes. This is accomplished by holding the rubber against the light, when the most obvious defects will at once be apparent. The use of a pair of shears to cut out the obvious spots or pieces of dirt or trash as a means of preserving the grade of otherwise excellent rubber is usual, and the rubber cut out is sold as off-grade.

Klippert (1946) listed the more obvious defects in smoked sheet as follows:

1. Small bubbles along the edges of the sheet are usually due to insufficient mixing of the acid with the latex when coagulating or, sometimes, to an insufficient amount of acid having been used to coagulate the latex.

2. Small bubbles about the size of pinholes occurring in clusters all over the sheet are caused by dirty utensils or coagulating pans.

3. Irregular small bubbles and small whitish specks all over the sheet are caused by pre-coagulation.

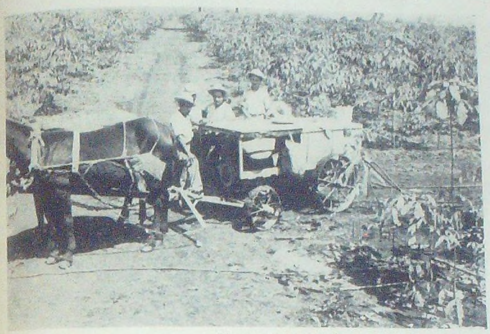
4. Large bubbles and blisters are almost always caused by too much heat in the smoke-house.

5. Small particles of sand in the sheet are due to coagulating the latex before the sand has a chance to settle in the dilution tank.

6. Dirt and bark in the sheet is the result of insufficient or careless straining of the latex, or of carelessness in the handling of the latex after it has been strained.

Shipment of Latex

Plantation latex is normally shipped in drums, tanks, or tankers. After being carefully bulked, strained, and concentrated to a rubber-content of from 60 to 70 per cent, the ammonia-content of the latex is adjusted to some 0·7 per cent for shipment. The containers in which the latex is shipped must be carefully and thoroughly sterilized, and it is usual to coat the insides of large tanks or tankers with paraffin to avoid



Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Horse-drawn power equipment used to protect nursery plants of *Hevea* from South American leaf-blight.

(*b*) A rootstock nursery of seedlings of *Hevea brasiliensis*.

PLATE 24

(*a*) Cutting a bud-patch from a stick of budwood.

(*b*) Removing the wood sliver from the bud-patch.

Photograph by permission of ARS, U.S. Dept. Agric.

Successfully budded seedlings cut back and ready for transplanting.

PLATE 26

Photographs by permission of ARS, U.S Dept. Agr.

(*a*) Using black friction tape to wrap a bud-patch inserted in the bark of a high-yielding clone above the head of the budder.

(*b*) Banana-leaf sheaths used to protect bud-patches from the sun.

PLATE 27

(*a*) A young three-component tree with a bud from a disease-resistant clone inserted high up in the bark of a high-yielding clone budded onto a 'seedling' rootstock.

Photographs by permission of ARS, U.S. Dept. Agric.

(*b*) Cutting back a successfully top-budded three-component tree.

PLATE 28

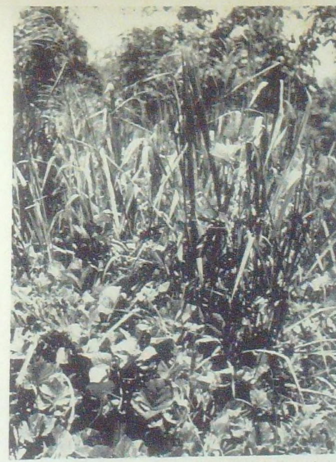
Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Small farm (one-family) *Hevea* interplanted with bananas.

(*b*) *Hevea* interplanted with cacao. Further, fast-growing leguminous shade-trees are inter-planted with the cacao, and a *Pueraria* ground-cover is planted between the rows of trees.

PLATE 29

(*a*) 'Seedling' rubber interplanted with sugar cane. Such plantings are highly susceptible to accidental or intentional fire damage. Seedlings 10-12 ft. high.



Photographs by permission of ARS, U.S. Dept. Agric.

(*b*) Elephant grass is difficult to control by cultivation but is being smothered out by aggressive *Pueraria*.

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Top-budded trees of *Hevea brasiliensis* with a luxuriant ground-cover of *Pueraria*.

(*b*) Young planting of *Hevea brasiliensis*. Natural vegetation in the alleys is being dragged down by *Pueraria*, which is kept under control in the rows.

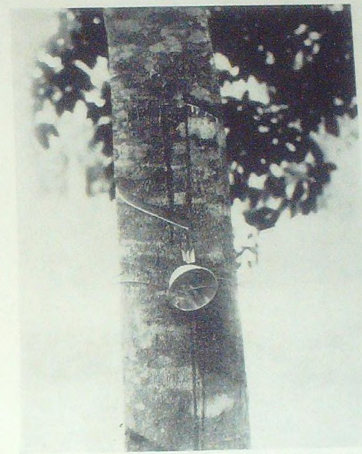
PLATE 31

Photograph by permission of ARS, U.S. Dept. Agric.

An excellent natural ground-cover in a closely-spaced planting of *Hevea brasiliensis.*

PLATE 32

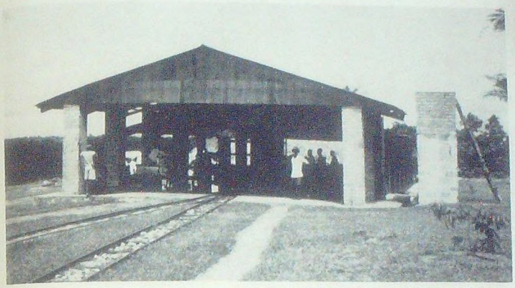
(*a*) A tapping knife being used to reopen a tapping cut on a tree of *Hevea brasiliensis*.



Photographs by permission of ARS, U.S. Dept. Agric.

(*b*) Tapping cut, latex spout, latex cup, and cup hanger on a tree of *Hevea brasiliensis*.

PLATE 33



Photographs by permission of R. D. Rands

(*a*) An estate rubber factory for the preparation of smoked sheet.

(*b*) Estate smoke-house for the preparation of smoked sheet.

PLATE 34

Photographs by permission of H. M. Tysdal

(*a*) A cultivated field of guayule, *Parthenium argentatum*. Guayule planted in rows 30 in. apart.

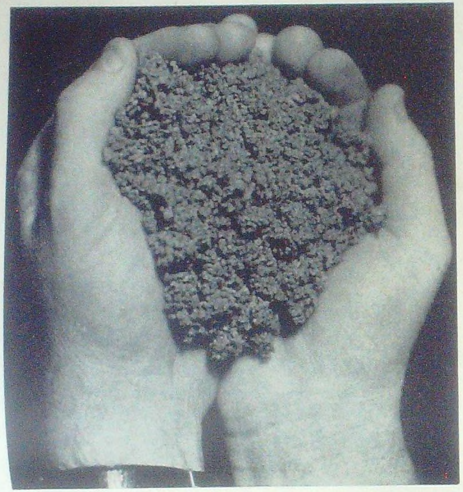
(*b*) A sparse stand of guayule, *Parthenium argentatum*, on a limestone ridge in Texas. It is intermixed with some larger plants.

PLATE 35

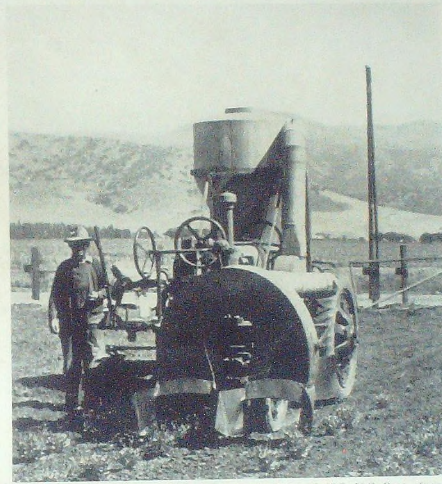
Photograph by permission of ARS, U.S. Dept. Agric.

Labourers sitting on wheeled supports used in weeding guayule nurseries. The duckboards used as tracks can be seen between the beds.

PLATE 36



... extracted in the pebble mill and



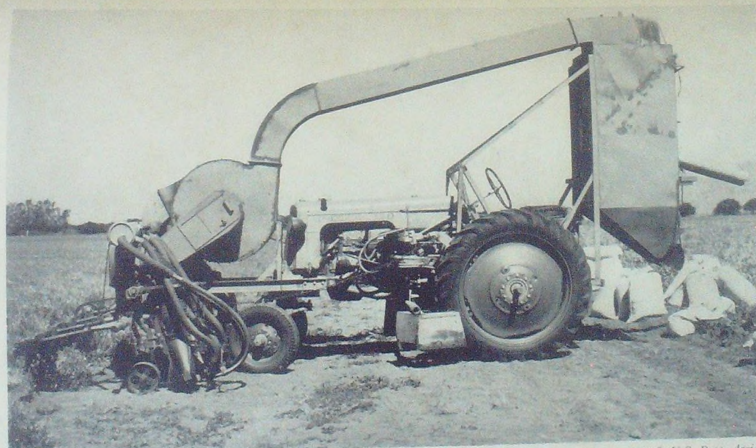
Photographs by permission of ARS, U.S. Dept. Agric.

(b) Seed harvester developed by the Intercontinental Rubber Company for harvesting guayule seed.

Photograph by permission of H. M. Ty

Flowering plants of guayule, *Parthenium argentatum* Gray.

PLATE 38



Photograph by permission of ARS, U.S. Dept. Agric.

The Tysdal guayule-seed harvester.

PLATE 39

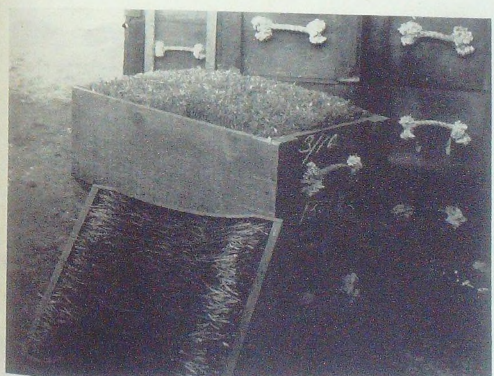
Photograph by permission of ARS, U.S. Dept. Agric.

'Seeds' of guayule. *Left*, thrashed seeds; *centre*, unthrashed seeds treated with Clorox; *right*, unthrashed, untreated seeds.

PLATE 40

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Hand weeding in double-row guayule nursery beds designed for furrow irrigation.



(*b*) Crates of guayule seedlings packed ready for shipment to the field for transplanting.

PLATE 41

any possibility of contamination. Specially constructed centrifugal pumps are used to pump the latex into the tankers at the port of embarkation, and out again at the port of destination. These pumps minimize agitation of the latex, for excessive force will coagulate the concentrated latex. Only latex with a comparatively high mechanical stability is shipped, this stability being measured by the time required to bring about coagulation in a high-speed mechanical mixer. Tank storage facilities are provided at large ports for the reception, handling, and redistribution of the latex.

Baling of Smoked Sheet

All plantation grades of smoked sheet and crepe rubber are shipped in the form of baled rubber. All plantations are equipped to bale their own rubber, and the rubber handled by the remiller is baled by him after being washed and dried. In some cases, small estates may sell their rubber in the form of loose sheet to larger estates or dealers equipped to do the baling.

The standard bale is 19 × 19 × 24 in. and contains about 5 cubic ft. The rubber sheets are stacked carefully in presses and compressed into solid blocks of rubber. Many types of bale covering have been used—packing boxes, burlap, rubber sheets, etc. The preferred covering is a sheet of rubber of the same grade as that in the bale. The bale covering is often broken in shipment and, if it is of wood, fragments of the packing material may be driven into the rubber. Wood and cloth mixed with the rubber in this manner must be separated from it in the factory to prevent such material from constituting a weak spot in the finished goods.

From the end of the production of the rubber on the plantation until it is ready for fabrication at the factory, its value is determined primarily by visual inspection. Recently, under governmental encouragement in the chief producing countries, classified rubber, marked to show its compounding characteristics, has been produced. This type of rubber still constitutes only a small portion of the rubber of commerce, and will be discussed in another chapter. For the general run of rubber, classification is made by buyers and sellers, each individual being interested in obtaining the best profit possible from his contribution to its transportation and merchandising.

X

PRODUCTION OF RUBBER FROM GUAYULE (PARTHENIUM)

INTRODUCTION

GUAYULE, *Parthenium argentatum* Gray (Plate 35(*a*)), can be grown on thousands of acres of land in semi-arid regions in the subtropical portions of the world. Although it is commonly known as a desert rubber-bearing shrub (Plate 35(*b*)), guayule cannot be grown satisfactorily in desert areas without irrigation. While the plant survives under extremely arid conditions, its rate of growth is slow and the acre-rate of rubber accumulation is equally retarded. However, guayule will survive and thrive under semi-arid conditions that are fatal to most crops. Its deep roots give it a decided advantage in reaching the available moisture, and the plant is highly resistant to desiccation during periods when there is not sufficient moisture to support active growth.

CLIMATE

Rainfall

Dry-land guayule does best with an annual precipitation of from 15 to 20 in. Under irrigation, the total moisture (rainfall plus irrigation) may be greater than that allowable with rainfall alone, and the total moisture may be as much as 30 to 40 in. provided the low moisture-stress induced by irrigation is balanced by periods of high moisture-stress for the accumulation of rubber. Guayule may grow well with an annual precipitation of from 30 to 40 in. but, under such conditions, does not build up a high concentration of rubber.

Temperature

Guayule prefers winter temperatures above 15° F., though temperatures as low as 0° F. have been recorded in south-west Texas where guayule is native. In nature, high water-stress keeps the plants dormant throughout the winter, and in such circumstances they withstand temperatures much lower than they can endure in areas where winter growth is induced by warm periods coincident with low moisture-stress.

Soil

Retzer & Mogen (1947) made detailed studies of the soil where one-, two-, and three-year-old guayule was grown in the United States during the period from 1942 to 1945. In general, they found that the best growth of guayule was on sandy loam, the texture classifications ranging from clay-loam through loam to sandy loam, silt-loam, fine sandy-loam, and gravelly loam. They found sand-gravel, loamy sand, or clay textures, clay-pans, hard-pans, moderate or heavy salt concentrations, erodable slopes, and poorly drained soils, to be unsuitable for guayule cultivation.

The moisture-holding capacity of the soil was found to be, in general, the most important consideration. Some degree of moisture-stress is required to encourage the formation of rubber in guayule, but excessive stress slows the growth of the plants. Excessive porosity of the soil and subsoil is wasteful of irrigation, and allows moisture-stress to occur even with an otherwise adequate amount of irrigation.

Campbell & Presley (1946) showed that, because of its high oxygen requirement, guayule is very subject to drowning in heavy or compacted soils where water stands during the winter resting period or in irrigated fields during the growing-season. Waterlogged plants suffered more at higher temperatures, those maintained at 100°F. wilting in two days, while those kept at 70°F. were not severely wilted in seven days although they underwent temporary wilt on the sixth and seventh days. Flooding is a significant factor in relation to soils for guayule, and soils that would otherwise be entirely satisfactory for guayule cultivation may prove unsatisfactory if subsoil drainage is not adequate. Flooding during the winter may be less harmful than flooding during the summer when temperatures are high.

Planting

The cultivation of guayule has only a recent and limited history. The Intercontinental Rubber Company planted about 8,000 acres in southern California but, in 1931, when the price of rubber dropped, the plantings were harvested for rubber and the Company discontinued planting. The Emergency Rubber Project (ERP) of the Forest Service of the United States Department of Agriculture planted about 32,000 acres of guayule from 1942 to 1945, but this operation was discontinued before more than experimental quantities of the rubber could be harvested. There are experimental plantings in Spain, Turkey, and the United States, and a production programme is planned in Turkey.

Standard Planting Methods

The single crop raised by the Intercontinental Rubber Company and the partial crop raised by the Emergency Rubber Project do not serve to establish a standard production pattern. The Company developed a workable system of rubber production and the basic principles of that method were followed by ERP, which at first struck rather closely to the Company's methods but later simplified the planting of guayule and made significant contributions to guayule harvesting and milling (*see* below).

After the liquidation of the war-time project, research was continued on a much reduced scale by the Bureau of Plant Industry, Soils, and Agricultural Engineering (now the Crops Research Division) and the Bureau of Agricultural and Industrial Engineering (now the Utilization and Development Division) of the United States Department of Agriculture. The Department of Agriculture was also instrumental in extending assistance to specialists from Spain and Turkey, who wished to familiarize themselves with the technical details of guayule rubber production.

Compared with other crops, the cultivation of guayule is strictly experimental; yet compared with the technical information available on most experimental crops, that available on guayule is extensive and detailed.

Production by the Intercontinental Rubber Company

The production of rubber from cultivated guayule was described in 1926, at the height of the operations of the Intercontinental Rubber Company,* by George H. Carnahan (1926), President of the Company, Wm. B. McCallum (1926), Chief Botanist, and David Spence (1926), Chief Chemist.

McCallum (1941, 1941*a*) summarized the production of rubber from guayule at the time the Emergency Rubber Project was started.

Nursery Operation. The Company produced seedlings in nurseries for later transplanting to the field. Their nurseries consisted of beds 4 ft. wide and 195 ft. long, separated from one another by 8-in. duckboards that served as tracks for the machinery used in caring for the nursery. The nurseries were furnished with overhead irrigation to keep the soil moist during the sprouting period, and for irrigation to force nursery growth.

The nursery beds were carefully levelled and then planted with pre-germinated seed, using special seeders that sowed seven rows of seed and covered each row with 1/10 in. of sand. This planter was designed to handle 150 beds a day, which number of beds produced sufficient seedlings to plant 375 acres of land at a spacing of 30 in. within and between rows (to allow for cross-cultivation). The nursery beds were sown in February, March, and April, and produced seedlings of a size suitable for transplanting to the field the following January.

The nursery was weeded by hand from wheeled supports that were pushed along the duckboards (Plate 36). When the plants were large enough for transplanting, heavy machinery was used to top and dig the plants. The topper mowed off the tops of the plants to within 2 to 4 in.

* The operating company in the United States was American Rubber Producers, Incorporated, a subsidiary of the Intercontinental Rubber Company. The name of the parent corporation is used here to avoid any confusion.

of the ground and was equipped to retain the tops for extraction of their rubber, if this was found desirable. The digger consisted of a machine with a heavy cross-blade long enough to undercut the plants of an entire bed at a depth of about 8 in. The seedlings were then lifted from the soil by hand and taken to the packing shed for sorting and packing in special crates for transportation to the field. The plants were inspected carefully and those that might cause difficulties in the mechanical transplanters were discarded, together with undersized or oversized plants, or those that showed damage from disease or that were otherwise not up to standard.

Field Operation. Transplanting was done with special machines designed to assure equal spacing and to give alignment of the plants both within and across the rows, so as to facilitate cross-cultivation. Six rows were planted at a time, with a planting rate of 360 plants a minute. There was considerable latitude in time of planting on irrigated land, where adequate moisture could be assured both before and after planting. Most of the land planted by the Company was unirrigated, however, and in such circumstances planting was confined to the early spring when there was sufficient moisture for quick response and renewed growth of the transplanted seedlings.

After transplanting, it was necessary to control weeds by frequent cultivation, supplemented by hand-hoeing. As the plants became larger and closed in, the frequency of cultivation had to be decreased to avoid excessive injury to the plants. No cultivation was contemplated after the fourth year.

It was planned that, for normal operations, the plants would be left in the ground for five years. This was regarded as the optimum time for harvest, but it was also believed that the plants could be left in the field for a period of up to ten years and that they would continue to accumulate rubber throughout that period. The shrub was harvested by ploughing up the entire plant to a depth of about 8 in. The plants were raked into windrows and either loaded into trucks loosely (sometimes being chopped coarsely to conserve space) for short-distance hauls to the factory, or compressed into bales for long-distance hauls or storage.

Farmer Contracts. The Intercontinental Rubber Company planned to contract with farmers for the production of the crop rather than to do its own farming. As guayule requires several years in the field, the farming operations would be subsidized currently by advances against the final value of the crop.

In addition to technical supervision of the farming operations, the Company contracted to furnish 7,200 seedlings per acre. A charge of $15 per acre was made for the seedlings, and this was to be deducted from the final payment for the crop. The Company contracted to make advances against the value of the crop for specific farming operations to be performed by the farmers on the instructions of the Company. The projected schedule of operations and advances is shown in Table XII.

TABLE XII

SHOWING SCHEDULE OF FARMING OPERATIONS AND ADVANCE PAYMENTS PER ACRE AGAINST FINAL VALUE OF CROP PROVIDED IN INTERCONTINENTAL RUBBER COMPANY FARMER CONTRACTS FOR GUAYULE CULTIVATION

First Year		
Land preparation before planting	$6.00	
Cultivations at $0.50 each	2.50	
Hand-hoeing, consecutive rates: $4.00, $2.00, $1.00, $1.00	8.00	
Rodent and pest control	1.00	
		$17.50
Second Year		
Cultivations at $0.50 each	$2.50	
Hand-hoeing, consecutive rates: $5.00, $2.00, $2.00, $1.00	10.00	
Rodent and pest control	1.00	
		13.50
Third Year		
Cultivations at $0.50 each	$2.00	
Hand-hoeing, consecutive rates: $3.00, $2.00, $1.00	6.00	
Rodent and pest control	1.00	
		9.00
Fourth Year		
Hand-hoeing, consecutive rates: $2.00, $2.00, $1.00	$5.00	
		5.00
Total		$45.00

The Company contracted to harvest the crop at its own expense and to pay the farmer $25 a ton (dry-weight) for the shrub. However, if the selling price realized by the Company exceeded 28 cents per lb. of rubber, the farmers would receive $1 a ton of shrub for each cent above 28 cents a lb. of rubber received by the Company.

When the price of rubber dropped to unprecedented levels in 1931, and continued low in 1932 and 1933, the Company discontinued the operation of the farmer-owned fields; the shrub was ploughed up and processed for rubber, and the leases and contracts were terminated. Under the terms of the contracts, the farmers were pleased with the operation; but the Company lost because of the low prices prevailing for rubber. The Company retained the shrubs on its own land but did not undertake further field planting.

Extraction of the Rubber. The rubber was obtained from the guayule shrub by maceration in a pebble mill, where chopped shrub was subjected to the action of flint pebbles in the presence of water. The pebbles disrupted the cells containing the rubber, tended to agglomerate the rubber into small masses that were known as 'worms' (Plate 37(*a*)), and ground the woody material finer and finer while at the same time helping it to become waterlogged. The rubber was then separated from the other plant material by flotation, the waterlogged plant debris sinking to the bottom and the rubber being skimmed from the surface of the water. The rubber was then washed, dried, and packed for shipment to market. Some thought had been given to the desirability of de-resinating the rubber, and chemical methods had been investigated; but these did not constitute a standard practice of the Company at the time the United States Government purchased the properties. According to Hildreth (1946), the 8,000 acres of guayule planted by the Intercontinental Rubber Company yielded a total of 3,068,630 lb. of rubber.

Production by the Emergency Rubber Project and Since

After the bombing of Pearl Harbor in 1941, the Government of the United States undertook the production of rubber from guayule in the United States as a defence measure. The first move involved the purchase of the guayule properties of the Intercontinental Rubber Company in the United States, including land, buildings, nurseries, growing shrubs, and seed. The Government assigned this project (including the production of rubber from other plants as well) to the Department of Agriculture, which organized the Emergency Rubber Project under the supervision of the United States Forest Service.

'Seed' Production. The first necessity of a planting programme is the propagating material. The chief selections of guayule are highly apomictic, and varietal characteristics predominate in successive generations with little danger of serious intermixture with other selections. Propagation is, therefore, by seed. The initiation of plantings by the Emergency Rubber Project was facilitated by the fact that some 13,000 lb. of guayule seed were obtained from the Intercontinental Rubber Company, together with nearly a thousand acres of mature shrubs from which additional seed could be harvested. Mature, irrigated guayule flowers profusely (Plate 38), and it is possible to harvest from 50 to 100 lb. of clean seed per acre.

The harvesting of guayule seed, which has presented a difficult problem, was carried out by the Company with a huge suction machine (Plate 37(*b*)). This collected only a fraction of the seed, however, and the chief harvest was obtained by shaking the seeds by hand into specially designed pans held under the plants. The Emergency Rubber Project designed more effective harvesters but still lost a large amount of seed. After the war, a seed picker was developed, under the direction of H. M. Tysdal of the United States Department of Agriculture, that used a vacuum to gather the seeds; it also used shaking devices to release more seed from the plants, and further suction to gather the fallen seed from the ground. This equipment, affectionately called 'the monster' (Plate 39), was effective in harvesting from 75 to 90 per cent of the available seed—without undue injury to the plants, which could be immediately forced into renewed growth, flowering, and further seed production.

Thrashing and Cleaning. As harvested, guayule 'seed' consists of the achene and attached sterile florets and floral parts that bulk much larger than the seed itself (Plate 40), and there is also a considerable amount of leaf and other trash. In material obtained by the newer suction method, including harvesting the seed from the ground, there is also a large amount of dirt and sand. The dirt and trash can be removed in cleaners, and the attached florets and flower parts can be removed in thrashing machines equipped with fine screens against which the seeds are thrown with some force.

Storage. Guayule seed can be stored for many years without deterioration if it is dried to a moisture-content of around 4 per cent and placed in air-tight containers for storage. For the first year or so, it increases in percentage germination because of the natural ending of the dormancy characteristic of fresh seed.

Germination. Following the practices of the Intercontinental Rubber Company, it is customary to treat guayule seed with a dilute solution of sodium or calcium hypochlorite before germination. A 1·5-per cent solution is used at the rate of 2½ gallons per lb. of seed. This treatment serves chiefly to break the dormancy of fresh seed and may often be dispensed with after storage.

Benedict (1946) made a detailed study of the germination of guayule seed. He found that delayed germination was attributable to: (*a*) a period of embryo dormancy, (*b*) a hard or impermeable seed-coat, (*c*) the presence of the pericarp, and (*d*) the presence of germination-inhibiting substances that seem to be derived from the sterile florets attached to the achenes. Embryo dormancy can be overcome by storage for two to three months or longer, and the other factors are largely overcome in the thrashing process that removes the sterile florets and flower parts, bares the achenes, punctures the pericarp, and abrades the seed-coat.

Emparan (1954) developed an air-pressure thrasher for guayule seed to be used in germination studies that was very effective in cleaning the seed and that could be used to thrash and clean as few seeds as those from a single head. Emparan & Tysdal (1957) showed that guayule seeds are quite light-sensitive, and that exposure to light during the first stage of germination had more influence on the rate of germination than had other treatments—including that with sodium hypochlorite.

Pre-emergence damping-off of guayule seedlings has been a serious factor in establishing stands. Several fungi have been isolated from young seedlings affected with damping-off and seedling rot, the most important being *Pythium ultimum* Trow. Sleeth (1946) tested a series of fungicides for pre-germination treatment of seeds as a means of increasing emergence and decreasing losses due to damping-off. In comparing Arasan, Spergon, Spergonex, Cuprocide, Semesan, No. 604, and Mersolite-19 with the standard hypochlorite treatment, Sleeth found that Arasan and No. 604 were the most promising for general use. Mersolite-19 was tested only in the greenhouse but gave excellent results there.

Planting and Care of the Nursery. The Emergency Rubber Project followed the practice of the Intercontinental Rubber Company of raising seedlings in nurseries and transplanting them to the field. Hildreth (1946) and Tingey & Clifford (1946) showed that, under favourable conditions, guayule could be planted directly in the field with considerable advantages in the cost of establishment and in spacing. However, all field planting was based on nursery-produced seedlings.

The Intercontinental Rubber Company used overhead irrigation in the nurseries, but the Emergency Rubber Project quickly changed to the use of raised beds and furrow irrigation (Plate 41(*a*)). It was found that from two to four, or sometimes more, rows of guayule seedlings could be grown between each two furrows. Guayule seed is light-sensitive as well as small (around 500,000 to the pound), and it is essential that the soil covering be kept to a minimum in depth, and optimum in moisture content, during the germination period. After the hypochlorite treatment, the seed could be planted directly in the nurseries without the pre-germination that the Company had considered essential.

The cost of weeding ran as high as $135 per acre of nursery until Benedict & Krofchek (1946) were able to control weeds in nursery plantings by spraying with a mixture of three parts of stove oil and one part of diesel oil at a rate of 32·4 gallons per acre—or 1·2 gallons per nursery bed of 4 × 400 ft. The first application of oil was made while the seeds were in the cotyledon stage, about two weeks after sowing. Almost complete killing of the weeds was obtained, with only minor injury to the guayule.

Greenhouse tests indicated that the oil should be applied when the air temperatures were between 70° and 80°F. Many plants were killed when oiled at temperatures of 50°F. or 94°F. Seedlings that had been subjected to unfavourable growing conditions, such as cold weather or drought, lost some of their resistance to the oil. Tests with lettuce indicated that there was no residual effect on the soil from the application of oil—even in cases where it was applied at a rate of as much as 250 gallons of diesel oil or 300 gallons of stove oil per acre.

Sanitation in the Nursery

Originally, it was thought that guayule was singularly free from disease as well as from insect enemies. Both of these assumptions were found to be unwarranted. In summarizing the available information on diseases in guayule nurseries, Campbell & Presley (1946) listed the following considerations for disease control in selecting and operating nurseries:

Soils. A well-drained soil, such as a sandy loam, is required for guayule nurseries. Coarse, sandy soil predisposes the seedlings to drought injury and to certain deficiency diseases. Heavy soils are hard to manage, waterlog easily, and often develop conditions favourable to root-rot.

Water supply. The frequent irrigation needed to obtain germination and emergence of guayule, tends to accumulate salts in the upper levels of the soil. A high concentration of salts is undesirable in the irrigation water. Guayule has a wide tolerance to boron, and thus may be grown in areas where that element is relatively abundant.

Previous crop. Cropland with a previous history of *Sclerotinia* or *Verticillium* infestation should be avoided in selecting a site for a guayule nursery. If the disease history is unknown, land long devoted to lettuce, cotton, tomatoes, or other susceptible crops, should be investigated for these fungi before being chosen for a guayule nursery. Old sugar-beet fields should be investigated for the presence of *Sclerotium rolfsii*.

Nematodes. Hoyman (1944) found guayule to be highly resistant to the root-knot nematode, *Heterodera marioni* (Cornu) Goodey. However, land infested with this nematode should not be used for a guayule nursery unless the land to be used for the field planting is near-by and already known to be infested with the nematodes.

Spread of disease. Care should be taken to avoid the spread of disease through contaminated cultivation tools being taken from one nursery to another, or from an infected area in one nursery to another portion of the same nursery.

Soil preparation. Tilth and drainage are all-important. Careful levelling is essential to avoid low spots that may become waterlogged and a source of infection, as well as high spots that dry out and result in poor germination.

Irrigation. The soil surface must be kept moist, but not wet, for the first seven to fourteen days. After the stand has emerged, less irrigation is needed. Plants receiving excessive irrigation during and just after emergence are subject to damping-off and seedling root-rot. Plants kept in forced growth due to ample moisture tend to develop large succulent tops that provide ideal conditions for the growth of pathogenic fungi which can be held in check by keeping the soil moisture relatively low.

Cultivation. Guayule seedlings are subject to pink rot if soil is piled against the lower leaves. Any cultural practice that tends to throw soil against the guayule seedlings should be avoided.

Fertilization. As with irrigation, forcing with fertilizers makes for lush growth and the development of conditions favourable for infection. Nitrogen, in particular, tends to increase the loss from damping-off.

Density. Crowding encourages development of pathogens and loss of plants. A density of about twenty-five plants per square foot is usually considered desirable.

Weeds. In addition to competing with the guayule plants for nutrients, weeds increase the crowding and this increases the spread of pathogenic organisms. Considerable damage is done to the plants in hand-weeding. Fairly good control of the common nursery weeds is obtained by the use of herbicides consisting of oil sprays. These do less damage to the guayule seedlings than does hand-weeding.

Transplanting

After from several months to a year in the nursery, the guayule seedlings are ready to be transplanted into the field. The Emergency Rubber Project made several attempts to speed up the planting programme by raising two nursery crops a year or three crops in two years, but found it necessary to restrict transplanting to a single season extending from 1st. December until the end of March. This is the dormant period for guayule, and the loss in transplanting at that time was much less than in transplanting at any other season.

Transplanting includes all operations from the beginning of hardening-off in the nurseries to the establishment in permanent positions in the field. In general, the standard operations are land preparation, hardening-off, topping, undercutting, lifting, sorting, grading, packing, storing, control of diseases in storage, transportation to the field, and planting. Transplanting can best be described in line with these separate operations.

Land Preparation. Land preparation for the planting of guayule is not different from that for other field crops. The land must be ploughed deeply and then levelled and the soil pulverized in preparation for the planting stock. The plough is essential where a cover-crop, weeds, heavy stubble, or other plant debris must be turned under to leave a clean, unlittered surface for planting. If the vegetable cover is not extensive, ploughing may be replaced by heavy chiselling to a depth of from 12 to 14 in.—to loosen the soil and to break up the old plough or irrigation soles. Heavy disking is used to pulverize the soil and this, as well as ploughing and chiselling, is followed by thorough harrowing, levelling, and the use, where needed, of a cultipacker * to leave a firm bed for the reception of the seedlings.

Hardening-off. Kelley *et al.* (1945) showed that, in transplanting guayule, it was necessary to harden the plants off by withholding irrigation before digging. Erickson & Smith (1947) studied the hardening-off process. They quoted unpublished data of Traub *et al.* (1947) that showed an increase in the laevulin content of plants which had undergone the hardening-off process. Smith (1945) reported that guayule plants which had been hardened contained less auxin than unhardened plants. There is invariably an increase in the carbohydrate reserves of guayule plants that is associated with the process of hardening off. Other than this, no specific alteration in the chemical composition can be attributed to the hardening-off, to account for the increased survival obtained in transplanting.

Hardening-off involves the transformation of the seedlings from a lush type of forced growth into a dormant, or semi-dormant, condition. It can be accomplished by any cultural deprivation that slows growth of the plants, though the principal factors are drought and cold. Withdrawal

* A tractor-drawn cultivating implement used to pulverize the surface soil in the planting of agricultural crops. It is used to give a suitable compact, mulched surface for planting seed or transplanting seedlings.

of irrigation soon brings active growth to a halt, and prolonged withholding of water brings the plant into a suitable condition of dormancy for transplanting.

Dormancy also follows the onset of cold weather in the autumn. Erickson & Smith (1947) showed that hardening-off resulted from cold, even though the moisture level remained high enough for continued growth. They concluded, '. . . the survival of transplants was the same whether they were only cold-hardened or were also subjected to drought. Carbohydrate analyses revealed that plants of both treatments had accumulated large amounts of laevulins and smaller amounts of inulin and other carbohydrates. While the drought- and cold-hardened plants had slightly higher reserve carbohydrate contents than those cold-hardened only, this was probably a result of the long period of hardening. On the other hand, cold-hardened plants were larger, a result of the longer initial period of growth.'

Topping. Topping guayule seedlings involves cutting off a major portion of the tops of the seedlings before digging. Smith (1944) has shown that leaves left on the transplants inhibit growth response and that the removal leaves should all be removed prior to transplanting. Erickson & Smith (1947) showed that some variation can be made in the standard practice of cutting back (topping) at the time of digging. They also showed that topping the plants a week before transplanting results in undesirable new growth prior to transplanting, but that topping three days prior to digging results in good survival.

Undercutting. Undercutting involves passing a long, heavy knife-blade under the seedlings at a depth of six to eight inches. The knife is held at a slight angle with the horizontal so that, in addition to severing the roots, it has a lifting action on the soil. This lifting action loosens the soil and facilitates the withdrawal of the seedlings. If the nursery planting has been hardened-off by withholding water, it may be necessary to soften the ground by irrigation prior to undercutting.

Normally, the plants are undercut either on the day or the day before they are lifted. Erickson & Smith (1947) showed that a significant increase in survival rates could be obtained by undercutting the plants from one to two weeks prior to lifting them. Their tests showed a survival after eight-and-a-half months of 71·7 per cent of the plants lifted on the day they were undercut, 73·4 per cent of those lifted four days after undercutting, 86·1 per cent of those lifted seven days after undercutting, 91·2 per cent of those lifted fourteen days after undercutting, but only 71·2 per cent of those lifted twenty-one days after undercutting.

When guayule seedlings are undercut, there is an immediate initiation of root primordia and, within a few weeks, a bushy mass of new roots may be formed. These are difficult to handle in transplanting machines, and damage to the new roots cannot be avoided. The roots also tend to tangle, and it is difficult for the planters to separate the seedlings quickly in feeding the planting mechanism. The ideal conditions seem to obtain when the plants are undercut at a time sufficiently in advance of the lifting to allow the development of new root primordia, but before there has been any material increase in the root-mass.

Lifting. Lifting, or pulling, is a hand operation. If the undercutting has been efficient, the soil is sufficiently loosened from the roots for the plants to be drawn from the soil with a minimum of damage and without great effort. If lifting is not done immediately after undercutting, recompacting of the soil may result in the need for more force in pulling, and consequently in an increase in the damage to the roots.

Sorting and Grading. Uniformity of size of the lots of guayule seedlings was originally considered essential for optimum efficiency in the planting machines. Paul H. Roberts (1946) reported that the Emergency Rubber Project selected a planting machine that would handle all classes of seedlings, and thus was able to use chiefly a classification calling for the stems of the plants to be from 3/32 to 16/32 in. in diameter at the crown, with roots 5 to 8 in. long, and tops 3 to 5 in. long. A more restrictive classification of 6/32 to 12/32 in. in diameter, with roots 5 to 7 in. long and tops $2\frac{1}{2}$ in. long, was preferred and demanded at times when the supply of seedlings was ample; nevertheless, satisfactory plantings were made with plants selected under the less restrictive classification.

Packing. The lettuce crate in regular use at Salinas, California, the centre of the guayule operations of the Emergency Rubber Project, was adopted for use in packing guayule seedlings for convenient handling. This crate measures $13\frac{1}{2} \times 17\frac{1}{2} \times 21\frac{1}{2}$ in. and, complete with top and wax-paper lining, weighs 10 lb. Such lettuce crates were not considered ideal, as seedlings with 6- to 7-in. roots and 2- to 3-in. tops did not overlap sufficiently to give a tight pack to brace the seedlings, or to occupy efficiently the bulk of the crate. It was found that as many plants could be accommodated in crates $15\frac{1}{2}$ or even $13\frac{1}{2}$ in. wide as in the standard $17\frac{1}{2}$-in. crate. A crate only $11\frac{1}{2}$ in. wide would accommodate 90 per cent of the plants that could be packed in a standard lettuce crate.

A portable packing table was developed that could be taken to the field to enable packing of the plants as they were lifted. Traub & Machlis (1943) found that the use of packing material was often harmful rather than helpful in packing guayule seedlings, as it encouraged sprouting and the spread of disease. The use of moss or other packing material was therefore kept to a minimum. For short storage, involving only twenty-four hours between lifting and planting, no packing material was used for crates lined with wax paper. Packing material was used sparingly on the tops and bottoms of crates that were to be stored for a longer period or had to be shipped (Plate 41(*b*)). The amount of packing material varied with the anticipated storage and transit periods.

Storage. In a large planting programme, it is not possible to dig the seedlings from the nurseries and plant them immediately in the field, as inclement weather may interfere either with the digging or with the planting. To ensure that seedlings are always available for the planting operation, it is necessary to maintain a supply of dug seedlings sufficient to keep the planting machinery busy whenever the conditions are favourable for planting.

In the absence of harmful disease organisms, it is possible to store the packed seedlings for a limited period at air temperature. For prolonged storage, or if there has been infection by *Sclerotinia* or other harmful organisms, it is necessary to store the crated seedlings at reduced temperatures. In a test reported by Erickson & Smith (1947), crates were packed each with 200 healthy plants and ten plants infected with *Sclerotinia sclerotiorum*, and then stored at varying temperatures.

After thirty days' storage, 4 per cent of the initially healthy plants had become infected at a storage temperature of 28° to 34°F., 20 per cent at 38° to 42°F., and 100 per cent at 40° to 60°F. At the end of sixty days, 14 per cent were diseased at 28° to 34°F., and 60 per cent at 38° to 42°F. Thus, if a pathogen comparable to *S. sclerotiorum* is present, it is necessary to store the guayule seedlings at near 32°F. and limit the period of storage to less than sixty days.

Campbell & Presley (1946) studied storage of guayule seedlings with regard to the development of disease. They found that plants dug during rainy periods could not be stored at normal temperatures for more than five days, whereas plants dug during dry weather could be stored at normal temperatures for much longer periods. They found that, even at 32° to 34°F., storage of moist plants and those with green leaves is hazardous after four weeks.

These authors reported heating to be a major difficulty in the storage, or shipment, of unhardened or moist plants. Heat injury usually manifests itself on the roots as water-soaked, discoloured areas, which may be limited in extent or may involve most of the roots. Tops and stems may be blackened and, in cases of severe 'burning', the plants in the centre of the crate may be a watery, sodden mass on opening. Heat-injured plants have little likelihood of surviving transplanting.

Diseases in Storage. The chief fungi described by Campbell & Presley (1946) as causing damage to guayule seedlings in storage were species of *Sclerotinia* and *Botrytis*. Under storage conditions, *Sclerotinia* develops a profuse, white, cottony mycelium on diseased plants, which spreads outwards from the centre of infection and attacks and rots other plants with which it comes in contact. This white mycelium frequently becomes very abundant and forms characteristic cottony tufts on the diseased tops and roots. Later, these tufts become firm, whitish or greyish nodules, that turn into black, irregular-shaped sclerotia. Groups of diseased plants, or nests, are usually conspicuous because of the white mycelium that binds them together. No spores are produced by *Sclerotinia* in a crate, and the only means of spread is by the mycelium growing from plant to plant.

Botrytis, like *Sclerotinia*, requires moisture for its development. It is most common on plants that have been dug during rainy periods when the tops cannot be dried to a desirable moisture condition before packing. The fungus is checked by temperatures of from 32° to 34°F. but develops readily near 40°F. *Botrytis* rot may be recognized by the grey fuzzy mould that grows on diseased plants. All the plants in crates containing seedlings infected by *Botrytis* should be discarded. Even though many of the plants appear healthy, they are probably coated with spores or have incipient infections that may develop and kill the plants in the field.

Shipment and Distribution. Guayule is essentially a large-acreage crop. The factory needed for the most efficient processing of the crop is a multi-million-dollar installation requiring the output of thousands of acres of guayule for its year-around use. On a continuous-production schedule, with a five-year rotation, a single factory would handle the shrubs from 25,000 acres of guayule. This factory would require the planting of 5,000 acres of guayule annually, and the production, storage, and distribution of the seedlings would require efficient, careful operation to ensure sufficient seedlings without excess production.

Transportation time is essentially an extension of the storage time. Problems of requisition, distribution, and supply make this one of the critical details of the planting programme. The seedlings must first be produced and transported to the chief storage area in sufficient quantities to meet the contemplated needs of the planting programmes in the various areas. Sub-storage facilities must be provided in these various areas for sufficient seedlings to meet current needs and likely demand. Distribution to the individual farms should be on a daily basis.

Except for the transportation of the seedlings from the primary storage locality to storage points in the districts, transportation would probably be mainly by motor vehicles. Long shipments would be by train, and refrigeration might be needed if the period of shipment was protracted, or if a prolonged period of refrigerated storage was contemplated at the local storage centre.

Machine Transplanting

Transplanting of guayule seedlings is accomplished by the use of machines capable of planting several rows at a time. The machines developed by the Intercontinental Rubber Company were made specially, and required special fabrication of all repair parts. They were soon replaced by standard transplanters. The preferred unit was the Holland celery planter but, because of war-time shortages, two types of Kindorf planters were also used. These machines were equipped with devices into which the guayule seedlings were fed singly and which then carried the seedling to, and released it into, a planting hole dug by the machine, which then firmed the soil around the roots of the transplanted seedling.

Spacing. The objective of spacing is to obtain maximum rubber production on a given area, and to facilitate cultivation, irrigation, seed collection, and shrub harvesting. The Emergency Rubber Project used principally a spacing of 28 in. between rows. Spacings of 16 to 20 in. within the row were standard, though these were increased to 24 in. under very dry conditions for dry-land farming. Spacings as little as 12 in. in the row were used to obtain early production of rubber at a maximum yield per acre.

Planting equipment. A Holland four-row planter was considered the basic unit for planting guayule. Because of shortages, the 'old' or 'new' Kindorf machines were also used. Planting units in operation are shown in Plates 42(*a*) and 43.

Crew personnel. The crew for the operation of the planting unit consisted of a foreman (usually known as a strawboss), eight planters (four feeders, two sorters, and two spotters), and a tractor driver. The feeders placed the individual plants in the planting pockets or arms of the planter. Plants were supplied to the feeders by the sorters, who separated the plants from the crate into small bunches of a size convenient and easy for the planters to handle. Each feeder was expected to feed at a rate of forty-five to sixty plants per minute, and the ease of separating the individual plants from the bunch was an important element in his performance. The spotters followed the planter, to replant all seedlings ineffectively set and to plant all 'skips'. All eight planters were trained in each of the three operations and obtained some relief from the boredom of the work by inter-changing at frequent intervals when this could be accomplished without slowing down the planting. The tractor driver was responsible for following closely the planting lines that were established in the beginning with laths as markers, driving at a pace suited to the planting rhythm of the feeders, and turning the equipment and realigning it expeditiously at the end of each row.

Field Planting

When equipment, crew, and plants have been assembled, the actual start on the field planting consists of the final ground preparation. For this, a twenty- or thirty-horsepower crawler tractor is used to pull in tandem a light chisel, a cultipacker, and a light steel harrow. This operation should leave the field surface moist, firm, and fully pulverized. One final land-preparation unit was considered able to service two planting crews if they were operating in adjacent fields.

The tractor driver first lines up the planter with the lath line that has been established for the start of the field. The four feeders seat themselves at the feeding units, facing towards the rear of the machine. The sorters seat themselves at the rear of the machine, facing the feeders. The spotters take up their position behind the machine. Each has a planter's apron with a handful of seedlings in the pocket, and a planting bar. The sorters furnish the feeders with an initial supply of seedlings. The strawboss stands at the end of the machine and, when all members of the crew are in position, gives the signal to proceed. The driver then proceeds at a pace compatible with the skill of the planters and the spacing of the plants in the row. A planting rate of forty-five to sixty plants per minute, with 20 in. between plants in the row, demands that the tractor driver maintain a speed of 75 to 100 ft. per minute.

The planting machines are equipped with pockets on revolving sprockets or endless belts. The feeder inserts a seedling into each pocket as it comes into position. The plant is then released into a suitable indentation made in the soil, and the soil is firmed around the root of the plant by suitable 'fingers' on the planter.

In planting, the feeder takes a handful of seedlings from the tray to his left, where they have been placed by the sorter. Holding the plants in his left hand, as close to the pocket as possible and with the roots toward himself, the feeder deals the seedlings from the left to the right hand, one by one, by rolling them out between the thumb and forefinger of the left hand. Each plant is grasped firmly in the right hand, with the forefinger extended full-length along the upper side of the stem so that the thumb underneath serves as a guide in placing the root collar each time in about the same position with respect to the end of the pocket.

The spotters are furnished with planting bars for use in planting the skips or in resetting imperfectly planted seedlings. The planting bar was designed to make a hole in the ground large enough for the root of a normal seedling, and is forced into the ground with foot pressure. The seedling is then held close to the ground and inserted into the planting hole and firmed, all with a single motion.

FIELD MAINTENANCE

Cultivation

Several years are needed for guayule to attain a size and rubber-content for optimum yield of rubber. Under cultivation, the most important factor in hastening the growth-rate is irrigation. With irrigation, guayule can be brought to harvest size in three years, and experimental harvests have been made at the end of the second year in the field. In dry-land farming, it is not usually thought that guayule should be harvested before the end of the fourth or fifth year in the field, and it is often advantageous to leave it in the field even longer.

It is essential that guayule be kept free from weeds. The use of herbicides (Plate 42(*b*)) has proved useful in controlling weeds in cultivated guayule and has decreased the need for cultivation and hand-labour. However, several cultivations are needed in each of the first three years to keep the ground in good condition and the weeds in check. As the plants become large enough to close in the alleys, the use of cultivation equipment must be kept to a minimum or the side branches of the plants may be injured or broken off. Loss from this cause may equal or exceed the gain in rubber from further growth of the plants (Plates 44 and 45(*a*)).

Nutrition. The use of balanced fertilizers improves the growth of guayule in most instances. Precise fertilizer requirements have not been established, but it is clear that good nutrition is necessary. The balancing of growth-rate and accumulation of rubber is the problem to be resolved in determining the optimum rate of fertilizer application. A high rate of fertilization, and consequently of growth, results in a low rate of rubber accumulation. On the other hand, it has been found that guayule can be kept in a state of active growth for over a year (in the greenhouse where winter-temperatures do not restrict active growth), and can then be induced to accumulate an amount of rubber as great as would have been stored with a reduced growth-rate or a shortened alternation of rapid and retarded growth.

Irrigation. Irrigation offers the most effective method of controlling growth and rubber accumulation in guayule. Ample irrigation encourages growth but slows the rate of rubber accumulation, while withholding irrigation slows down the growth-rate and increases the rate of accumulation of rubber. The Emergency Rubber Project kept irrigation to a minimum in 1943 and 1944, when 19·29 and 17·28 acre-inches, respectively, were applied, on an average, to the fields under irrigation in California. The rate of application of water was increased somewhat to an average of 23·0 acre-inches in 1945.

Diseases of Guayule

No disease has been reported that is peculiar to guayule; but guayule is subject to many common diseases that affect other crops. Some of these diseases are quite serious—such as the cotton root-rot caused by *Phymatotrichum omnivorum*, charcoal rot caused by *Sclerotium bataticola*, and dieback caused by *Diplodia theobromae*. Perennial occupation of the same land by a single crop of guayule increases the damage from disease.

Campbell & Presley (1946) reviewed the available information regarding the diseases of guayule and described those that had caused field losses.

Pre-establishment Losses. Transplanted guayule is frequently attacked by pathogenic fungi before it becomes established. Infections may originate in the nursery, in storage, or in the field after planting. Seedlings infected by *Botrytis* or *Sclerotinia* in the nursery will probably not survive transplanting. Seedlings that bear spores of *Botrytis* but that have not actually become infected may survive if planted in dry weather, but are poor risks if planted in cloudy or rainy weather that is favourable for the development of the disease.

Soil fungi commonly associated with pre-establishment loss include species of *Fusarium*, *Pythium*, *Phytophthora*, and *Sclerotinia*. In addition, *Phymatotrichum omnivorum* has been observed to cause pre-establishment loss in Texas, and *Sclerotium rolfsii* in Arizona. In some areas, one or more of these organisms may be present in newly cultivated land; but they are more abundant in land that has been under cultivation for a number of years.

'Phytophthora' Rot. A root- and crown-rot caused by *Phytophthora drechsleri* has been observed in all of the principal guayule-producing areas. Wilting usually develops several days after irrigation and is the first evidence of *Phytophthora* rot. Affected plants wilt suddenly and the leaves dry up, turn grey, and generally remain firmly attached to the plant. Root lesions are characteristically black, slightly sunken, and firm in texture. The diseased zone of phloem and cortex becomes dark brown to greenish-black on drying. The woody portion of the root at the lesion is also discoloured. On newly wilted plants, the lesion is ordinarily delimited by a clearly defined margin. Lesions of the tap-roots of wilted plants may be from 1 to 4 in. long. These develop most frequently from 2 to 6 in. below the soil surface, but they may also occur deeper down or, alternatively, at the root-crown.

Phytophthora drechsleri is most commonly found on guayule growing on heavy, wet soil and it develops most rapidly in warm weather, being held in check by cool weather. Some control can be obtained by careful irrigation to avoid even temporary waterlogging of the soil, and the disease can be largely avoided by confining the plantings to light, well-drained soils. Even in the latter, however, saturation of the soil for periods as long as eighteen hours at the time of irrigation should be avoided.

'Phymatotrichum' Rot. *Phymatotrichum* root-rot, or Texas root-rot, is caused by *Phymatotrichum omnivorum*, a fungus that is widely distributed in the calcareous soils of the southwestern United States and on the eastern and western coastal plains of Mexico. The fungus is indigenous to this area and attacks both native and cultivated plants. More than 1,700 species, representing field crops, garden and truck crops, deciduous fruit trees, weeds, shade trees, and other native vegetation, are susceptible.

The first symptom of Texas root-rot on guayule is wilting that develops when lesions girdle the tap-root. Wilting is usually sudden and complete if the plants are in a lush state of growth when attacked. Diseased plants are conspicuous among healthy plants because of their light-grey, wilted leaves that quickly become dry and curled. In plants that are not in a lush state of growth when attacked, wilting is less pronounced. The lower leaves of such plants die first, and the plant may persist for some time with sparse foliage. Plants that have only a portion of the root system affected, may recover during the winter, when the fungus is dormant, and resume growth in the following season. The diseased root-tissue is brownish and firm on newly wilted plants, but it becomes darker and shredded with age.

Similar symptoms are produced by other root-rotting fungi, and positive identification depends upon isolation of the causal organisms. Field diagnosis of Texas root-rot may sometimes be made by examining the roots of affected plants with a hand lens. Fine, yellowish to brownish, fuzzy mycelial strands are usually present on the surface of the roots of plants killed by *Phymatotrichum*.

The vegetative (*Ozonium*) stage of *Phymatotrichum* consists of strands and masses of interwoven mycelium. The spore-mat (*Phymatotrichum*) stage is usually produced during August or September on moist soil surfaces near dead or infected plants, but apparently it has no function in perpetuating the fungus. Sclerotia, or resting bodies, formed in the soil near diseased roots, enable the fungus to survive unfavourable conditions. The fungus spreads from plant to plant along the roots, or for short distances through the soil independently of roots. Although the fungus is active during most of the year, high temperatures are particularly favourable for its development. The fungus may over-winter either as vegetative mycelium on infected plants that are still living, or as sclerotia.

Guayule should not be planted on land known to be heavily infested with *Phymatotrichum*. There is not much hazard on the lighter, non-irrigated, uninfested lands; but heavy soils under irrigation, if already infested with *Phymatotrichum*, are hazardous for guayule.

'*Sclerotinia*' *Rot*. Root-rot due to *Sclerotinia minor* and *S. sclerotiorum* caused the death of about 1 per cent of the plants in a field near Salinas, California, over a period of two years, and of 5 per cent of the plants in a 20-acre field in Arizona during their first season. Campbell (1946) found that in fields studied by him in which both species were present, 83 per cent of the loss was due to *S. minor*.

Wilting of the affected plants is the first symptom of *Sclerotinia* rot. The fungus usually attacks the tap-root from 3 to 6 in. below the soil surface and causes a lesion that girdles the root. The presence of sclerotia on the surface of the plant or in the diseased tissue distinguishes *Sclerotinia* rot from all others. Sclerotia may not be present on newly-formed lesions, but identification can usually be made by the soft, shredded appearance of the rotted tissue, whose colour does not differ materially from that of the healthy tissue. Wefts of white mycelium are also commonly present on the surface of the diseased roots.

Sclerotinia root-rot has not proved serious with guayule; but before planting fields which are known to be infected, the soil should be worked and allowed to dry thoroughly, so as to kill the mycelium of the fungus.

'*Fusarium*' *Root-rot*. Norton (1954) reported a minor root-rot caused by *Fusarium solani* that caused severe but localized injury in an irrigated nursery as well as in a non-irrigated two-year-old planting in Texas. The root-rot was first observed owing to a wilting of the plants in a roughly circular area in a dense, eight-months-old nursery planting. In the field, all or only part of the branches wilt. A brown to reddish-brown discoloration of the internal root-tissue is evident. Inoculation tests and field observations indicate that the pathogen is not highly virulent under normal growing conditions. It was suggested that insect injuries or other predisposing factors must be present for the disease to be destructive. While the fungus had been noted by other investigators, this was the first report to indicate that the disease could be serious.

Bacterial Rot. Campbell (1947) reported that a root disease caused by an unidentified bacterium and, in the advanced stage, characterized by stem lesions, had caused severe losses in several irrigated plantings in the San Joaquin Valley in California, while a similar infection was observed on several small plantings in Texas. The first indication of the disease is similar to that of other rots, namely, wilting of the affected plant. Wilting is frequently progressive, starting with one or more of the lower branches and followed in a few days by the remainder of the top. If the plant is growing vigorously when attacked, wilting may be sudden and complete; but if the plant is in a less succulent condition, the leaves may gradually dry without noticeable wilting. By the time wilting is observed, most of the tap-root is badly diseased. The surface of the diseased portion of the tap-root is covered with black, resinous masses to which soil adheres when the plant is pulled from the ground. In the advanced stage of the disease, these resinous masses cause the root lesions to appear swollen. The affected bark is soft, watery, and more or less spongy, separating readily into layers. It is light or dark brown, depending on the age of the lesions; occasionally it has a vinaceous tint. The wood of the lower portion of the tap-root is usually blackened, but a red or pinkish ring in the cambium and youngest wood may extend for some distance above the lesion.

Contrary to the condition observed in other root-rots, the lesions continue to develop after the plants wilt. If not stopped by drying, they may advance for some distance into the stems and smaller branches. The progress of the lesions is marked by conspicuous black, resinous masses, or bubbles, on the stem.

In the stems, where it is possible to observe the advancing margin of the lesions, the cortex seems to be involved first and progressive deterioration of the associated tissues follows. In some cases, the resin exudate is thin and spreads over the surface in a brownish film, which later becomes black.

Charcoal Rot. A root- and crown-rot of guayule, caused by *Sclerotium bataticola*, was first reported by Ezekial (1943) and later studied in greater detail by Presley (1944), who first demonstrated its pathogenicity on guayule, by Norton & Frank (1953), and by Norton (1953). During a prolonged drought-period in Texas, this was by far the most serious disease of guayule, resulting in the death of up to seventy per cent of the plants in some plantings. Presley considered the disease as primarily a crown-rot.

The disease developed during July and August, 1944, after a prolonged period of hot, dry weather, and was characterized by dark-brown, sunken lesions that developed at or near the ground line. The lesions gradually enlarged around the point of infection, causing a progressive dying of the top. It was possible to find plants in all stages of the disease, from those in which partial girdling had killed one or more branches, to those in which the entire top was killed. In contrast to plants killed by a root-rot, the root systems ordinarily remained alive for some time after the tops had died from the girdling lesions at the ground line. Field counts made in August 1944 at Pearsall, Texas, showed that 7·6 per cent of the plants in 10-in. spacings were affected by the disease, 11 per cent in 20-in. spacings, and 13·9 per cent in 40-in. spacings. Cooler weather checked the disease, and many of the affected plants eventually recovered.

'*Verticillium*' *Wilt.* A wilt disease caused by *Verticillium albo-atrum* results in light to heavy damage to guayule. Mild infections that do not result in the death of the plants may be observed merely as stunting, without recognizing the fact that the stunting is the result of infection. The first evident symptom in young plants is a wilting of the lower leaves, which turn yellow after several days and gradually become brown and dry. Occasionally, a single branch will wilt before the rest of the plant is affected. After this initial wilting, some of the plants apparently recover and resume normal growth, whilst others continue growth at a reduced rate. The older leaves of affected plants wilt and die, and the newly-formed leaves are smaller than in healthy plants. The more severely affected plants die, as the root system of plants infected by *Verticillium* are usually affected by root-rot. The most reliable symptom for diagnosing *Verticillium* wilt is a discoloration in the wood of the stems and roots, resulting from the presence of the fungus in the vessels. The walls of the cells turn brown and the lumina of many of the vessels become filled with a yellowish or brownish wound-gum.

The strains of guayule vary considerably in their susceptibility to *Verticillium* wilt. Both Campbell & Presley (1946) and Schneider (1948) have shown that some strains of guayule do not recover from an attack of the wilt, whereas others show partial to complete recovery. Gerstel (1950) reported an apparent relationship between chromosome number and resistance to *Verticillium* wilt. Diploids showed little resistance, whereas triploids and tetraploids showed a significantly lower rate of infection.

Verticillium wilt is not a major disease of guayule but has done considerable damage in some instances. The selection and use of resistant strains of guayule would undoubtedly be the best means of control.

'*Diplodia*' *Dieback.* Presley (1946) reported a dieback of guayule that was first observed in the summer of 1944, following the summer rains, in southern Texas. In two-year-old irrigated plantings, where the crowded conditions of the plants favoured the disease, practically every plant was infected and many plants were dead by mid-October. In dry-land plantings and in one-year-old irrigated plantings, infections were few and there was relatively little damage from the disease. Dry weather retarded the disease and, during the winter, fungus activity ceased entirely. With the return of high temperatures and rain, in the spring of 1945, many of the old lesions again became active and, in addition, the pycnidia which were produced in large numbers on the diseased plants furnished abundant inoculum for new primary infections.

Insects Affecting Guayule

Cassidy *et al.* (1950) reported on the insects that had been found on guayule in nursery, field, and greenhouse plantings in California, Arizona. New Mexico, and Texas.

Insects in the Nursery. Guayule plants in nurseries were injured by several insects. *Ulus crassus* (Lec.), *Diabrotica undecimpunctata* Mann., and *Pogonomyrmex* spp., when they were sufficiently abundant, reduced the stand of cotyledon-stage guayule. Thrips (principally *Frankliniella* spp.), the onion thrips (*Thrips tabaci* Lind.), and *Chirothrips aculeatus* Bagn., caused the leaves of small plants to curl and become distorted, but they did little damage. Wireworms (*Limonius* spp.) killed as many as 14 per cent of small nursery plants. Larvae of a stem borer, *Agromyza virens* Loew, bored down through the pith of the main shoots of nursery plants, but killed only a small percentage of them.

Insects in the Field. Field plants were also injured by several insects. Grasshoppers, principally *Melanopsis* spp. and *Oedaleonotus enigma* (Scudd.), were the most destructive insects to plantation guayule. They bred within California fields, but also migrated into them from other breeding areas, killing and damaging the plants by removing the cortex from the branches. A tube-forming termite, *Amitermes tubiformans* (Buck.), encased newly transplanted plants and removed cortex material from them in southern Texas. *Empoasca arida* DeL. was the second most abundant insect on plantation guayule in California, but little damage, if any, was attributed to it. *Corythuca* spp. reproduced on guayule so abundantly in Texas, New Mexico, and Arizona, that the plants were damaged. *Sixeonotus areolatus* Knight also damaged guayule in southern Texas.

Plant bugs (*Lygus* spp.) were very abundant during the flowering period in California fields. *Lygus hesperus* Knight reduced the viability of guayule seeds and stunted plant growth, so that the bugs were forced to feed on the terminal shoots. *Lygus sallei* Stal. stunted the terminals. Adults of the carrot beetle (*Ligyris gibbosus* Deg.) killed guayule plants in California, Arizona, and Texas in 1942, but did not reappear until 1944 (at Indio, California).

Wireworms (*Limonius* spp. and *Melanotus* sp.) did little damage to plantation guayule, except in a 20-acre field in California where the latter species greatly reduced the stand. Larvae of the salt-marsh caterpillar (*Estigmene acrea* Drury) and the yellow-striped army-worm (*Prodenia ornithogalli* Guen.) periodically defoliated guayule in California. Larvae of the garden webworm (*Loxostegia similalis* Guen.) seriously defoliated guayule in Texas and New Mexico in 1943 and 1944. A fire ant, *Solenopsis xyloni* var. *maniosa* Whlr., weakened and killed thousands of plants in California by feeding on the root cortex. Colonies of the red harvester ant, *Pogonomyrmex barbatus* F. Smith, defoliated guayule plants and removed seeds and cotyledon-stage plants in southern Texas within areas from 6 to 10 ft. in diameter. The Texas leaf-cutting ant, *Atta texana* Buckl., also defoliated plantation guayule in Texas.

Insects in the Greenhouse. The following insects have been reported as attacking guayule plants in the greenhouse: the two-spotted spider-mite, *Tetranychus bimaculatus* Harvey, which reproduced abundantly on guayule; a field cricket, *Achata* sp.; the green peach-aphid, *Myzus persica* Sulz.; the melon-aphid, *Aphis gossypii* Glov.; the Mexican mealy-bug, *Phenacoccus gossypii* T. & C.; the greenhouse white-fly, *Trialeurodes vaporariorum* Westw. and *Aleyrodes spiracoides* Quaint.; a leaf miner, *Phytomyza atricornis* Meig.; and larvae of the orange tortrix, *Argyrotaenia citrana* Fern.

Harvesting Guayule

Economic Maturity of Guayule

The economic maturity of guayule is the point at which the maximum financial return can be obtained through harvesting the shrub and disposing of the rubber. It depends not only on the size and rubber-content of the shrub, but also on the cost of harvesting the shrub and extracting the rubber and, naturally, on the current price of the rubber. At any given price of rubber, the economic maturity of the guayule is the point at which the most rubber can be produced per unit of production cost. Guayule continues to accumulate rubber for at least ten years, and can remain in the field for even longer without decrease in the amount of rubber. Up to five years, there is a steady increase in the amount of rubber—providing the normal alternation of seasons takes place and summer's active growth is followed by winter shock and the normal accumulation of rubber, and providing of course that the plants are not killed by disease or insects.

Under irrigation, economic maturity may occur before the age of five years. After that time, less rubber may be accumulated in the plants in further growth in the field than can be obtained by harvesting the accumulated rubber and replanting. Under dry-land conditions, the economic maturity of guayule comes in the fifth year or later.

The economic maturity is determined also by the method of harvesting. If the guayule is to be ploughed up and the entire plant milled for rubber, the cost of replacing the crop will be much greater than if only the aerial portions of the shrub are harvested and the roots are left in the ground to regenerate a new crop. For replanting is more costly and time-consuming in obtaining a new crop. On the other hand, between a quarter and a third of the stored rubber is left in the roots if only the aerial portion of the plant is harvested.

Harvest Season

The major portion of the information on which the determination of the optimum harvest season is based is from tests with young plants. Relatively little of the available information is from tests with economically mature shrubs. With the younger shrubs, the size of the plant increases throughout the growing-season, but during this period there is not a corresponding increase in rubber-content. The percentage of rubber in the plant thus tends to decrease as a larger and larger amount of non-rubber tissue is formed. After active growth is terminated in the autumn, or after a severe drought if the plants are not irrigated, the rubber-content begins to build up until it reaches a maximum for the season. The major portion of this rubber accumulation is in the new tissues, but O. F. Curtis (1947) has shown that the old cells of the inner xylem and pith continue to accumulate rubber for several years. No seasonal response has been shown with regard to the accumulation of rubber in old tissues.

Traub (1946) and Benedict (1949) have reported that rubber, once it is formed in guayule, is not further used by the plant, and that it is an end-product not utilized by the plant as a reserve food-material. It would appear, therefore, that there is no diminution in the rubber-content even though the percentage of rubber decreases after the onset of spring growth. From a practical standpoint, the amount of rubber recoverable by mechanical processing might be reduced, as the efficiency of the extraction is influenced directly by the concentration of the rubber in the plant tissue.

The amount of dilution of the rubber due to new spring and summer growth would be much greater in young shrub material. The dilution in old shrubs would be less and less as the proportion of new growth becomes less and less. It would appear, therefore, that the harvest period of old plants might be extended or even be a year-round operation. The only rubber lost would be that from the current year's growth that has not yet accumulated; but any harvest date would be subject to the same consideration.

Lengthening the harvest season of old plants is important not only from the standpoint of obtaining the maximum yield of rubber, but also to make maximum use of the extraction facilities. If the harvest is confined to a comparatively short period, either the operation of the factory must be relatively restricted or storage facilities must be provided to retain a large share of the crop for a relatively long period. Extending the harvest period throughout the year and thus keeping the factory operating on a twelve-months basis, except for the necessary periods for overhaul and repair, would increase the economic efficiency of the extraction facilities and make it possible for smaller factories to handle the shrubs from a given acreage, or for a larger mill to handle an even larger acreage.

The Harvest

Digging. The standard method of harvesting guayule is to plough up the plants (Plate 45(*b*)) and use both tops and roots for rubber extraction. The Emergency Rubber Project utilized a sugar-beet lifter to harvest the plants, but had some difficulty in separating attached soil from the roots. Standard baling equipment was adapted for compressing the harvested shrub for transportation to the factory and for storage until milling-time.

Clipping. Some attention has been given to the possibility of a partial harvest in which only the aerial portion of the guayule shrub would be harvested for rubber, the roots being left in the ground to regenerate a new crop. The Intercontinental Rubber Company had considered the possibility of such a method, after it was suggested by Lloyd (1911). O. F. Curtis (1948) made detailed studies of harvesting the aerial portions of guayule, and found that the tops of plants cut off at 1½ in. above the ground contained two-thirds of all the rubber in the entire plant. Tingey (1945) also studied various factors involved in the partial harvest of guayule. Both Curtis and Tingey found that, under certain circumstances, over 90 per cent of plants that had been cut back for the harvest of the tops survived and regenerated new tops.

Hunter *et al.* (1959) made further studies of partial harvest of guayule, when research was renewed after the liquidation of the Emergency Rubber Project. In reporting their experiments, these authors designated the method as 'clipping'. Hildreth (1946), while calling the method 'pollarding', repeatedly used the word clipping in describing the method, and it would appear that this latter term is suitable as a general one for this method of partial harvest.

Hunter *et al.* established a well-designed test to determine the value of different harvest sequences. This consisted of a replicated test to compare yields obtained by digging guayule at various ages with yields obtained by clipping at the age of five or six years, followed by digging one, two, three, and four years later. Unfortunately, budgetary considerations resulted in the termination of these tests before they could be completed as originally planned. As direct comparison of the data furnished by Hunter *et al.* is difficult because of the different ages at which the various plots were terminated, Table XIII has been compiled from their data to express the results in terms of yield per acre per year. This makes all data comparable, so that the yields from plots terminated in the fifth year can be compared directly with those terminated in the sixth, seventh, eighth, or ninth years.

Plots harvested by a single digging at five, six, seven, or eight years of age, yielded at the rate of slightly more than 200 lb. of rubber per acre per year. The irrigated plots yielded only about 6 lb. of rubber a year more

TABLE XIII

COMPARATIVE YIELDS OF GUAYULE RUBBER, IN POUNDS OF RUBBER PER ACRE PER YEAR, FROM SHRUBS HARVESTED BY DIGGING AT VARIOUS AGES, AND FROM SHRUBS HARVESTED BY VARIOUS CYCLES OF CLIPPING AND DIGGING

Treatment	No.	Clipped age *years*	Dug age *years*	Irrigation or dry	Cumulative yield *lb./acre*	Mean annual yield *lb./acre*
(1)	1	—	5	—	1,003	201
	2	—	6	dry	1,210	201
		—	6	irrigated	1,297	216
	3	—	7	dry	1,410	201
		—	7	irrigated	1,392	199
	4	—	8	dry	1,625	203
(2)	1	5	—	—	686	137
	2	5	6	dry	1,210	201
		5	6	irrigated	1,297	216
	3	5 & 7	—	dry	986	141
		5 & 7	—	irrigated	1,085	155
	4	5	7	dry	1,498	214
		5	7	irrigated	1,661	237
	5	5	8	dry	1,924	241
		5	8	irrigated	1,856	232
	6	5	9	dry	2,105	234
		5	9	irrigated	2,153	239
	7	5 & 7	9	dry	1,985	221
		5 & 7	9	irrigated	2,116	235
(3)	1	6	—	dry	923	154
		6	—	irrigated	937	156
	2	6	7	dry	1,565	224
		6	7	irrigated	1,610	230
	3	6	8	dry	1,831	229
		6	8	irrigated	1,872	234
	4	6	9	dry	2,105	234
		6	9	irrigated	2,153	239
(4)	1	—	5	—	1,003	201
	2	—	5 & 6	dry	1,033	172
		—	5 & 6	irrigated	1,074	179
	3	—	5 & 7	dry	1,231	176
		—	5 & 7	irrigated	1,259	180
	4	—	5 & 8	dry	1,437	180
		—	5 & 8	irrigated	1,518	190
	5	—	5 & 9	dry	1,726	192
		—	5 & 9	irrigated	1,676	187
(5)	1	—	6	dry	1,210	201
		—	6	irrigated	1,297	216
	2	—	6 & 7	dry	1,244	178
		—	6 & 7	irrigated	1,343	192
	3	—	6 & 8	dry	1,466	183
		—	6 & 8	irrigated	1,562	195
	4	—	6 & 9	dry	1,707	190
		—	6 & 9	irrigated	1,781	198

than the dry plots, which was not enough to repay the additional cost of irrigation. The lowest cost per pound of rubber produced as determined by farm costs (planting and replanting), and costs of factory operation, would be on at least an eight-year cycle—or perhaps longer, as the test was not continued long enough to determine the point of diminishing returns in retaining shrubs in the field.

A single clipping at either five or six years of age, followed by digging from one to four years later, gave significant increases in yield amounting to 250 to 300 lb. of rubber per acre over a nine-year cycle. Double clipping and double digging resulted in decreased yields, but could not be considered conclusive as the tests were terminated before the longer cycles involved could be tested. The yields from the irrigated plots averaged about 10 lb. more rubber per acre per year than those from the dry plots. In some cases, the yields of dry-land plots exceeded those of the comparable irrigated plots. The value of irrigation for long-term production is questionable. The general results indicate quite definitely that, for short-term production of shrubs and rubber, irrigation is of great value but that, if the shrub is to be maintained for several years, the increased yields from irrigation probably will not repay the additional costs.

Baling. War-time harvest of guayule was entirely by digging the shrub. For field storage and transportation to the factory, the shrub was compressed into bales. The standard bale used for guayule was 17 × 22 × 40 in.; the compressed bale had a density of 23 lb. per cubic foot, and weighed around 200 lb. (the guayule having a 25 per cent moisture-content). This required that the shrub be handled mechanically in loading and unloading. Because of a lack of storage space at the factory, it was necessary to store the baled shrub in the field until shortly before milling. Condensation of moisture on the underside of the covers used to protect the bales caused damage from heating in the upper bales, and it was necessary to remove the covers after rains to minimize this effect.

Shrub Conditioning

Although no latex is apparent when a guayule shrub is cut or broken, the rubber is contained in the shrub in the form of latex. In early milling tests, a poor recovery of the rubber resulted from milling fresh shrub which contained uncoagulated latex that was lost in the water added in milling. It was accordingly considered necessary to condition the shrub before milling, to bring about the coagulation of the latex.

Coagulation could be brought about by storage for a sufficient period prior to milling, but several conditions needed attention. Elevated temperatures, such as were found in Texas and the inland valleys of California, were effective in bringing about coagulation, but direct exposure to the sun caused a loss of rubber if permitted for more than a single day. Drying of the shrub to below about a 20 per cent moisture-content reduced the recovery of rubber in milling. It was therefore necessary to restrict the exposure of the shrub to direct sunlight and to control moisture-loss during storage, while at the same time providing a storage period of thirty to forty-five days to obtain complete coagulation of the latex.

A major contribution to the milling of guayule shrub was made by Taylor & Chubb (1952) who demonstrated that, by the use of suitable coagulants in the water used in milling, lush shrub direct from the field could be milled successfully. This eliminated the necessity for prolonged storage and produced a superior type of rubber with a low content of insoluble plant debris.

Extraction of Rubber from Guayule

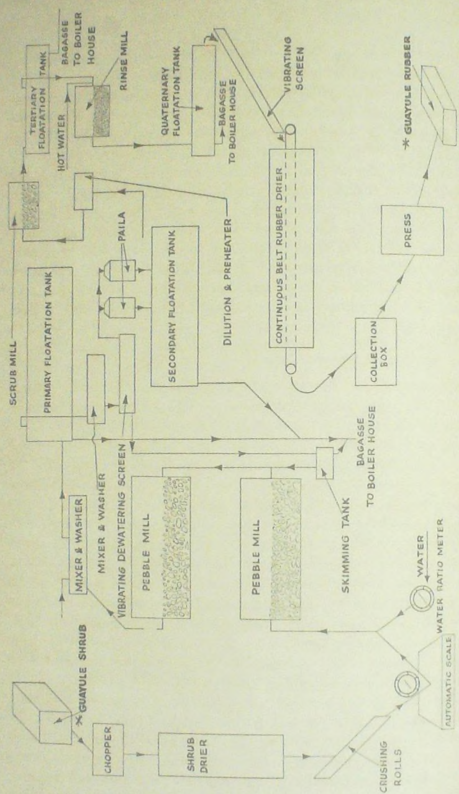
General Process

Since the beginning of the twentieth century, thousands of tons of rubber have been extracted from guayule—mostly from wild shrubs in Mexico. The mechanical processing has consisted primarily of macerating the shrub in the presence of water in a pebble mill. Shredded shrub and water are fed into a pebble mill in predetermined proportions. The grinding and macerating action of the mill is furnished by flint pebbles of assorted sizes. The mill consists of a horizontal tube that is revolved slowly. As it turns, the pebbles roll over and over and continuously fall on and crush particles of shrub. The non-rubber portions of the shrub are ground finer and finer by this action and at the same time become waterlogged. When particles of rubber are caught together between the stones, or between the stones and the rough lining of the mill, they stick together and gradually form small masses that are commonly known as 'worms' (cf. Plate 37(*a*)).

At first, the milling of guayule was done in small individual mills, the batch process that required loading, unloading, and reloading of many small mills being employed. It was found later that long tubes could be loaded and unloaded continuously. A diagrammatic outline of the process is shown in Fig. 5.

The baled and conditioned shrub is first run through a chopper; from there it goes through a heated dryer to a crusher consisting of two heavy, corrugated, slowly revolving rolls. The crushed shrub is then mixed with water and fed into the first of a series of pebble mills, after which the slurry—consisting of moisture-laden, ground, partially waterlogged plant material and rubber particles agglomerated in the form of worms—flows into the flotation tanks, where the rubber particles float and the waterlogged plant debris sinks.

Additional washing and flotation processes are required to rid the rubber of adhering particles of cork and fibre and to eliminate as many as possible of the insoluble impurities. The rubber is next carried over a vibrating screen to free it from as much water as possible. It then goes



Courtesy of United States Forest Service

FIG. 5.—Diagrammatic outline of guayule extraction process.

through a dryer where the remaining moisture is removed and, lastly, to a press which compresses it into 100-lb. blocks for shipment to market.

Elimination of Leaves

A significant improvement made by the Emergency Rubber Project in the processing of guayule was the elimination of the leaves prior to extracting the rubber. The leaves constitute 15 to 33 per cent of the dry-weight of young guayule shrub and contain very little rubber—indeed none that could be extracted in the standard milling process. Guayule leaves are not deciduous and do not form an abscission layer. It is not possible to remove the leaves in the field by the use of defoliants. However, following up work previously started by the Intercontinental Rubber Company, it was found that, after boiling, the leaves could be removed from the shrub merely by shaking the plants vigorously. It was then found possible to pass the entire bale through tanks of boiling water and thereafter eliminate the leaves on shaking machines. The leaves, having no value as a source of rubber, were used as fertilizer because of their high nitrogen-content.

Post-war Research on the Processing of Guayule Shrub

Post-war research by the Bureau of Agricultural and Industrial Chemistry of the United States Department of Agriculture was effective in simplifying and improving the extraction of rubber from guayule. Two major accomplishments of this project were the demonstration of the milling of lush shrub, which has already been discussed above, and the de-resination of guayule rubber. These two contributions resulted in the production of rubber on a pilot-plant scale that was fully equal to *Hevea* rubber in the manufacture of heavy-duty vehicle tyres.

Milling of Lush Shrub. Guayule rubber extracted from wild shrub had as high a proportion as 20 per cent of plant debris insoluble in either benzol or acetone. This material weakened the rubber and caused its failure in tensile tests. Preconditioned shrub from cultivated fields was also difficult to process without leaving a high percentage of insoluble materials in the rubber. Lush green shrub does not powder so easily in the milling, and does not contribute the fine materials that remain in the rubber in milling dried wild or cultivated shrub.

De-resination of Guayule. A practicable method of de-resinating guayule has been sought for a long time. In the second decade of the present century, at least one large manufacturer in the United States de-resinated guayule rubber on a fairly large scale. The Intercontinental Rubber Company conducted extensive research on methods of chemical de-resination of guayule rubber. The success of the Bureau of Agricultural and Industrial Chemistry stemmed not only from developing efficient equipment and processes for the chemical extraction of the resins, but also from preceding this treatment with effective processing of lush shrub to eliminate the insoluble impurities.

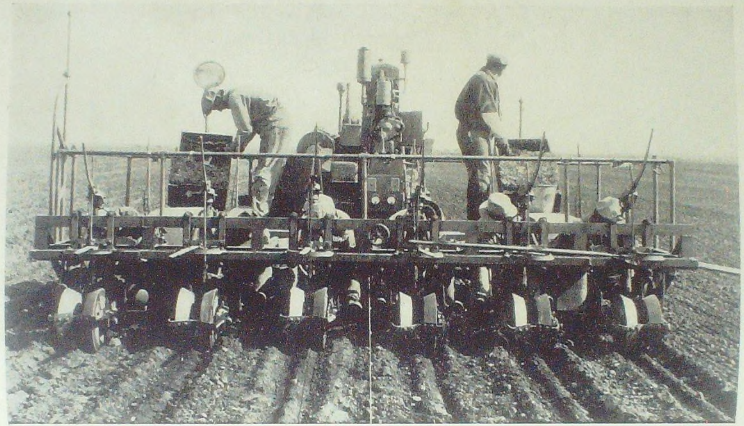
By-products. In the de-resination of guayule rubber, it was demonstrated that many of the non-rubber constituents of the rubber, that are eliminated in the de-resination process, have considerable potential value. These include polyisoprenoids, saturated and unsaturated fatty acids, waxes, and shellac-like drying resins. Such by-products do not have commercial value at present; but if guayule rubber were produced in quantity, commercial uses would undoubtedly be found for them.

Photographs by permission of ARS, U.S. Dept. Agric.

(*a*) Front view of guayule transplanter showing crated seedlings and assembled crew.

(*b*) Oil being applied as a herbicide in a guayule planting.

PLATE 42



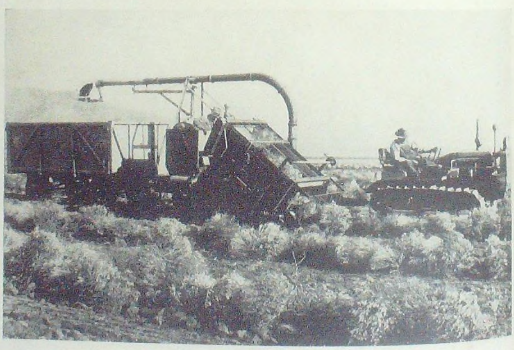
Rear view of guayule transplanter in operation.

PLATE 43

A dry-land planting of guayule. Plants in rows 36 in. apart.

PLATE 44

(*a*) Cultivating a field of guayule in California. As the plants become larger, some mechanical injury of the plants is unavoidable.

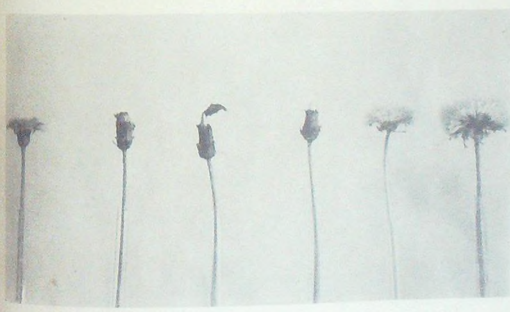


(*b*) Guayule plants harvested for rubber extraction.

PLATE 45

Photograph by permission of ARS, U.S. Dept. Agric.

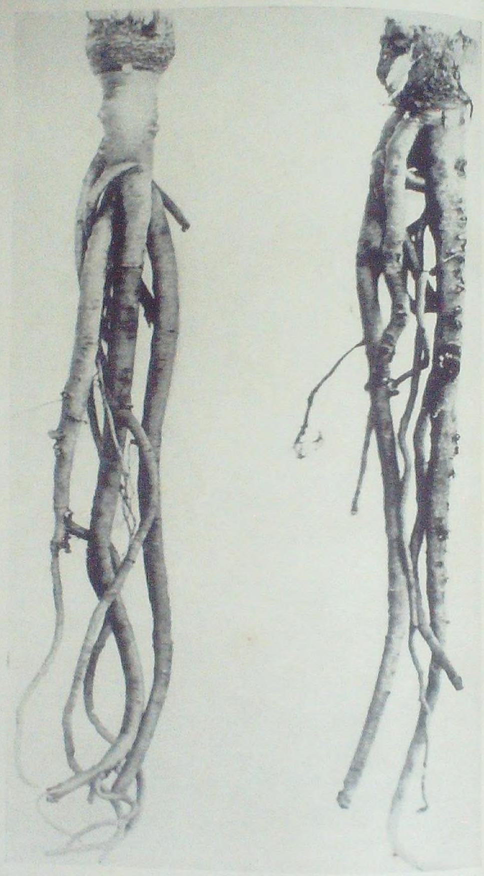
(*a*) Harvesting the 'seed' of kok-saghyz by hand.



Photograph by permission of U.S. Dept. Agric.

(*b*) Stages in the development of the kok-saghyz flower-head—cf. p. 251 (Table XIV).

PLATE 46



Photograph by permission of United States Forest Service

Typical roots of kok-saghyz. Such roots may have a length of from eight to twelve inches.

PLATE 47

Photograph by permission of U.S. Dept. Agric.

Showing various degrees of branching of kok-saghyz roots.

PLATE 48

XI

PRODUCTION OF RUBBER FROM KOK-SAGHYZ

CLIMATE

Temperature and the Seasons

DURING the growing-season, kok-saghyz thrives at a cool mean temperature in the 60° to 80°F. range, with minimum temperature, down to 43°F. and maximum temperatures up to 95°F. or higher. Young seedlings have been killed by early frosts when planted in the autumn, and winter killing of dormant, mature plants has resulted from damage caused by heaving of the soil during winter thaws.

Whaley & Bowen (1947) state: 'The fact that best results have been attained in the northern third of the United States and in southern Canada suggests that the plant grows better where average daily temperatures are not too high, where very high temperatures do not remain for continued long periods, and where nights are usually moderately cool.'

R. H. Roberts (1947) found that, in the greenhouse, kok-saghyz plants grew better and attained a higher rubber-content when grown continuously at a temperature of 55°F., or alternating 55°F. night and 75°F. day temperatures, than when grown at 75°F. continuously. Borthwick *et al.* (1943) found that cool temperatures and long photoperiods were favourable to early blooming of kok-saghyz seedlings.

Kok-saghyz as a Winter Crop. Kok-saghyz can be grown as a winter crop in the southern parts of the United States, where winter temperatures simulate those found in the northern States in the summer growing-period. Low temperatures restrict the areas suitable for winter planting, as the young seedlings do not survive temperatures below about 20°F. High summer temperatures in these areas favour the development of root diseases, and it is necessary to harvest the crop before the onset of hot weather.

Over-wintering of Kok-saghyz. Carrying kok-saghyz over the winter, for spring harvest or for seed production and second-year harvest, is difficult in many areas where the climate is nevertheless quite favourable for the production of kok-saghyz as an annual crop. Freezing and thawing of certain soils may result in a heaving that damages kok-saghyz, irrespective of the temperature. Winter snow-covers favour the over-wintering of kok-saghyz by minimizing the occurrence of winter thaws and of soil heaving.

Rainfall

An annual precipitation of around 20 in. is needed for kok-saghyz. The high water-holding capacity of the soils of its native region, and the low rate of evaporation, are equally effective with the actual precipitation in maintaining the moisture-content of the soil. Under cultivation, it is essential that the moisture-level of the soil be high during both the germination period and the early stages of growth of the young seedlings. In nature, summer dormancy stems from the extreme drought at the end of the initial growing-period of summer. Under cultivation, this dormant period does not occur if there is low moisture-stress during July and August.

SOILS

Kok-saghyz has certain specific requirements that must be considered in selecting soils. The 'seeds' of kok-saghyz are small and, in planting, are covered very shallowly. Heavy rains or soil washing during the period of germination may result in the loss of many seeds or seedlings before the crop can become established. After germination, aerial growth is extremely slow until a substantial amount of root growth has occurred. During this period, weed growth may crowd out the kok-saghyz seedlings, hide the planting lines, and make machine cultivation difficult or impossible. The crop history of the soil is, therefore, of great importance, and abandoned fields, or those that have not been maintained in a high state of cultivation and weed suppression, should be avoided.

Kok-saghyz is a root crop that must be ploughed out at harvest time and, as the roots are relatively small, the soil must be of a type to encourage maximum root growth, and must moreover be sufficiently friable for easy ploughing and separation of the roots from the soil. Good capillarity and water-holding capacity are important to ensure adequate moisture for germination and growth. Good drainage, both superficial and internal, is essential.

Soil Type. Altukhov (1939, 1939*a*) indicated that both chernozems (black mineral soils) and organic soils are suitable for kok-saghyz culture. He stated (1939) that the soil must be rich in organic matter, in nitrogen, and in phosphoric acid. Russian farmers were advised by the U.S.S.R. Government (1941) to select for kok-saghyz plantings the best plots, using first the peat soils under cultivation, truck garden plots, flood-plains of rivers, and fertilized fields planted previously with hemp. Polovenko *et al.* (1943) considered as unsuitable for kok-saghyz any soils with poor structure that formed a crust after rain, or that were too shallow, poor in nutritive value, or too light to retain water.

Soil Texture. In the United States, the most satisfactory results were obtained where surface soils and subsoils ranged in texture from loam to silty clay-loam. Light soils are more desirable from the standpoint of workability, but are more subject to drought and soil-blowing, and are usually less fertile, than heavier-textured soils. However, light soils underlain by a clay layer or permanent water-table at about 30 to 40 in. usually provide adequate moisture. In humid regions, soil textures ranging from silty clay-loam to clay are generally favourable from the standpoint of moisture, but they tend to compact and to bake and crust. In regions of low rainfall, these soils are not considered favourable. Difficulty is experienced in harvesting roots from heavy-textured soils, and the roots are often distorted, their penetration into the lower layers of the soil being limited or inhibited.

Soil Acidity. Kok-saghyz does best on soils with pH ranges of 5·5 to 8·5. Whaley & Bowen (1947) concluded that, unless the supply of available calcium in a soil is known to be high, it would be unwise to select for kok-saghyz production any soil, mineral or organic, where the pH is below 5·5. Even at this pH, it would be advisable to use lime in addition to the regular fertilizers. Where the surface soil has a range in pH of 8·5 to 9·3, satisfactory growth results if the underlying soil horizons are permeable and have good drainage and less than 0·2 per cent of soluble salts.

Organic Material. Kok-saghyz can be grown on soils that range from as low as 2 per cent to as much as 90 per cent of organic matter. Good results have been obtained on peats, on mucks, on mucky phases of mineral soils, and on mineral soils that range in organic-matter content from about 2 to 8 per cent. The beneficial effect of organic matter results from the physical properties of the soil. Organic matter tends to promote granulation and increase moisture-holding capacity, the rate of percolation, and the amount of total pore space.

CULTIVATION

Land Preparation

Careful land preparation is essential to promote root growth and facilitate weed control: autumn ploughing for spring planting is considered best. Only a minimum of seed-bed preparation should be done in the spring, and that immediately prior to planting, while light harrowing at intervals, or use of shallow cultivating or weeding devices, is necessary to control weeds without causing excessive loosening of the soil after the preliminary ground preparation.

Deep ploughing is essential, as shallow ploughing may fail to create a suitable zone for the development of the roots. The shallow plough sole may create a difficult barrier for the roots to penetrate, and this may constitute a point of shear at the time of harvest, resulting in the breakage of roots and the loss of the root material below that level.

After ploughing, efforts are directed toward firming the soil and establishing sufficient capillarity and permeability to ensure effective moisture distribution and control. The final step is to provide a level seed-bed without clods, and with a thin dust mulch not over ½ in. in thickness. This last step is the only one to be taken immediately prior to planting, and should be accomplished with a minimum stirring of the previously prepared soil.

Levelling of the seed-bed surface is an essential operation. Unevenness of the surface makes it nearly impossible to ensure evenness of the seeds' covering in planting. Slight depressions that allow water to accumulate and stand may result in the loss of seedlings. In laboratory tests, it was found that evenness of cover is vital with kok-saghyz seed. The best germination resulted with 1/8-in. cover, whilst a progressive drop in germination rate occurred with covers from 3/16- to ½-in.; with covers of ¾-in. or more, there was no germination. In field operations, moisture control is not equal to that possible in the laboratory, and the goal is to have a ¼-in. cover over the seed. Less than this results in the loss of seed through drying, and covers of over ½-in. reduce the rate of germination.

Planting

Time of Planting. It is desirable that kok-saghyz seeds be planted as early in the spring as possible, as they germinate readily at low temperatures which delay germination of the seeds of many competing plants. Kok-saghyz also needs a maximum period for building up a large root and a high rubber-content before the end of the growing-season. Late autumn planting has been tried, both in Russia and the United States, with some success. It is necessary to plant late enough to avoid germination before winter and, under favourable conditions, excellent stands of kok-saghyz have thus been obtained. In the South, where kok-saghyz is grown as a winter crop, it should be planted around the first of November—to give a maximum period of growth and allow harvest before the onset of summer temperatures.

The Seed. Kok-saghyz seeds are very small and must be handled carefully to get even distribution and uniform cover in planting. Lysenko (1941*a*) states that kok-saghyz seeds average about 1,360,000 to the lb. Whaley & Bowen (1947) state that seed produced in Minnesota ran about 1,217,000 to the lb., and that the seed received from Russia ran about 940,000 to the lb.

Germination of the Seed. Freshly harvested seeds of kok-saghyz germinate readily, but soon enter into a dormant condition that must then be broken to get uniform and quick germination. Several methods have been developed to pre-condition the seed before planting. These methods were originated primarily by various Russian investigators, including Poptsov (1935), Lysenko (1941, 1941*a*), and Zasiadnokov (1941). In the United States, Brandes (1942), Coster (1943), Kluender (1943), Roe (1943), Zehngraff (1943), and Hamm (*see* Steinbauer, 1944) made specific contributions to the understanding of the factors involved in the pre-conditioning of kok-saghyz seed. The pre-conditioning treatments involve primarily the soaking of the seed for short periods, with or without the use of reduced or otherwise controlled temperatures, followed by drying at a low temperature to a moisture-content suitable for feeding through a seed planter.

The basic stratification * system developed in Russia involved keeping moistened seed at a freezing temperature for ten to fifteen days, or until test seeds germinated readily. The seed can then be partially dried at a low temperature and taken to the field for planting. For slowly germinating seed, treatment at 50° to 55°F., including stirring at two- or three-hour intervals for a day or so, may be necessary between the stratification and planting. Lysenko (1941) outlined an alternative method by which the seeds are soaked for several hours, partially dried, aerated at room temperature until germination starts, and then stored in a cold room until they are ready to plant. Roe (1943) simplified the latter method by merely soaking the seeds for twenty-four to forty-eight hours, and then drying them sufficiently to enable feeding through the planter.

Hamm (*see* Steinbauer, 1944) studied the relationship of temperature to germination of kok-saghyz seed and found two optimal germinating temperatures, 5°C. (41°F.) and 25°C. (77°F.). At these temperatures germination was complete, while at intermediate temperatures it was incomplete. Hamm found that, if the seed-coat was removed, the seeds germinated completely at all of the temperatures tested, and concluded that the seed-coat probably was the principal cause of incomplete germination at the intermediate temperatures, and quite likely at all reasonable temperatures.

Zehngraff (1943) made a comprehensive test on a field scale of the value of different methods of pre-conditioning kok-saghyz seed. His tests included untreated seed, pre-chilling, KNO_3 treatment by a method suggested by Hamm (1944), the Roe method (*see* above), and complete vernalization or pre-germination. The last-mentioned treatment involved exposing moist, pre-chilled or soaked seed to slightly below room temperature (60°F.) for two days, or until about 2 per cent had sprouted. The seed was then placed in cold storage (32° to 40°F.) to prevent further germination. A standard planting rate was used and the results of the test were measured in terms of the number of plants per linear foot of row at the end of thirty days. The results were: pre-germinated seed, 11·6 plants; pre-chilled, 6·9 plants; Roe method, 3·3 plants; KNO_3 treatment, 0·7 plants; and untreated check, 0·2 plants.

* Stratification is a term used to designate any method of inducing germination of seeds that are difficult to germinate by normal techniques, by stratifying them in soil, vegetable, sand, or other suitable material. In this condition the seeds are subjected to temperatures and moisture conditions comparable to those that would be encountered in their natural habitat, particularly to those occurring in winter.

Coster (1943) found that pre-conditioning of the seed was not necessary if irrigation facilities were available so that the plantings could be kept moist. Kluender (1943) reported that, in wet weather or when plentiful moisture was available in the ground, untreated seed germinated as well as, or better than, pre-conditioned seed.

Planting Equipment. Altukhov (1939) recommended sowing kok-saghyz with a disk drill to which rollers were attached to firm the seed in the soil. To get even distribution of the seed, he suggested, as did Zasiadnokov (1941), the use of fillers such as millet chaff or dry sawdust at mixture rates of up to fifteen parts of filler to one of seed, by weight. The use of sugar-beet equipment was advocated by Takushin (1939). Single-row plantings were the commonest, four rows being planted at a time using horse-drawn equipment, and eight to nine rows at a time using tractor-drawn equipment. Altukhov (1939) found that, in weed-free areas, two to four, or more, rows could be planted together, leaving strips for cultivation between the beds. This increased the number of plants per acre but made subsequent cultivation difficult.

Sugar-beet planters did not prove satisfactory in the United States. Planet Junior-type planters proved best when hooked up as single units to a planting bar so as to give flexibility in conforming to the contour of the ground. An eight-unit planter was found suitable.

It was thought at first that the seed could not be dried to less than a moisture-content of about 35 per cent after the pre-conditioning. Considerable difficulty was experienced in obtaining an even flow of this seed through the planters. However, tests showed that the seed could be dried to 25 to 30 per cent moisture-content without damage. Seed of this lower moisture-content can be fed through the planter without difficulty.

Seed Covers. In Russia, the use of seed covers such as peat and sand was found to be advantageous. This was also found to be true in the United States where, however, the additional cost did not appear to be justified, although it was possible to demonstrate that the use of a sand cover would reduce the sowing rate by as much as 50 per cent and still give as good or better a stand of plants.

Seeding Rate. Whaley & Bowen (1947) stated that, to obtain fifteen plants per foot of row at the end of the season, it is necessary to make the initial planting at a rate of about 3 lb. of seed per acre. They conclude, however, that even this heavy rate should be increased by as much as 50 or even 100 per cent under poor conditions or in rough seed-beds.

Vegetative Propagation and Transplanting. Kok-saghyz can be propagated readily by cutting the root into 1-in. pieces, when each piece can be rooted. The crown can also be preserved and rooted. This method of propagation is highly advantageous in increasing the number of individual plants that are to be used for breeding purposes in a plant-improvement programme. If the cuttings are to be shipped to another location, it is preferable to ship the whole root and to make and root the cuttings where they are to be planted.

Spacing, Density, and Thinning

In general, the farming equipment available in any community, and the farming practices of that community, will dictate the spacing for kok-saghyz within rather flexible limits. If row crops are raised in 18-in. rows, it is usually best to plant kok-saghyz at that spacing so as to use the available farm equipment without change.

The problem of spacing and density involves both root and seed production. On the basis of the available information, it is not possible to state categorically whether it is best to have the plants spaced thickly in widely-spaced rows, thinly in closely-spaced rows, or in multi-row beds. Probably no general rule would be possible, and soil and other variables, including the availability of planting and cultivating equipment, would dictate the spacing between rows; moreover the desirable density within the row will be related to soil types as well as to the total number of plants per acre. The extremes in spacing between single rows or beds are from 16 to 24 in., with the wider spacings necessitated by irrigation furrows or separation of closely-planted beds. There is considerably greater variation allowable within the row. This may be unthinned and have a density of over forty plants per linear foot of row, or the density may be as low as three or four plants per foot. With lower densities and wider spacings, the individual plants grow larger but, in general, the weight of roots per acre and the yield of rubber are greater with closer spacing and higher densities.

Thinning. Thinning is a hand operation, as the close spacing required is difficult to attain mechanically. Whaley & Bowen (1947) state: 'The evidence suggests that thinning is not warranted in stands having less than 40 plants per linear foot of row.' Lysenko (1941) maintained that the thinning of heavy stands at the time of the first hoeing is essential. He recommended that several plants be left in a group to occupy 3 to 4 cm. (1·2 to 1·6 in) of a row, with about 10 cm. (about 4 in.) between groups.

Weed Control

After kok-saghyz emerges from the ground, its aerial growth is almost static for a period of several weeks while the root is developing. During this time, the development of weed plants may obscure the kok-saghyz rows and make machine cultivation and weed control difficult. Nurse crops, such as lettuce, have been used with some success to mark the rows and facilitate initial machine cultivation. Even with this, however, it is necessary to keep away some distance from the row, to avoid injury to the kok-saghyz.

Nutrition

Kok-saghyz requires rich soil and, on soils that are deficient in one or more of the elements needed for plant growth, reacts favourably to the application of fertilizers. In some cases, it has been possible to do better than double the yield of roots through the use of fertilizers. On the other hand, if the soil already contains an adequate supply of any given element, the addition of that element in the form of fertilizer will not result in increased growth and may even decrease the yield. Heavy applications of phosphates when ploughing in the autumn have been effective in increasing the growth of kok-saghyz the following spring. Phosphorus may be added either at the time of ploughing or in early spring. Nitrogen and potassium should be applied as to one-half at planting time, one-quarter at the bud stage, and one-quarter at the time of full flowering. On acid soils, the application of fertilizers has usually been ineffective unless accompanied by the application of lime.

Diseases of Kok-saghyz

An unidentified yellowing of the leaves of kok-saghyz in plantings in the Red River Valley in Minnesota was reported in 1943. The inner leaves of the rosettes were yellow and curled, and the flowers and scapes were conspicuously distorted. The disease was distributed throughout the fields, but affected only a few plants. Pathologists thought this to be an aster-yellows disease, but no positive identification was made. Other than this, and minor leaf-spots caused by species of *Ramularia* and *Alternaria* and various bacterial infections, all diseases reported in the United States were either of the damping-off type, before and after emergence, or root-rots.

Specimens of diseased material were collected from most of the kok-saghyz-producing areas in the United States. Hanson (1943) and Steinbauer (1944) were able to make preliminary reports on studies of the disease-producing organisms; these included species of *Rhizoctonia*, *Fusarium*, *Pythium*, *Sclerotium*, *Sclerotinia*, *Botrytis*, *Ramularia*, *Alternaria*, and *Phoma*, also *Erwinia caratovora*, *Agrobacterium tumefaciens*, and *Xanthomonas* sp.

Seed-borne Diseases. Disease organisms may be carried on the seed and result in pre-emergence losses, damping-off, or root-rots. Extensive tests were conducted on the seed received from Russia, as well as from lots of seed produced in the United States. The most common organism isolated from the Russian seed was a species of *Fusarium*, but the seeds were relatively clean, and less than 3 per cent of them were found to be infected. Infection of seed produced in the United States ran much higher, being from 6 to 55 per cent. Seed grown under the comparatively dry conditions in the West showed very little infection, whereas that grown under more humid conditions showed relatively high incidence of infection.

Effective fungicidal treatments were developed for the seed. Metrox (purple cuprous oxide) proved best, and copper carbonate was also satisfactory. The use of fungicides increased the rate of germination of the seed and reduced post-germination damping-off. Seeds that had been treated could be given the pre-conditioning treatments without impairing the effectiveness of the fungicidal treatments.

Root-rots. Root-rots tend to limit the cultivation of kok-saghyz to northern areas where the temperatures serve to keep the rotting organisms in check. In most areas, kok-saghyz is little affected by disease as long as its growth is vigorous. Lack of nutrients, poor soil-drainage, high temperatures that bring on summer dormancy, and other conditions that slow growth, result in a high incidence of root-rots. A heavy incidence of root-rot was reported by Coster (1943) in plants carried over a second winter. Root-rot is the principal factor terminating the winter growing-season in Florida, where the roots must be harvested before the onset of weather favourable for the diseases.

The chief cause of failure in making and shipping callused root-cuttings was the incidence of root-rots. No satisfactory method was developed of treating the cuttings after they became infected, although several precautions were found that would minimize the occurrence of root-rots in cuttings. Roots for cuttings should be in a state of vigorous growth, as the incidence of rots on dormant roots is high. Roots should be hardened and stored at low temperatures as soon as they are dug. It is better to ship the whole root rather than rooted cuttings. Storage rooms, callusing trays, packing materials, etc., should be kept free from pathogenic organisms, and diseased roots should be carefully eliminated at the time of digging.

Root-rots were also a serious factor in the shipment of roots harvested for rubber. In several instances rotting started in temporary piles in the field, and the piles had to be spread out to dry in the open air and sunshine. In another case, a railcar-load of fresh roots arrived at the pilot extraction factory in Philadelphia, Pennsylvania, with about one-half of the shipment rotted, owing to heating in transit. This did not harm the rubber, but the putrid mass of roots was difficult and unpleasant to handle.

Insect and Other Pests

Grasshoppers and leafhoppers did some damage in the kok-saghyz plantings in the northern United States. Approximately 20 per cent of the plants in one field were completely defoliated when about four months old. The plants were not killed but sent up new leaves by late autumn. The development of the plants was delayed, and they did not flower by June of the next year as would have been expected of normal second-year plants.

Root injury caused by white grubs in the Lake States and in Montana was not serious. In Florida, there was a serious infestation by two species of cutworms that required the use of poison baits for control.

Skabrilovich (1940) reported that, in Russia, kok-saghyz is quite susceptible to nematode injury. There was some nematode injury in the United States but it was not serious.

At Edinburgh, Texas, nearly half of the seed-heads were infested with larvae of a small moth, *Homoeosoma electellum*. This moth laid its eggs in the flowers, and the larvae fed on the seeds as they developed. Engstrom *et al.* (1944) reported a reduction in this infection after dusting the flowers with calcium arsenate; but there was some question as to whether the reduction resulted from the dusting, or whether the end of the insect's larval cycle had been reached.

Rogueing

In nature, kok-saghyz occurs in mixtures with other dandelions. It hybridizes readily with several of these, and collections of wild seeds contain seeds both of the other species and of natural hybrids. None of the other species contains sufficient rubber to justify its use for rubber production, and none of the hybrids has been reported to be of value for rubber. Many of these species and hybrids are more vigorous than kok-saghyz and, if allowed to grow, will soon dominate the planting.

Before using any field of kok-saghyz as a source of seed, it is essential that all off-type plants be eliminated. The rogueing should be done at least three times, the first occasion being as soon as the leaf characters are apparent, i.e. about the time the leaf rosette is first formed. The second rogueing should also be made on the basis of leaf characters; it should be carried out when the full complement of leaves has been formed, but before flowering starts. The third rogueing should be done on the basis of the floral characters, but before the off-type plants have produced pollen.

It is also important that rogue plants be eliminated from fields that are to be used only for rubber production. Many of the rogue dandelions are relatively vigorous, and tend to outgrow and crowd out the slower-growing kok-saghyz. If allowed to remain, this aggressive minority may contribute a majority of the root-crop at the end of the season. The earlier these non-rubber species are removed the better for the kok-saghyz, as the competition of these close relatives may be more restrictive of the growth of kok-saghyz than is that of other weeds. For rubber production, therefore, the first and second rogueings, which depend on leaf characters, are the most important. The third rogueing, performed on the basis of floral characters, should not be eliminated but, as the aerial portion of the plant has reached its maximum, scarcely serves to decrease competition to the degree that the first two rogueings do. As seed production is not an object of the plantings, the third rogueing may be delayed until the field is in full flower.

Seed Production

Flowering. In Russia, kok-saghyz flowers some sixty to seventy days after sowing. In the United States, the first flowers have been reported from forty-two to ninety days after sowing. There are two types of plants that are distinguishable only through their flowering habits; one type regularly flowers in its first year, and the other does not flower until the second year. By selecting for first-year flowering, Koroleva (1940*a*) demonstrated clearly that the two types are genetically different. In nature the plants do not flower in the first year; however, under cultivation, 20 to 30 per cent of the plants flower in the first year. Koroleva selected only first-year-flowering plants, and in the first generation was able to get 50 per cent of the plants to flower in the first year. Selection was continued in successive generations and the fourth generation of plants were pure for this character and all flowered in the year of sowing.

Conditions of growth affect the flowering of kok-saghyz and, under adverse conditions, plants that otherwise might be expected to flower in the first year may fail to flower then. In the United States it was also noted that there was a difference among the plants that flowered in the first year, some flowering early and some late. Zehngraff (1943) studied the correlation between flowering habit and rubber-content, and reported that plants which flower early in the year have a lower rubber-content than those which flower later. Coster (1943) reported that the plants which did not flower in the first year produced the largest roots, the greatest tonnage per acre, and had the highest rubber-content. It was not demonstrated whether this higher rubber production resulted from a genetic difference, or from physiological differences that might have been due to the failure of the plant to flower.

Pollination

Kok-saghyz is primarily insect-pollinated, bees appearing to be the chief agents. Wind-pollination may occur but, being limited to a short distance, is probably not a substantial factor in the reproduction of the plant. Cross-pollination is the rule—probably without exception during the flowering-season, though there is some self-pollination during the latter part of the season.

Seeding Season

A period of only twelve to fifteen days elapses between the fertilization of the flower and maturity of the seed, and seeding (active seed production) starts soon after the initiation of flowering. Summer dormancy may put an end to seeding or, if there is no summer dormancy, the seeding may continue for several weeks. In Florida, it was reported by Erambert (1944) that kok-saghyz started flowering fifty-six days after a November planting, though the plants did not reach maximum flowering until 20 February. Seed was produced in considerable amounts over a sixty-day period. In the northern States, first-year kok-saghyz produces seed in June and July, but in the second year, seed production may start in May. Seed of good quality has been produced in Wisconsin during a period of mild weather in October, following a hard freeze in late September. Altukhov (1939) reported that the seeding season in Russia lasts for two to three months in first-year fields, and for two months in second-year fields.

Seed Harvest. When the seeds of kok-saghyz are ripe, the flower-head develops into a fluffy round ball and the seeds are easily detached and dispersed by the wind. The seed-collecting season extends for a long period and it is necessary to pick the seed daily (Plate 46(*a*)) to avoid considerable loss of seed. Altukhov (1939) reported that seed collection in first-season plantings requires the services of three or four men per hectare (2·47 acres), and in second-year plantings eleven to twelve men per hectare, each day of the seed season. Yields were reported as 20 to 30 kg. of seed per hectare (18 to 27 lb. per acre) in first-year plantings, and 80 to 100 kg. per hectare (71 to 89 lb. per acre) in second-year plantings.

The best yield of seeds in the United States, as reported by Whaley & Bowen (1947), was 1,218 lb. of seed from 31·16 acres—an average of about 39 lb. of seed per acre. Hurtt & Reed (1944) computed a theoretical yield from a small plot at Miles City, Montana. They counted all of the seed-heads produced on sample plots during the period from 20 May to 15 June, 1943, and reported that the average head contained 100 seeds and that 95 per cent of these were filled. Their computation indicated, for the stock seeded in the autumn of 1942, 265 lb. of seed per acre from single rows, 255 lb. per acre from double rows, and 381 lb. per acre from triple rows.

Both in Russia and in the United States, hand-harvesting of the seed has been the most effective method of obtaining maximum yields. Lysenko (1941) revealed that Russian investigators had developed a suction machine that could readily be constructed by a farmer. This machine was said to increase the efficiency of collection by no less than fifteen times, and to reduce the trampling and compaction of the soil by large numbers of labourers engaged in daily hand-picking.

Stoeckeler (1943) described the Aamodt machine, a modification of the Russian machine, that was constructed in the United States, first as a one-row manually-operated picker and then as a two-row power-operated machine. Ramp (1944) combined the best features of the Russian machine and the Aamodt machine, and developed a new picker that could be used either as a single-row picker or combined into a four-row unit. There has not been sufficient experience with any of this equipment to determine its efficiency in harvesting a maximum portion of the crop.

Stage of Development for Harvest. Whether the seed is picked by hand or by machinery, it is necessary to know the stage of flowering that is best for picking. As reported by Whaley & Bowen (1947), the Lake

States Experiment Station and the Minnesota Agricultural Experiment Station co-operated in preparing the guide to the stages of floral development that is shown in Table XIV and illustrated in Plate 46(*b*).

TABLE XIV

STAGES OF DEVELOPMENT OF KOK-SAGHYZ FLORETS AND SEEDS

Stage	Development
1	The yellow florets are fully open.
2	The florets have closed, with the tips of the yellow corolla-lobes protruding above the involucral bracts. Pappus not visible.
3	Seed-head closed, with dried yellow to brown corolla resting on top of visible white pappus. Remains of corolla can be pulled off readily. Seed still firmly attached.
4	Remains of corolla sloughed off. Pappus protruding as white tuft above the urn-shaped to slightly spreading involucre. Seed adhering fairly firmly. This is the best stage to collect seed by hand.
5	Seed-head partially open, so that pappus forms a hemisphere. Seed comes loose with moderate pull but cannot be blown loose by light puff of wind. Hairs of each pappus are unfolded to give shape of a small parachute. Seed should not be allowed to advance beyond this stage if it is handpicked and if maximum recovery is desired.
6	Seed-head forming practically a full sphere. Involucral bracts reflexed. Seed readily detached by a slight puff of wind. At this stage, seed must be picked as often as twice a day to prevent natural dispersal. This is the only stage at which efficient mechanical seed-collection by suction devices appears feasible, although some seed in late stage-5 of development may be detached with strong suction.

Seed Thrashing and Cleaning. Much trash and dirt is collected with the seed. In hand-picking, the entire seed-head is picked, and the flowers, immature seed-heads, and flower scapes, constitute the major portion of the collection. Machine collection is done after the seed-head has expanded, and less of the flower-head and other plant parts may be included; but there is a high proportion of dirt that is even harder to separate from the seed than the plant debris.

The plant trash collected with the seed in hand-picking may be separated by rubbing the mass on a screen, consisting of a 1-in. chicken wire or ½-in. hardware cloth, followed by final rubbing on a 14-mesh screen. Dry weather and a gentle breeze help the operation, which is quite difficult in humid weather. Under optimum conditions, it is possible to separate plant debris and remove the pappus by a single rubbing through a 14-mesh screen.

Storage of Seed. The storage of seed dried to less than 12 per cent moisture has apparently not been a serious problem in Russia, although in the United States it has been difficult to store kok-saghyz seed for an extended period without serious loss in germination. Roe (1943) made a test on seeds of Russian origin. The test sample was dried to a moisture-content of 9·3 per cent and kept in a sealed jar at 41°F. A check sample was stored unsealed at room temperature. The test was initiated in May 1942 and, in July, the original seed lots showed an actual germination of 82 per cent, with no abnormal seedlings, and a potential germination (by adding the number of hard, ungerminated seeds at the end of the test) of 92 per cent.

Tests of the unsealed check sample held at room temperature were made in April, 1943, and showed a germination rate of 45 per cent, with 19 per cent additional abnormal seedlings. By September 1943, viability of this lot had dropped to 13 per cent plus 26 per cent abnormals. The September 1943 tests of the sealed sample showed a germination rate of 88 per cent.

Tests made in March of 1945 and 1946 of one- and two-year-old seeds grown in the United States and stored in sealed containers under cool conditions gave, respectively, 80 to 90 per cent germination. Seed kept in open storage at Salinas, California, had a germination of 35 per cent after several years of storage in uncontrolled conditions.

Root Harvest

Time of Harvest

The optimum time of harvest of kok-saghyz for maximum yield of roots and rubber is in the spring, before there has been any appreciable growth. Accumulation of rubber continues throughout the winter period. However, soon after growth is resumed in the spring, the root bark, containing most of the accumulated rubber, is shed by the plant and is soon lost, being no longer available for harvest. The maximum concentration of rubber is present just prior to the shedding of the root bark.

Spring harvest, however, may be delayed by unfavourable weather, and the shedding of the bark may take place before the harvesting of a major portion of the crop has been possible. Spring rains are essential to the germination and initial growth of kok-saghyz, but interrupt ploughing and field preparation. Even though the harvest may be accomplished successfully, there is additional difficulty in restoring the fields and re-planting in time to get satisfactory germination for the succeeding crop.

In the southern United States, the time of planting and the time of harvesting are dictated by the changing seasons, and the crop must be harvested before the onset of hot weather. In the north, the changing seasons affect the time for harvesting but there is much greater latitude in determining the precise time. Decisions as to when to start harvesting the roots must take into consideration factors other than the maximum yield of rubber. If the field is to be replanted with kok-saghyz, it must, after the harvest is completed, be re-established in suitable condition for replanting. These preparatory operations must be completed before the soil freezes. With these factors in mind, a time must be selected for harvest that is as late in the autumn as possible to ensure maximum size of roots and highest concentration of rubber. If the soil does not normally freeze, it is possible to do both harvesting and ploughing as winter operations; but, in most areas where kok-saghyz can be grown to the best advantage, winter freezing of the soil is normal and establishes an end-point for farming operations.

The Roots of Kok-saghyz

The roots (Plate 47) are the only parts of the kok-saghyz plant that are important for rubber, the aerial portions being discarded at the time of harvest. The roots are extremely variable in shape, size, and rubber-content. These factors are inherited separately, and it is possible to select and breed for specific shape and size as well as for ability to accumulate high concentrations of rubber.

The roots vary from single, unbranched roots to fibrous, many-branched types (Plate 48). The root shape is important with respect both to the rubber-content and to the ease of harvesting. In general, the proportion of bark to stele in the root is directly correlated with the rubber-content, and the thicker the bark is with respect to the stele, the higher is the content of rubber. Single, unbranched roots are usually larger but have a lower percentage of bark and thus a lesser amount of rubber than have branched roots. Fibrous roots have a higher percentage of bark but are difficult to separate from the soil in harvesting. Roots that are somewhat branched can be separated from the soil mechanically more easily than simple, unbranched roots, even though the simple roots may be somewhat larger.

Harvesting the Roots

Topping. In harvesting the roots of kok-saghyz, the first operation is to eliminate the non-rubber-bearing tops. Ramp (1943) designed two types of topping machines: one was a motor-propelled rotary mower, which was effective in topping at or just under the surface of the ground. It was considered desirable, however, to top about ½-in. above the root-crown, and the machine proved incapable of topping at that height. The other topping device developed by Ramp was of a sliding-knife type that cut the tops at the desired level but was difficult to keep sharp. Knutson (1943) developed equipment that used weeding knives for topping the kok-saghyz plants. At first, the tractor operator raised or lowered the knives and was able to perform satisfactorily in keeping the knives at the correct height. Later, a shoe was mounted to run on top of the ground to keep the knife from cutting too low, and a compression spring was mounted to keep the knife down. Four sets of these weeding knives were mounted on a cultivator bar to permit topping four rows at a time, but this adaptation was not entirely satisfactory as, on uneven ground, one or more sets of knives either floated or cut too deeply. An advantage of the weeding-knife device was that it left the tops in place to mark the rows for the digger that followed.

Digging. Several devices were used for digging the roots. Milner (1939) states that a sugar-beet lifter was used successfully in Russia for digging kok-saghyz. In the United States, several modified sugar-beet and potato lifters were used. A potato lifter was modified by Ramp (1944) to be mounted below the frame of a farm-type tractor and proved quite satisfactory. This machine, according to Green (1943), was effective in digging and gathering 76·5 per cent of the total weight of roots to a depth of 18 in. An additional 11·4 per cent of the roots were dug but not recovered, and the remaining 12·1 per cent of the roots were below the level to which the digger penetrated.

Washing and Drying the Roots. Dirt and peat particles from the soil must be removed from the roots to facilitate drying, handling, storage, and shipment. If it is not done before, this operation must be performed at the extraction factory, and it is best done before the dirt becomes dry and hard. This is particularly true of roots grown in peaty soils, as the peat after drying is almost impossible to separate from the roots, and constitutes a serious obstacle to effective extraction of the rubber.

Washing. Knutson (1943) described a root washer consisting of a section of corrugated-iron culvert pipe mounted on rollers and set at a slight slope on a frame. Holes $\frac{1}{2}$ in. in diameter were drilled in every other ridge of the pipe, to allow drainage of water and dirt. A spray pipe was inserted into the upper end of the culvert pipe, and roots, fed through it into the upper end of the culvert pipe, gradually worked their way to the lower end as this latter pipe was rotated.

Drying. The roots must be dried if they are to be stored or shipped for some distance. If the roots are to be milled immediately in a local factory, drying may not be necessary under certain conditions, but, with the milling method of extraction used in the United States, some alternative method of coagulating the latex must be employed if the roots are not dried.

Russian recommendations, as reported by Whaley & Bowen (1947), were that the roots be dried at temperatures below 140°F. to a moisture-content of 30 per cent. They cautioned against drying the roots in the sun. McQueen (1943) reported that, in an experimental drying test at Cass Lake, Minnesota, in early May, 1943, the roots dried satisfactorily in the open air in ten to twelve days. In most cases, both artificial heat and forced ventilation were needed to obtain satisfactory drying without the development of moulds or rots.

McQueen's studies (1943) showed that the weight of a cubic foot of uncompressed fresh roots of the second-year crop at Cass Lake averaged 16 lb. In the process of drying, the roots lost an average of 26 per cent of their volume, and their weight was reduced to an average of 6·1 lb.

per cubic ft. A cubic ft. of dry roots, compressed slightly, averaged 8·3 lb. in weight. It is apparent that, in addition to the gain in storability due to the drying, there is a considerable reduction possible in storage and transportation costs, and that this alone could more than pay for the cost of drying.

Yields

In Russia. Whaley & Bowen (1947) summarized the reported yields of kok-saghyz in Russia as follows:

> Altukhov [1] reports 100 to 112 centners * per hectare, while in another paper [2] he reports only 50 to 60 centners per hectare. Elkin [3] indicates the average yield is 35 centners but that this may be increased to 100 by good practices. Lysenko [4] states that some collective farms which were successful in securing good stands produced as much as 50 to 70 centners per hectare. Milner [5] records that one farmer harvested 36 centners per hectare, but he also speaks of another farm on which 35 centners were harvested one year and only 23 the following year. One report [6] gives the yield of first-year roots as 30 to 50 centners per hectare, while Takushin [7] reports 100 to 118 centners. Another publication [8] indicates that one farm produced only 19 centners of second-year roots. It also gives various other figures ranging from 23·7 to 46 centners per hectare and lists two high yields of 75 centners. Zasiadnokov [9] reports 23 to 45 centners. It would thus appear that the average Russian yields range from 35 to 45 centners per hectare.
>
> A centner is equivalent to approximately 110 lb. However, as it is understood that the centners referred to in the cited Russian papers on kok-saghyz are actually double centners, the average weight of roots produced per hectare in Russia would be from 7,700 lb. to 9,900 lb. This would be approximately 3,100 lb. to 4,000 lb. per acre.

In the United States. On the whole, the yields in the United States were disappointing. Many of the plantings were almost or complete failures. Good stands and good yields were obtained in other cases. Whaley & Bowen (1947) summarize the yields in the United States as follows:

> In 1942, 5,260 pounds of roots, fresh-weight, were dug at Cass Lake, Minn., and 8,600 pounds at Manistique, Mich. The yield of roots averaged 1,846 pounds per acre at Cass Lake and 2,688 pounds at Manistique. . . . In late October 1942, 5 acres dug at Missoula (Montana) yielded 2,950 pounds, fresh-weight, or an average of 590 pounds per acre. . . . The best production of roots in 1942 was a calculated yield of 8,328 pounds, fresh-weight, per acre from a small test plot at Geneva, N.Y. A small plot at St. Paul, Minn., gave an indicated yield of 7,934 pounds per acre, fresh-weight. . . . Root samples were dug on March 16, 1944, at Belle Glade, Fla. These samples

[1] Altukhov, 1939*a*.
* 1 Centner = 110¼ lb., but apparently these were 'double centners' (*see* below).—Ed.
[2] Altukhov, 1939. [3] Elkin, 1939. [4] Lysenko, 1941.
[5] Milner, 1939. [6] Polovenko *et al.*, 1943. [7] Takushin, 1939.
[8] U.S.S.R., 1941. [9] Zasiadnokov, 1941.

indicated relatively light yields per acre for both the November and January sowings, but samples dug on April 21 indicated a maximum yield of 6,444 pounds per acre for the November sowing and almost as much, 6,408 pounds, for the January sowing. . . . At San Clemente, Calif., samples were taken on June 6, 1944, for calculation of root yields. The calculated yield of the October 1943 sowing was 4,455 pounds while that for the November sowing was 3,940 pounds. Samples taken at Edinburgh, Tex., on June 2, 1944, gave a calculated weight of 7,579 pounds of roots per acre, with the roots averaging from 3/8 to 1 inch in diameter.

Erambert (1944) sampled the roots from a thinning test in Florida and reported that the higher the density of roots was, the higher became the yield. His calculated yields were: 3,456 lb. of roots per acre where the plants were thinned to four plants per linear foot of row, 4,176 lb. with eight plants per linear foot, and 5,616 lb. where there were twenty plants per linear foot. The highest yield of roots was from an unthinned plot with 115 plants per linear foot of row.

Zehngraff & Aamodt (1944) calculated yields of second-year stands in Minnesota as from 64 to 97 lb. of rubber per acre on 27 May, and from 74 to 108 lb. per acre on 12 June—a significant gain showing that there is an appreciable change of other substances into rubber in the beginning of the second year's growth before the sloughing of the old bark. It is not clear whether this new formation of rubber consists in the enrichment of the rubber-content of the vessels formed during the previous year, or whether it consists in the formation of new latex vessels inside the separation layer prior to the sloughing off of the old bark.

The yield records furnished by Whaley & Bowen (1947) do not serve the purpose of determining average yields of rubber from the plantings in the United States, as the yields are given in terms of fresh-weight and the yields of rubber are given as percentage of dry-weight. It is understood that the mean acre-yield of rubber in the United States was less than 40 lb. of rubber. Yields of rubber at the rate of over 100 lb. per acre were, however, obtained in several instances.

Storage

Ignatiev *et al.* (1940) and Neuman & Dobrovolskaia (1940) have reported on extensive tests of different methods of storage and their effects on the roots and their rubber and carbohydrate contents. Fresh roots were stored outdoors in shallow pits and covered with burlap, straw, or other material. Roots were also stored in bags and protected against rain but not against temperature changes. Laboratory tests were made of the effects of the various conditions upon small lots of roots. The general conclusion was that undried roots can be stored for a period of six months following harvest in October. Stored roots are not harmed by temperatures down to −12°F. It was found that during this storage the amount of rubber increased but the carbohydrates decreased.

No tests were conducted in the United States on the storage of undried roots, but an unfortunate occurrence of 50 per cent rot in a shipment of fresh roots convinced most of the investigators in the United States that drying was necessary, if the roots were to be stored or shipped in bulk.

Shipment. According to Whaley & Bowen (1947), an average 40-ft. railway truck, such as kok-saghyz would be shipped in, will hold 8 tons of loose dried roots. In the United States, however, freight rates on agricultural commodities require payment for a minimum of 10 to 15 tons in truckload lots, and it was necessary to compress the volume of the roots by baling them.

Two types of bale covering, hardware-cloth and burlap, were tested. Six cubic ft. of loose, dried roots were compressed into 4·12 cubic ft. in the hardware-cloth bale, and 10 cubic ft. of such loose roots were compressed into 4·68 cubic ft. in the bales with burlap cover. After ten days, the roots in the hardware-cloth bale were in good condition, exhibiting little breakage. Roots in the burlap covers also showed little breakage, but some mould had developed on them. In shipment to the extraction factory, the hardware-cloth bale arrived in perfect condition, while the burlap bales became loose.

Under some conditions, it was found that dried roots gained moisture in storage or after baling. Knutson (1943) found that roots which had been dried to a moisture-content of 15 per cent, or less, resorbed moisture more slowly than roots which had been dried to a higher moisture-content. In fact, some of the low-moisture samples even lost weight after exposure to atmospheric conditions, and all shrank in volume.

Extraction of the Rubber

Though the rubber in kok-saghyz is contained in an articulated latex-vessel system comparable with that of *Hevea*, it is impossible to obtain the rubber by tapping. It is necessary, instead, to utilize mechanical methods of extraction comparable with those that have been used for extracting the rubber from guayule which, though it contains rubber in the form of latex, has the latex in separate cells.

Extraction as Latex. It has been possible to extract the rubber from both guayule and kok-saghyz in the form of latex. This is somewhat more easily accomplished in the case of kok-saghyz than it is with guayule, as the latex vessels in the former are continuous. The latex is readily captured as a dilute suspension in water and can then be stabilized with suitable anticoagulants. High-speed centrifuging of this dilute latex is effective in bringing about a concentration to a usable level, at which the latex is comparable with that of *Hevea*.

Extraction by Chemical Digestion. The latex in kok-saghyz can be coagulated by dilute alkalis that also serve to digest the plant tissue. This principle has been used extensively in Russia for the commercial extraction of rubber from this plant. After digestion by boiling with the alkali, the fine particles are separated by repeated centrifuging and flotation.

Mechanical Extraction. Kok-saghyz roots contain up to 45 per cent of soluble carbohydrates, by dry-weight, which have considerable by-product value. These carbohydrates are leached out of the roots with hot water—a treatment which also softens the root tissues and coagulates the rubber in fine filaments.

When the leached roots are milled in a pebble mill, such as that used for the extraction of rubber from guayule, the separation of the rubber by flotation is difficult, due to incomplete isolation of the rubber from the plant tissues.

Eskew & Edwards (1946), of the Eastern Regional Research Laboratory of the United States Department of Agriculture, devised and patented a new process that overcame the difficulties and resulted in an easy and effective procedure for extracting kok-saghyz rubber. This process consists in pebble-milling the leached roots for about twenty minutes in water, using a ratio of 20 parts of water to one of solids, which rolls together the fine filaments of rubber and loosens most of the soft tissues. The slurry resulting from this milling is diluted with five times its weight of water, being then passed over a vibrating screen, whereby 60 to 65 per cent of the solids other than rubber are eliminated through the screen. The material passing *over* the screen consists almost entirely of rubber, with some root 'skins' and other tissue fragments. A secondary pebble-milling for twenty-two minutes, using 22 parts of water to one of solids, further eliminates the non-rubber constituents so that the conventional continuous flotation process that is utilized for guayule is effective in recovering the rubber. The rubber is then washed on a vibrating screen and floated to eliminate traces of entrapped debris. After de-watering in a centrifuge, anti-oxidant is added to the rubber in a mixer and it can then be dried in a continuous through-circulation, multiple-belt drier.

This process was effective in recovering over 90 per cent of the total rubber in the roots. Because of the character of the roots, the extraction of rubber from kok-saghyz is simpler and less expensive than the similar process used for extracting the rubber from guayule. A schematic outline of the process is shown in Fig. 6.

Economics of Production

Crop Production. Kok-saghyz is one of the most costly of all rubber crops. This is owing primarily to the high cost of field production, since factory costs are not excessive. On the basis of war-time experience, Whaley & Bowen (1947) estimated that in the United States the field costs, exclusive of costs for the production of seed, would be \$208·81 to \$640·73 per acre. On the basis of available information, these authors estimated that future costs of production in the United States might be

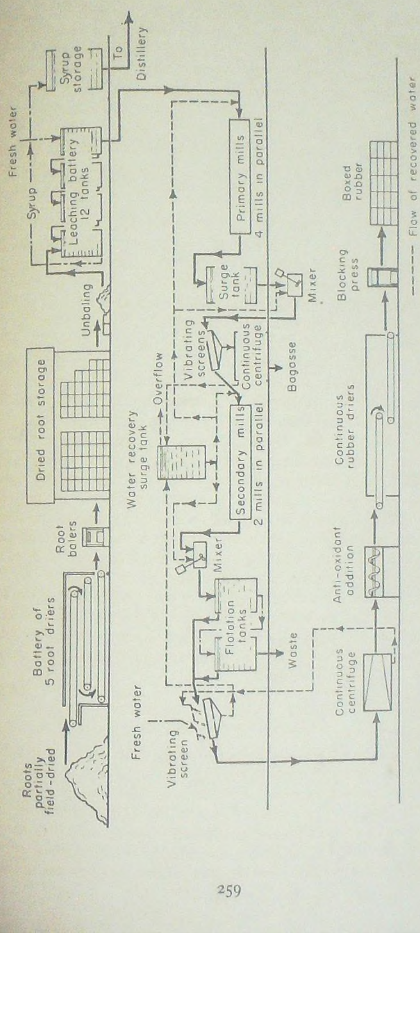


FIG. 6.—Flow-chart for the mechanical extraction of rubber from kok-saghyz roots. From Whaley & Bowen (1947).

reduced to \$219·50 per acre on mineral soil in the Lake States, \$259·50 on peat soils in the Lake States, and \$360·25 under irrigation in the western states. Even with the best yields recorded, this would make the field costs of producing rubber \$2 to \$4 per lb. Quadrupling the yields by breeding and selection is biologically possible, but would still leave the field cost of the rubber excessive—unless it were possible to reduce the cost of field operations materially.

Extraction Costs. Whaley & Bowen (1947) presented estimates of the factory costs, prepared by the Eastern Regional Research Laboratory of the United States Department of Agriculture, showing that the extraction costs would amount to 19·73 cents (including 7·83 cents for fixed charges, interest, taxes, amortization, and insurance) per lb. of rubber for plants harvested in the autumn, and 14·54 cents (including 5·49 cents for fixed charges) per lb. of rubber from plants harvested in the spring. The difference in costs results from the higher carbohydrate-content of the fall-harvested plants. However, the carbohydrates recovered would have a net by-product value of 13·78 cents per lb. of rubber, reducing the cost of extracting the rubber from fall-harvested plants to 5·95 cents per lb. The carbohydrate-content of the spring-harvested plants would be too low to justify their recovery.

XII

PRODUCTION OF RUBBER FROM OTHER PLANTS

PRACTICAL methods of rubber production have been worked out for several plants other than those that have been treated in detail in the preceding chapters. From the standpoint of understanding modern methods of rubber production, it is not necessary to study these other plants. Yet special methods of production were needed for each, and a recognition of the methods used, and of the responses of the various plants, is essential to a broad understanding of the occurrence of natural rubber.

Since the plants that are to be considered are not commercial sources of plantation rubber, it does not seem desirable to go into great detail in describing the methods of production. Rather, it seems best to describe rubber production in general terms, and to reserve detailed discussion for those features that are comparable to processes used in rubber production from *Hevea*, guayule, or kok-saghyz, and thus useful for classification, or that are unique, and thus of possible use in understanding the natural processes of rubber formation as revealed by the site of rubber formation, or by the reaction of the plant to tapping or other methods of harvest.

CASTILLA

From the standpoint of rubber production, *Castilla* (*see* pp. 91 ff.) is comparable to *Hevea* in that the rubber is obtained by tapping. Mechanical methods of exploitation, tested in the attempt to produce rubber quickly during World War II, were ineffective in obtaining rubber either from the bark of old trees or from young 'seedlings'. These methods consisted of squeezing the bark obtained from old trees, or else whole yearling trees, through heavy rolls such as are used in sugar-cane mills.

Records show that *Castilla* was planted several decades earlier than the first *Hevea*. Large plantations of *Castilla* were being planted in Mexico when the first experimental plantings of *Hevea* were being set out. Several differences in the methods of exploitation led to the choice of *Hevea* over *Castilla* in the early days of planting.

The early planting of *Castilla* was guided by the speculator rather than by the planter, but although the speculator was a valuable and necessary factor in the development of *Hevea* plantings, the actual planting was in the hands of highly skilled agriculturists. Adequate recognition has never been given to the role of the English Kew Gardens in the initiation of the rubber plantation industry. The Gardens have been noted as the centre through which Wickham's seeds passed on their way to the East; but they were also the *Alma Mater* of hundreds of skilled botanists and agriculturists who were basically responsible for starting the industry on a sound, practical basis.

Unstable governments provided unsuitable conditions for the development of a plantation industry in Mexico where *Castilla* was planted, while a stable colonial system of government provided an economically healthy environment for agricultural development in the Eastern tropics under the control of the British and Dutch. The availability of research stations, and the application of their findings to rubber production, were made possible by governmental stability and constituted an outstanding feature of the development of *Hevea* plantations.

Fast-bleeding *Castilla* was peculiarly subject to bandit depredations during the unstable period of Mexican government. A half to a whole year's yield of rubber could be stolen in a single night—which could not be accomplished with *Hevea* in the post-war period of unsettled conditions in the Far East, in spite of constant and continued thefts.

Planting

Planting of *Castilla* has been chiefly of *Castilla elastica*, though many of the plantings have actually consisted of other, closely similar species such as *C. costaricana* and *C. panamensis*. For some unknown reason, there is no record of extensive plantings of *C. ulei*, the Amazonian species that has served as the chief source of the Caucho rubber of the Amazon Valley.

Planting of *Castilla* has been almost solely by seed. Vegetative propagation by cuttings is possible but has not been utilized extensively in plantation development. The seeds are small and are normally produced in large numbers. The gathering of seed in native stands is easily accomplished, though there is no record of any consistent efforts to select superior types of *Castilla*, and no breeding work has been done. *Castilla* seeds are similar to those of *Hevea* in that they are short-lived and must be planted promptly. They can be shipped considerable distances, after being packed with a suitable moist packing material, and have been sent throughout the tropical world.

Castilla is a fast-growing but slow-maturing tree and, while it outgrows *Hevea* in its early stages, it is much longer in attaining its maximum rate of rubber yield. Because of its wide-spreading buttress roots (Plate 13 (*b*)), it cannot be planted as closely as *Hevea*. *Castilla elastica* requires less rainfall than *Hevea* and can be cultivated in areas that are more healthy for the planters and tappers. *Castilla* also thrives in areas that are favourable for *Hevea* and thus has a much greater over-all adaptability to soil and climate than has *Hevea*. The characteristic differences between *Castilla* and *Hevea* with respect to rubber production are the character of the bark, latex flow, latex renewal, and the separation of the rubber from the latex.

The Bark

The untapped bark of a 'seedling' *Castilla* tree is smoother than that of a similar tree of *Hevea*. However, it is thicker and more difficult to tap. The tapping knives used for *Hevea* are not suited for *Castilla*, which requires a heavier knife (Plate 50) that is capable of making a deeper cut. Even with the heavier knife, it is customary to have a sharp edge on the reverse edge of the knife-blade to deepen the groove and open up all latex vessels. This is even more essential than close-tapping of *Hevea*, as the latex vessels of *Castilla* do not anastomose. In *Hevea*, latex is drained from unsevered latex vessels through the anastomosing connections with severed vessels, but such drainage is not possible in the non-articulated vessels of *Castilla*.

The bark of *Castilla* does not renew itself as does that of *Hevea* after tapping. Instead of smooth, new bark being formed as in *Hevea*, the bark of *Castilla* forms callus tissue along the tapping cut. This callus tissue is hard and difficult to penetrate in subsequent tapping. The cut in *Castilla* is to the full depth at one tapping and it is not possible to approach the cambium gradually as in *Hevea*.

It is possible to tap *Hevea* repeatedly and leave a relatively smooth surface for bark renewal and subsequent re-tapping. With *Castilla*, this is not possible and, even with the most conservative tapping, a tree that has been tapped a dozen times presents a scarred surface with little smooth bark for further tapping.

Latex Flow

When *Hevea* is first tapped, there is little or no flow of latex but, after the initial period, the flow of latex is instant and copious when the cut is reopened. *Castilla* bleeds freely when first tapped and does not respond to repeated tapping. The latex in untapped trees does not attain the high concentration of rubber that is characteristic of untapped *Hevea* and which, in the latter, must be overcome through dilution resulting from repeated tapping before the flow rate is established. When the *Castilla* tree is first tapped, the fluid latex gushes out without need of dilution and flows from the severed tubes without hindrance. Internal friction is much less in the simple latex-vessel system of *Castilla* than in the articulated, anastomosed latex-vessel system of *Hevea*.

Latex Renewal

After the flow of latex stops in *Hevea*, renewal is prompt and, by the afternoon of the same day or the next morning, the flow can be renewed by re-opening the cut. Regeneration of the rubber is an extremely slow process in *Castilla*, and a period of from two to six months is required before re-tapping of the trees becomes profitable. It is not practicable to re-open a cut in *Castilla*, because of the callus formation during the long interval between tappings. New tappings are made parallel to the first ones, or across them. Both types of cuts are applied until finally the surface of the tree is crossed and criss-crossed with ugly scars.

Whereas *Hevea* is tapped with only one or at most two cuts that are re-opened on a regular schedule through several to many years, *Castilla* is tapped with many cuts reaching as far up the tree as possible (Plates 49 and 50). The restricted area drained in a single tapping of *Hevea* yields little latex compared with that obtainable in a single tapping of *Castilla*. On repeated tapping, however, *Hevea* yields far more rubber per tree over a year's time than does *Castilla*. The *Castilla* tree yields heavily at each tapping but can be tapped only from one to four times a year. A tapper can tap from 250 to 400 *Hevea* trees in a day; but twenty trees may constitute a hard day's work for a tapper of *Castilla*.

Coagulation

Rubber is the chief constituent of *Hevea* latex, in which it constitutes over 90 per cent of the solid material. Coagulation of *Hevea* latex is simple, direct, and easily controlled as described earlier.

Rubber is also the major constituent of *Castilla* latex, but here the proportion of non-rubber constituents is large and variable. They are of a character which affects the stability of the latex, and must be eliminated to obtain a high-quality rubber. The non-rubber constituents of the latex can be removed advantageously before the coagulation of the latex. The latex is first diluted with from one to three volumes of water and allowed to cream. The water, containing a portion of the water-soluble substances in the latex, settles to the bottom and can be withdrawn. This process may with advantage be repeated several times. Coagulation can then be brought about by the addition of five volumes of water.

Unwashed *Castilla* latex can be coagulated by natural fermentation or by the use of decoctions of native climbing plants. These methods are crude and not capable of precise control; the rubber contains a major portion of the non-rubber constituents of the latex, being much less pure than that produced by the treatment with water.

Ficus

Ficus elastica (*see* pp. 32, 38, 43), the Rambong rubber tree, is one of the older of the known rubber plants, and was probably the first native of the East to serve as a commercial source of rubber. It is most closely related to the *Castilla* rubber tree, and is similar to that tree in its ability to produce rubber and in the methods required for its exploitation. It is a large tree and must be grown at low planting densities.

In the United States, *Ficus elastica* and its close relatives are grown as house plants and are commonly known as 'rubber plants'. It is possible that more people think of *Ficus* as the real rubber plant than are familiar with *Hevea*.

Like that of *Castilla*, the latex of *Ficus* is very stable and will remain fluid much longer than the latex of *Hevea*, without the need of a preservative. The latex of both *Ficus* and *Castilla* can be purified by adding water and creaming.

FUNTUMIA

Funtumia (*see* pp. 33, 36) is a slender tree with thin bark, and thousands of acres of it were planted in the belief that it was the best rubber tree for use in Africa. Though it has a simple latex-vessel system like that of *Castilla*, *Funtumia* is tapped for its rubber with a knife similar to that used for *Hevea*. It must be tapped with multiple cuts to drain as much latex as possible at a single tapping, and requires a comparatively long time for the regeneration of the rubber after tapping.

The unique feature of *Funtumia* is the unusual stability of the latex, which coagulates spontaneously in the air but, if kept sealed, can be stored for long periods without a preservative. Coagulation can then be induced by the addition of fruit acids or by the use of heat.

Funtumia is propagated entirely by seeds which are produced in long, blunt pods (Plate 3(*b*)). The tree is tall as well as slender, and may be planted at from two to three times the density of *Hevea*. It is highly susceptible to root diseases and must be grown in well-drained soil. Because of root diseases, *Funtumia* is easily blown over by winds and cannot be grown successfully where winds of high velocity are common.

MANIHOT

In the early days of rubber planting, the Ceara rubber tree, *Manihot glaziovii* (*see* pp. 33, 51), was planted extensively. It was considered particularly promising for tropical areas where the rainfall was not sufficient for the cultivation of *Hevea*. Plantings of *M. glaziovii* were made throughout the tropics and even in parts of the subtropics, but the largest area was in the then German and British East Africa, where millions of trees were planted.

Planting

Manihot was planted entirely by seed. Like other members of the Euphorbiaceae, *Manihot* produces its seeds in pods containing three seeds each. The seeds of *Manihot* are not as perishable as those of *Hevea*, and may be shipped for long distances without danger of loss of germinating power.

Manihot glaziovii is a small tree compared with *Hevea* or *Castilla*, and can be planted much more densely, normal rates of planting in Africa being reported as 700, or more, trees to the acre.

Tapping

Manihot has a thin, scaly bark and cannot be tapped in the same manner as the medium-barked *Hevea* or thick-barked *Castilla*. The methods of tapping that were used can be classified into two groups: multiple cuts, such as the various herring-bone taps; and pricking methods by which the outer, scaly bark was removed first by mild scraping, and then some type of a pricker (such as a roller with numerous fine needle-points) was applied to the surface of the bark. The pricking device made many small incisions through the bark, and the latex oozed out and trickled down the surface of the tree.

The latex of *Manihot* coagulates spontaneously and most tapping has depended on allowing the latex to coagulate on the surface of the bark. The dried rubber was then stripped off after several days. The rubber comes off in long strips that can then be wound into small balls.

Some efforts were made to develop devices to induce the latex to run down the tapping cut so that it could be collected in the form of latex and coagulated with acids, as is done with *Hevea*. Allowing a small trickle of water with a slight ammonia-content to run down the tapping cut was effective in promoting the flow of latex. Various other materials, such as pepper, were used as stimulants to increase the flow of latex. A superior type of rubber was said to be obtained by collecting the latex in liquid form instead of allowing it to coagulate on the tree.

CRYPTOSTEGIA

Cryptostegia grandiflora (*see* pp. 152 ff.) is a climbing shrub that can be planted at a high density as compared with *Hevea*. It can be propagated vegetatively, and it is necessary to propagate the hybrid strains entirely by cuttings as they do not come true from seed. The species, both *C. grandiflora* and *C. madagascariensis* are, however, propagated entirely by seed. The seeds are produced in abundance in pods that are somewhat stouter and more pointed than those of *Funtumia* (Plate 51).

Like *Hevea*, *Cryptostegia* has its rubber in the form of latex; but the latex vessels are similar to those of *Funtumia* and *Castilla*, being long, non-articulated tubes that branch but do not anastomose. These latex vessels have nuclei only in the growing tips and, as in the cases of those of *Funtumia* and *Castilla*, require an appreciable time for the regeneration of the rubber after the latex has been drained off. The rubber can be obtained by tapping the individual stems of the plants, and this is the manner in which native rubber has been obtained from this plant since the middle of the nineteenth century.

Planting

Cryptostegia is similar to the tree crops in its ability to grow to great heights. However, it requires a support to do so as the stems are too small for efficient individual tapping by hand, and the plant is best grown as a field crop of fairly high density. Density is, of course, relative and, in the tree crops, ranges from around fifty trees per acre for *Castilla* and *Ficus* to 100 to 200 trees per acre for *Hevea*, and 700 or more trees per acre for *Manihot*.

Among the field crops, guayule is planted at densities of 8,000 to 16,000 per acre and kok-saghyz at from 100,000 to over a million plants per acre. *Cryptostegia* is best planted at spacings allowing 1,000 to 8,000 per acre, and thus is above the highest density suggested for tree crops but below that for guayule. Faulks & McGavack (1945), however, considered that for their clipping method of harvest of *Cryptostegia* a much greater density would be best. They suggested a spacing of 1 × 1 ft. in eight-row blocks, with a one-row skip between blocks. This would give a density of some 38,720 plants per acre.

Under most conditions, *Cryptostegia* will give satisfactory growth at spacings of from 5 to 8 ft. between rows and with the plants spaced at from 2 to 4 ft. in the row. The seed can be planted direct by machine, or seedlings may be raised in nurseries and transplanted to the field at predetermined spacings. Normally, the seeds have a high rate of germination and, if seeds are abundant, it is best to plant direct in the field rather than in nurseries. If rainfall is uncertain, irrigation should be available at the time of germination. Under dry conditions, field irrigation is necessary to maintain an optimum rate of growth. Under wet conditions, quick germination may be expected but suitable drainage is necessary for the best growth, though *Cryptostegia* has been found growing wild in swamps.

In Mexico, *Cryptostegia* was found to be susceptible to damage from Texas root-rot caused by *Phymatotrichum omnivorum*. Land known to be infested with this fungus, or lying in areas where the fungus is found on native vegetation, should be avoided.

In the early stages, *Cryptostegia* can be cultivated in a manner similar to many other field crops. Within one to three years, the plants close in and occupy the entire area; thereafter little cultivation is necessary, except for weed suppression, and the use of mechanical equipment is difficult.

Rubber Harvesting

Cryptostegia produces a rubber of good quality but the harvesting of the rubber is difficult. The plants can be tapped, but the operation is slow and the plants have a slow rate of rubber regeneration. The various tip-bleeding methods have been discussed previously (*see* pp. 162 ff.), the most successful being that used in Haiti (Plates 52 and 53). Faulks & McGavack (1945) combined the tip-bleeding with collection of the plugs that formed at the tips of individual stems after bleeding. The rubber in the plug was obtained by mechanical treatment similar to that used for obtaining rubber from guayule. This represented the most highly mechanized method developed for the harvest of *Cryptostegia* rubber.

GOLDENROD

Planting

Goldenrod (Plate 54 and *see* pp. 164 ff.) is a field crop comparable with guayule and kok-saghyz. It was not found practicable to propagate goldenrod by seed, except in breeding tests where the seedlings were grown in the greenhouse and transplanted to the field after attaining a height of from 4 to 6 in. Field propagation has been by means of the new shoots that come from the underground stolons. These stolons are produced in great abundance in some species of goldenrod, and may send up a shoot at every internode. Goldenrod is grown at a density of from 10,000 to 20,000 plants per acre, in rows of a suitable spacing to permit mechanical cultivation by the available machinery.

Goldenrod cultivation does not differ in any major respect from that of other field crops which are grown in rows. The plants react favourably to fertilization, requiring heavy applications for optimum growth on poor soils, but possibly somewhat less fertilizer than other row crops when grown on the better soils. Goldenrod can be grown as a perennial crop but in the second and subsequent years requires drastic thinning of the new stolon shoots (Plate 55).

Harvesting the Leaves

Goldenrod has no latex-vessel system such as is found in the tree rubbers and in kok-saghyz. It also lacks the specialized storage cells found in guayule. It is probably not unique in having its rubber associated with the chloroplasts in the parenchymatous cells of the leaves and green tips of the stems and branches. *Cryptostegia grandiflora* also has been reported to contain such rubber, in addition to its characteristic latex rubber, and it is probable that many other plants also have rubber in this form. Though comparable with guayule in having its rubber in separate cells, rather than in continuous latex vessels as in most rubber-bearing plants, goldenrod has these cells in the leaves, while in guayule the leaves are almost worthless so far as rubber content is concerned.

The harvesting of the leaves separate from the stem fragments is extremely difficult, and it has not been possible to produce pure leaf-tissue for use in extracting the rubber. Hand-picking of the leaves is slow and costly, and all machines that have been tested for mechanical harvesting collect a preponderant proportion of stem and branch pieces.

Extraction of the Rubber

Haefele & McGavack (1944) developed a successful method of extracting rubber from goldenrod in a pebble mill similar to that used for extracting rubber from guayule and kok-saghyz. When goldenrod leaves are milled in water, they form a heavy froth and it is impossible to get the rubber to agglomerate properly. Haefele & McGavack found that a 1 to 5 per cent solution of alkali hydroxide, including hydroxides of the alkali metals and ammonia but not of the alkaline-earth metals, repressed the frothing due to the saponin-like materials and freed the rubber from the cells. They deresinated the leaves chemically before milling.

Solvent Extraction

Under the Emergency Rubber Project of the United States Department of Agriculture, the task of extracting rubber from goldenrod leaves was assigned to the Southern Regional Research Laboratory of the Bureau

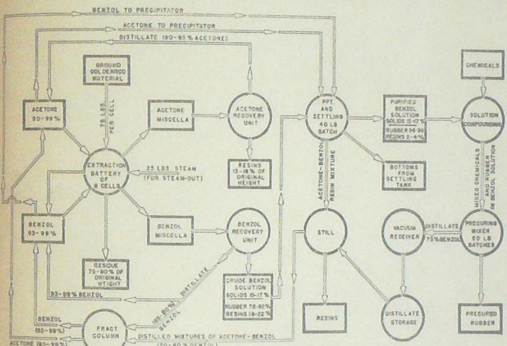


FIG. 7.—Flow-chart of pilot-plant process for extracting rubber from goldenrod. From McKennon *et al.* (1948).

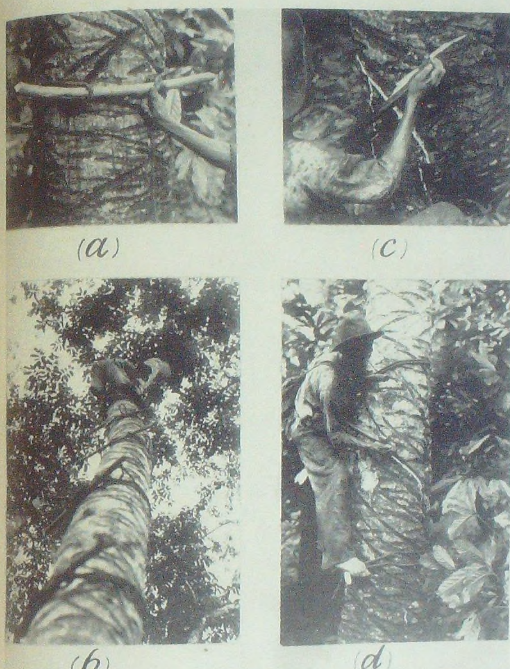
of Agricultural and Industrial Chemistry. Extraction of the rubber by solvents was decided upon as the most promising procedure. This work was greatly retarded by the impossibility of producing trash-free leaves, the laboratory receiving material with less than 2 per cent of rubber as compared with an average of 6 per cent in the pure leaves (by dry-weight).

The process that gave the best results involved, as a first step, the treatment of the dried and ground leaves with acetone to eliminate the non-rubber materials usually designated as resins. The rubber was then extracted with benzol. At first, it was found that, in spite of the preliminary extraction with acetone, the resin content of the benzol fraction ran as high as 15 to 20 per cent. Even after the major portion of the resin was eliminated, the rubber was too soft for use on mixing rolls and so a method of partial vulcanization was developed for combination with the extraction process to produce a rubber suitable for commercial use.

Attention was also given to the extraction of the water-soluble materials prior to the acetone extraction and to the elimination of some of the non-rubber portions of the plants by retting. These additions to the processing of goldenrod were not perfected for use, but there was indication that the bulk of the material to be handled in the extraction cells could be reduced.

While commercial production of rubber did not result from these tests, several hundred pounds of rubber were produced and the feasibility of producing rubber by solvent extraction was demonstrated. In this case, the rubber was extremely soft and needed to be pre-vulcanized to some extent before it could be handled satisfactorily on the mixing mills in the rubber factories.

The extraction method has been described by McKennon *et al.* (1948). The flow chart for the process is shown in Fig. 7.



Photograph by permission of ARS, U.S. Dept. Agric.

Tapping *Castilla*. (*a*) and (*b*), a temporary ladder is made by tying sticks to the tree. (*c*) and (*d*), the first cut is made at the base of the tree and successive cuts are made between the steps of the ladder. The handle of the tapping knife is held in the arm-pit and the cut is made with one hand, leaving the other free to support the tapper on the tree.

PLATE 49

Photograph by permission of ARS, U.S. Dept. Agric.

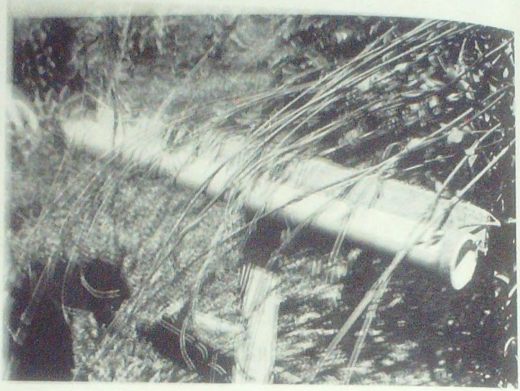
Tapping *Castilla* from a high ladder. The new cut is being made between old, unhealed cuts made previously. *Inset* Special knife used for tapping *Castilla*. The round roller at bottom is adjustable to control depth of tapping, and the upper edge is sharpened for use in making an additional cut along the bottom of the groove to ensure cutting all latex vessels in the bark.

PLATE 50

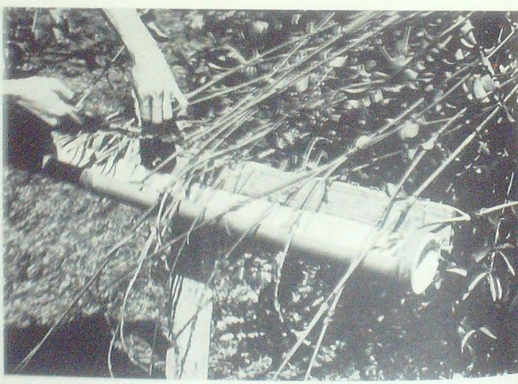
Photograph by permission of ARS, U.S. Dept. Agric.

Seeds and seed-pods of *Cryptostegia grandiflora*.

PLATE 51



(*a*) The shoots are positioned over a bamboo trough.



(*b*) The ends of the shoots are cut.

PLATE 52—Harvesting *Cryptostegia* rubber, I.

(*c*) Shoots cut and dripping latex into trough.

(*d*) Pouring latex from trough into pail.

PLATE 53—Harvesting *Cryptostegia* rubber, II.

Photograph by permission of ARS, U.S. Dept. Agric.

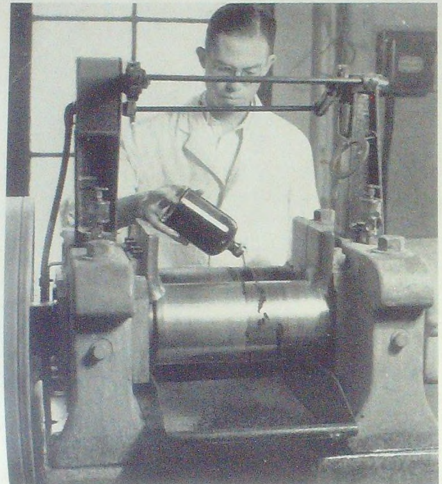
(*c*) An experimental planting of goldenrod.

PLATE 54

Photograph by permission of ARS, U.S. Dept. Agric.

Heavy stand of stolon shoots of goldenrod (4-6 in. high) from a row planting established in the preceding year.

PLATE 55



(a) Laboratory-size mixing rolls in use at the National Bureau of Standards, Washington, D.C.

Photographs by permission of National Bureau of Standards

(b) Laboratory vulcanizing press used for the preparation of test pieces at the National Bureau of Standards, Washington, D.C.

XIII

PRODUCTION OF SYNTHETIC RUBBER

Plantation *v.* Factory Production

The rubber plantation industry replaced the wild rubber industry in the early part of the twentieth century and left stranded populations with little chance of survival. Now, in its turn, the plantation industry is rapidly being equalled, and may eventually be overmatched in importance, by factory production. Yet, so far, there has been no diminution in plantation production due to the competition of the factory product, and plantation workers have not been deprived of employment. The rapid gain in importance of manufactured rubber in comparison with plantation rubber has resulted from the war, which encouraged the development of synthetic rubbers and at the same time strangled the expansion of plantations. Tremendous commercial development in the post-war period has led to greater and greater needs for rubber. Owing to lack of expansion during the war period, the plantations have been unable to increase production in line with the growing demand. Biological limitations on the growth-rate of trees put a definite check on rapid expansion. Financial inertia due to psychological uncertainties regarding the future competition of natural and synthetic rubbers has further retarded expansion. The same financial uncertainties have also beset the synthetic industry, but they have not held back the expansion of factory production to the degree that planting has been retarded.

The development of a plantation—from the first clearing, through the planting of the seed, budding, transplanting, and growth of the tree to a tappable size—is matched in the construction of a factory in the development of architectural and engineering details, and the transposing of those details from the drawing board to the factory site. Adequate pressure and increased man-hours can greatly reduce the time of this translation of plans into factories; but no such speed-up is possible in growing a tree. The entire initial expansion of the American synthetic-rubber industry during war-time took less time than that needed to bring a single rubber tree into tap, and less than half the time needed to bring a tree into full yield.

The Beginnings of Rubber Culture

The development of the synthetic rubber industry has been contemporaneous with that of the *Hevea* plantation industry. The introduction of

Hevea into the East was reportedly urged by James Collins in 1869. He was abetted by Sir Clements Markham, Assistant Secretary of the India Office, and Sir Joseph Dalton Hooker, Director of the Royal Botanic Gardens at Kew. The actual collection of seed was made by H. A. Wickham in 1876.

The Beginnings of Rubber Synthesis

The idea of synthesizing rubber came from studies of its chemical structure and the discovery that rubber is a polymer of a simple hydrocarbon. Himly (1838) reported that he had found a low-boiling fraction and a high-boiling fraction in substances isolated in the destructive distillation of rubber. He called the low-boiling fraction 'faradayine' and the high-boiling fraction 'caoutchine'. C. G. Williams (1860) announced the isolation of a hydrocarbon, C_5H_8, from the distillation products of rubber and gave it the name of 'isoprene', which is the name that has been continued since that time. Williams was the first to observe that, under certain circumstances, this material changed into a white spongy mass. His studies led him to observe that the destructive distillation of caoutchouc involved the disruption of a complex material into substances having a simple relationship to the parent hydrocarbon.

Bouchardat (1875) treated isoprene with hydrochloric acid and obtained an elastic, rubber-like solid. He was thus the first to synthesize rubber. Tilden (1882) suggested the structural formula, $CH_2:C(CH_3).CH:CH_2$, for isoprene. Further proof of the structure of isoprene was obtained by Euler (1897), who synthesized it from methyl pyrrolidine. Tilden obtained isoprene in 1884 by the pyrolysis of turpentine, and produced a rubber-like material by treating it with hydrochloric acid as Bouchardat had done. Wallach (1887) reported the spontaneous polymerization of isoprene exposed to light in sealed bottles.

Historical Summary

As was indicated in the last two paragraphs, the period from 1860 to 1900 was the incubation period, both for rubber planting and for rubber synthesis. In 1900, neither was of outstanding importance. The next two decades saw a tremendous expansion in the plantation industry, coupled with failure of synthetic materials adequately to replace natural rubber during World War I. Then came two decades of increase in plantation rubber and the development of restriction schemes to control supply. This period also saw a slow but steady improvement in the quality and numbers of synthetic rubbers. The first development of buna rubbers took place in Germany. Neoprene was discovered in the United States, and a new class of commercially useful rubber-like polysulphides, the Thiokols, appeared on the market.

Synthetic Rubber in 1940

Wood (1940) reviewed the current information regarding synthetic rubbers in 1940. In a preface statement to the circular giving this information, Lyman J. Briggs, Director of the National Bureau of Standards, stated:

> The production of synthetic rubber on a commercial scale in the United States and abroad has increased very greatly in recent years. The increasing use of synthetic rubber in this country has been due entirely to its superiority over the natural product for many applications. In some countries it has been developed as a substitute for natural rubber as a measure of national economic self-sufficiency.

With regard to production, Wood stated:

> In Germany, a plant at Schkopau with a capacity of 25,000 tons a year began production in April 1939. Another at Huls, Westphalia, of the same capacity has been under construction, and is probably now in operation. Recent Russian figures are not available, but estimates as high as 50,000 tons a year or more are not uncommon.
>
> Compared with these figures for the countries where synthetic rubber is used in tires, the production figures seem very small for the United States, where such is not the case. The total production of synthetic rubber of all types in the United States in 1939 did not exceed 2,500 tons. . . . Neoprene and Thiokol have been produced in far larger quantities than the other types.

Wood stated that the market price of Neoprene was from 65 to 75 cents a lb., depending on the variety, and that Thiokol was from 35 to 60 cents a lb. This compares with prices of 39 to 75 cents a lb. for Neoprene in 1957, and of 47 cents to $1.00 a lb. for Thiokol.

War-time Expansion

The fifth decade of the twentieth century saw the plantation rubber industry hamstrung by war, and the factory industry crash-programmed into full flower with unbelievable suddenness. Before the end of the war, the negligible pre-war production of factory rubbers had, of necessity, swollen to predominate the market in the United States and had found a place in many other countries. The few types of factory rubbers available before the war had now become hundreds—some with generally useful qualities in the fields where rubber had been used, and others with special qualities that made them valuable in many uses that had not previously been served by rubber. Thus, the sources of rubber were infinitely increased and the uses of rubber also expanded.

Post-war Development

We are now commencing the seventh decade of the century. The sixth decade was characterized by the lifting of restrictions on production and marketing of rubber. Factories in the United States were transferred from governmental to private ownership, and price-levels came to be determined in the market-place rather than in executive offices. Restrictions on the marketing of plantation rubber have been largely removed, and trade even with ideologically unfriendly nations is countenanced. Scientifically, the most important pertinent development of the past decade was the announcement of the successful synthesis of a rubber with a chemical structure essentially identical with that of the purified hydrocarbon from plantation rubber. Research workers in the United States and Russia made this announcement, and the common factor is that all but one used isoprene as the monomer. This would complete the cycle back to the findings of Bouchardat, as in the third, fourth, and fifth decades of the century there had been a switch to butadiene and co-polymerization rather than the use of isoprene as the basic monomer for the synthesis of rubber.

The production of synthetic rubber has become an important factor in world economy. A total of 1,261,916 long tons of synthetic rubber was produced in Canada, the Federal Republic of Germany, and the United States, in 1957. Synthetic rubber constituted 64·7 per cent of all the rubber consumed in the United States in 1957, 53·8 per cent of that consumed in Canada, 25·7 per cent of that consumed in the Federal Republic of Germany, 24·3 per cent of that consumed in the United Kingdom, and nearly 2·1 per cent of the consumption of rubber in Brazil, the native home of the *Hevea* rubber tree. Nearly 80 per cent of the synthetic rubber produced in Canada and the United States in 1957 was SBR (formerly known as GR-S), formed by the co-polymerization of butadiene and styrene.

Types of Synthetic Rubber

Structural Relationships

Chemically, rubber is considered to be a polymer of isoprene. Structurally, isoprene is represented as follows:

$$\begin{matrix} & 1 & & 2 & & 3 & & 4 & \\ \text{(head)} & CH_2 & : & C(CH_3) & . & CH & : & CH_2 & \text{(tail)} \end{matrix}$$

Isoprene

The numbers 1 to 4 refer to the normal order of the designated carbon atoms in the recurrent isoprene molecules in the polyisoprene chain. It can be seen that in the polymerization of isoprene, the successive repetitions of the monomer unit might be 1,4 (head to tail) or 1,1-4,4 (head to head, tail to tail). Additions may also be at the Nos. 2 and 3 carbons. The 1,4 (head to tail) arrangement is the only one that has been demonstrated in natural rubber.

Butadiene, which has been used much more extensively than isoprene in the synthesis of rubber, lacks the methyl group shown attached to carbon number 2 in isoprene, and is represented as follows:

$$\overset{1}{CH_2} . \overset{2}{CH} : \overset{3}{CH} . \overset{4}{CH_2}$$

Butadiene

When polymerized, the recurring repetitions of this monomer may be either 1,4 or 1,2. Structurally, carbons 1 and 4 are identical, as are carbons 2 and 3, as they are symmetrically arranged around the double bond. Thus, the designations 'head' and 'tail' are not applicable as in isoprene, which has an asymmetric arrangement.

The commercial synthetic rubbers based on butadiene, however, have been produced by co-polymerization of the butadiene with other monomers that modify the resulting product. The adoption of butadiene as the best monomer for the synthesis of rubber, together with the co-polymerization of butadiene with other monomers, constituted an abandonment of the immediate aim to synthesize a substance with a chemical structure identical with that of the natural rubber molecule. Instead, the aim was to produce a material with physical properties equal to or better than those of the natural product—without regard to chemical structure, except as any given structural member was found to impart particular qualities to the product.

General-purpose Rubbers

The initial purpose of the government synthetic-rubber programme in the United States was to produce a sufficient quantity of general-purpose synthetic rubber to replace the strategic supplies of natural rubber that were no longer available from the East. Lack of general knowledge of the production of synthetic rubbers dictated the decision to make only one type of general-purpose rubber and to standardize the production of that rubber so that all factories would, so far as possible, be producing a common grade. It was determined that the best material available at the time was a co-polymer of butadiene and styrene, and this was adopted for production for general-purpose use, and was designated GR-S (government rubber—styrene). Special-purpose rubbers were also included in the government programme, and many new types of rubber were originated and tested. Even before the end of government control of rubber production, specifications had been issued for some thirty-two kinds of GR-S alone.

Special-purpose Rubbers

Semon (1954) states: 'The introduction of the chemical rubber polychloroprene in 1931 marked the beginning of a philosophy that has had a profound influence on the rubber industry, namely, that speciality rubbers could be manufactured and used to perform functions that could not be matched with natural rubber.'

This recognition marks the commercial acceptance of special-purpose rubbers as distinct from general-purpose rubbers in the production of rubber goods. Since then, the production of speciality rubbers and closely allied plastics has proceeded to fulfil many old functions better, and to create new uses that were undreamed of until these new structural materials were available. In the field of rubber, a partial list of these new materials would include:

Neoprene—a generic term that Neal & Mayo (1954) define as a synthetic rubber-like polymer made either by polymerizing chloroprene (2-chloro-1,3-butadiene) or by polymerizing a mixture of polymerizable monomers of which the major component is chloroprene.

Nitrile rubber—rubber-like co-polymers of unsaturated nitriles with 'dienes', including isoprene, butadiene, piperylene, 2,3-dimethylbutadiene, etc. The most common nitrile rubbers are co-polymers of acrylonitrile with butadiene.

Butyl—vulcanizable hydrocarbon polymers of low unsaturation, used to make products that must be chemically stable and resistant to gas permeation. At present, all commercial grades of butyl are produced by the co-polymerization of isobutylene with small proportions of isoprene. Similar products can be made by the use of butadiene, dimethylbutadiene, or piperylene instead of isoprene but, according to Thomas & Sparks (1954), the isobutylene-isoprene co-polymers have superior qualities.

Thiokol—Fisher *et al.* (1954) define thiokols as elastic polysulphides resulting from the reaction of dihalides and alkali sulphides. Dihalides that are or have been used commercially in the production of polysulphide rubbers include ethylene dichloride, propylene dichloride, bis- (2-chloroethyl) ether, di-2-chloroethyl formal, and 1,3-glycerol dichlorhydrin.

Acrylic rubbers—elastic materials obtained by the co-polymerization of ethyl acrylate and a chlorine-containing monomer such as 2-chloroethyl acrylate or 2-chloroethyl vinyl ether, but including a halogen-free poly-acrylic ester as described by The B. F. Goodrich Company.

Silicone—polymers formed by the poly-condensation of silicols (with loss of the elements of water) which, in turn, are obtained by hydrolysis of the chlorosilanes.

Polyester rubbers—linear polyesters of high molecular weight prepared by the poly-condensation of hydroxycarboxylic acids or of mixtures of dibasic acids and glycols.

Di-isocyanate-linked condensation elastomers—substances of relatively high molecular weight resulting from the treatment with di-isocyanates of short, linear polyester molecules obtained by the condensation, by means of heat, of simple reactants such as dicarboxylic acids and dihydric glycols.

Market Types of Synthetic Rubber

There are now hundreds of types of synthetic rubber that are available commercially. Each of these has special characteristics which give it a

TABLE XV

SYNTHETIC RUBBERS QUOTED IN *Rubber Age*, NOVEMBER 1957

DRY RUBBER

Butadiene-acrylonitrile Types

	types		types
Butaprene	4	Hycar	9
Chemigum	5	Paracril	8
Herecol	1	Polysar	4

Butadiene-styrene Types

	types		types
Ameripol	15	Philprene	20
ASCR	13	Plioflex	8
Baytown	4	Polysar	9
Copo	4	S	18
FR-S	15	Synpol	16
Naugapol	8		

Butyl Rubbers

	types		types
Enjay butyl	9	Polysar butyl	6

Neoprenes

	types
Neoprene	10

Silicone Rubbers

	types		types
GE	2	Union Carbide	2
Silastic	2		

Polysulphide Rubbers

	types
Thiokol	4

LATICES

Butadiene-acrylonitrile Types

	types		types
Butaprene	3	Hycar	9
Chemigum	5		

Butadiene-styrene Types

	types		types
Copo	4	Pliolite	4
FR-S	7	S	4
Naugatex	7		

Neoprenes

	types
Neoprene latex	8

Polysulphide Rubbers

	types
Thiokol	3

particular value that justifies its manufacture and use—some in large amounts and others in relatively minor quantities. *Rubber Age* for November 1957 lists, on page 358, the prices of commercially available rubbers. A mere listing of the types for which market prices are quoted will indicate the range of synthetic rubbers that are used in manufacturing processes. The listing of 196 dry rubbers and of fifty-four latices as quoted in *Rubber Age* is given in Table XV.

MANUFACTURE OF SYNTHETIC RUBBER

Manufacture of SBR

It was necessary, at the start of the highly accelerated programme for the production of synthetic rubber in the United States, to settle on a single general-purpose rubber, and to establish a standard method of production and a single uniform quality. This was not an easy decision to make, but it was recognized that something had to be sacrificed in order to establish a production programme. The need for a general-purpose rubber was paramount. Neoprene, thiokol, and butyl were ready for manufacture on any scale desirable. They could replace natural rubber in many important uses, and their manufacture was expanded to meet those uses; but they could not replace natural rubber satisfactorily in the manufacture of tyres.

The best class of synthetic rubbers for use to replace the natural product in the manufacture of tyres was considered to be that of the co-polymers of butadiene and styrene. The rubber adopted and given the governmental designation GR-S (Government Rubber—Styrene) was obtained by co-polymerization of a mixture of butadiene and styrene as an aqueous emulsion in a soap solution. It was necessary to add suitable chemicals to catalyze the polymerization. Also, regulators were used to control the speed of the reaction, and substances known as short-stoppers were used to bring the reaction to a close.

Both butadiene and styrene may polymerize spontaneously in shipment or storage. It is necessary, therefore, to add polymerization inhibitors at the time of manufacture. Before being added to the polymerization mixture, the butadiene must be washed with caustic soda to remove the inhibitor. The amount of inhibitor needed to preserve the styrene is very small, and it need not be removed. As the polymerization reaction is stopped before completion, a certain percentage of both monomers is recovered and fed into the succeeding reaction. The proportions of fresh monomer and lower-purity recovered monomer are adjusted to meet the specifications of the mixture being used.

Polymerization is brought about in glass-lined steel reactors equipped with water jackets for the control of temperatures during the reaction. The monomers and other reagents are measured into the reactors through meters, or by weight, in accordance with the required specifications. By means of the water jackets, the temperature is controlled at approximately 50°C. during the reaction. The internal pressure is maintained at 45 to 60 lb. per square in., and the reacting mixture is subjected to constant agitation while the reaction is going on. As soon as the reaction has proceeded to the desired stage, with around 30 per cent of the monomers still unpolymerized, the reaction is ended by the addition of the short-stopper solution.

The finished polymer is then in the form of a latex that contains a large amount of unreacted monomers. These are recovered for use in the succeeding reaction. The unused butadiene can be removed and recovered by controlled distillation. The styrene can be removed by treatment with low-pressure steam and can then be recovered in a perforated plate column.

The purified latex is stored in large tile-lined tanks, after the addition of an antioxidant in the form of an emulsion or dispersion. Coagulation of the latex is brought about by the addition of dilute sulphuric acid, after the latex has been creamed by the addition of a concentrated solution of sodium chloride. The crumb resulting from the coagulation is thoroughly washed to remove the soluble salts and then shredded, dried, baled, dusted with talc, and packaged for shipment to the factory.

Manufacture of Low-temperature SBR

The first big improvement in SBR (GR-S) was the development of low-temperature polymerization. In the belief that some increase in quality could be obtained by decreasing the temperature of polymerization, batches were polymerized during World War II at temperatures of around 30°C. instead of the standard 50°C. The reaction time was slow and no perceptible increase in quality was detected. Immediately after the war, information became available regarding the German redox formulas and their application to polymerization at low temperatures. This led to renewed research in low-temperature polymerization and the development of new low-temperature polymerization systems.

The first conversion of an American synthetic plant to the production of low-temperature (5°C.) rubber was made in 1947 and this was followed by further conversions so that, at present, over three-quarters of the American output of SBR is produced by the low-temperature process.

New powerful oxidants, such as di-isopropylbenzene and *p*-menthane hydro-peroxides, and the installation of improved heat-transfer equipment in the co-polymer plants, have made it possible to polymerize cold rubber to 60 per cent conversion in seven to ten hours, compared with an average time previously of fourteen hours. Reactions as fast as five hours to 60 per cent conversion at 5°C. can be controlled by the perfected cooling devices.

Sulphoxylate

A more recent formulation that has come into commercial use in the production of cold rubber involves the employment of sulphoxylates. In

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these formulas, the activator is composed of sodium formaldehyde sulphoxylate, ferrous sulphate, and Versene Fe-3 or another chelating agent. The use of sulphoxylate has definite advantages that increase the ease of plant operations. The activator solution is clear, not a slurry, is simple to prepare, and does not involve critical time-temperature factors; polymerization ranges are more uniform from batch to batch, and small quantities of activator can be added to maintain a satisfactory rate of polymerization. The cost of chemicals for the sulphoxylate recipe is substantially less than that for formulas using iron pyrophosphate or the iron-minimizing peroxamine recipe. No improvement in quality is claimed for polymers prepared with sulphoxylates, but the resultant latices are much lighter in colour than latices prepared by the usual recipes.

Types of SBR

Svetlick (1957) compared the various types of SBR that are available. In general, the hot SBR is preferred where a good processing rubber is required, while cold SBR is used widely in tyres and other applications where wear and excellent physical properties are essential. Both the hot and cold SBR rubbers have types that are staining, slightly staining, and non-staining. The hot and cold rubbers of each class are used for similar purposes, the determination of which to use being based on the service requirements.

Special-purpose SBR rubbers are also available. High electrical resistance is obtained by reducing the ash-content through coagulation with glue. High-Mooney types are useful for adhesives, and low-Mooney types for blown sponge. High-styrene rubbers have poor freezing resistance but are used in can-closures, adhesives, soles, and heels. Low-styrene rubbers have good freezing resistance but poor processing characteristics.

SBR master-batches are made by mixing carbon black with the rubber. They are much cleaner to work with in the factory because the carbon black is already incorporated, and they can even be mixed adjacent to white stock without danger of contamination.

Oil-extended master-batches are also available and are found to be useful and economical because of their low compounding costs. Staining types are used in tyres, moulded goods, and mechanical goods. The non-staining types are used in soles and heels, in floor tiles, and in toys.

Manufacture of Neoprene

Chloroprene is the basic monomer used for the production of neoprene. It is prepared from acetylene by first polymerizing the latter to monovinyl-acetylene in accordance with the process described by Nieuwland *et al.* (1931). In this process, acetylene is polymerized in the presence of an aqueous catalyst solution of cuprous chloride acidified with hydrochloric acid and containing additional chlorides as solubilizing agents. Chloroprene is then prepared by causing the monovinyl-acetylene to react with hydrochloric acid in the presence of a cupric chloride solution according to the process described by Carothers *et al.* (1931).

Neal & Mayo (1954), in reviewing the production of neoprene, listed ten neoprenes of the dry-polymer type, and nine latices. As a basis for comparison of the neoprenes, they chose for description the most familiar of the dry-polymer type—the general-purpose neoprene type GN, which is identical with that designated GR-M (Government Rubber-Monovinyl-acetylene) during the war.

Purified chloroprene is emulsified in water by means of sodium rosinate soap, and polymerized at 40°C. with the aid of potassium persulphate as a catalyst and in the presence of elemental sulphur as a modifier.

After completion of the polymerization, as determined by specific gravity changes described by Barrows & Scott (1948), an emulsion of tetraethyl-thiuram disulphide is added and the alkaline latex is allowed to age. The latex is then acidified with acetic acid to a point just short of coagulation. Ultimate coagulation is accomplished by freezing the surface of a large, rotating, brine-cooled drum partially immersed in the latex. The resulting film is stripped from the freeze roll, thoroughly washed in water, passed through squeeze rolls, and dried in air at 120°C. The dried film is gathered into rope form and cut into short lengths for bagging. The resulting sticks are flexible, free from odour, light amber in colour, and have a specific gravity of 1·23.

Manufacture of Nitrile Rubbers

German manufacture of a new oil-resistant synthetic rubber called Buna N, marked the beginning of the development of the speciality rubbers classified by the American Chemical Society as nitrile rubbers. While the classification includes all rubber-like co-polymers of unsaturated nitriles with 'dienes', the most important products in this classification are the co-polymers of butadiene and acrylonitrile. Other 'dienes', such as isoprene piperylene and 2,3-dimethylbutadiene, have been substituted for butadiene, and other nitriles such as methacrylonitrile or ethacrylonitrile can be substituted, in part, for the acrylonitrile. A small substitution of acrylonitrile by these homologues improves the plasticity and other properties of the rubber for use in cements, but large proportions yield rubber with higher hysteresis though higher oil-resistance.

Acrylonitrile may be prepared from ethylene oxide and hydrocyanic acid, or by the direct reaction of hydrocyanic acid and acetylene. A large excess of acetylene is passed through a concentrated solution of cuprous chloride and sodium, ammonium, or calcium chloride. The acrylonitrile is separated from the excess acetylene and the latter is re-cycled. The crude product contains many impurities, of which divinylacetylene is the most troublesome as it is difficult to separate, and even a fraction of a per cent has a profoundly adverse effect on the processing properties of the nitrile rubber.

Butadiene and acrylonitrile will co-polymerize when heated together in bulk with a trace of benzoyl peroxide. However, if butadiene and acrylonitrile are stirred with an aqueous solution of an emulsifying agent in the presence of a peroxide, polymerization occurs at a much lower temperature and proceeds at a more rapid rate. The ratio of butadiene to acrylonitrile affects the vulcanized polymer, a high proportion of acrylonitrile giving high resistance to oil and a low proportion giving low resistance.

Manufacture of Butyl Rubber

According to Thomas & Sparks (1954), all commercial grades of butyl are produced by the co-polymerization of isobutylene with small proportions of isoprene at a temperature of about −150°F. These authors state that products similar to butyl can be made by employing butadiene, dimethylbutadiene, or piperylene instead of isoprene in the co-polymerization, but that the isobutylene-isoprene co-polymers have the most advantageous properties.

The isobutylene is obtained from cracked refinery gases. The fraction of the cracked gases containing isobutylene consists of 10 to 35 per cent of isobutylene by weight, mixed with normal butenes and varying amounts of saturates. The isobutylene is separated by absorption in sulphuric acid of such a strength that it does not absorb the other components of the mixture to a significant extent. The absorbed isobutylene is then liberated from the acid extract by treatment with steam. This product is washed with caustic soda and water, compressed, condensed, and delivered to storage. At this stage, the isobutylene content is approximately 96 per cent by weight, the impurities being chiefly normal butenes. A final distillation step removes butene-2 and yields isobutylene of more than 99 per cent purity.

Feed stock for the manufacture of butyl is prepared by mixing isobutylene and isoprene in the desired proportions with an inert diluent, methyl chloride, which serves as an aid in controlling the violence of the polymerization reaction. This blended fuel, cooled to a temperature of about −140°F., is supplied continuously to individual reactors. The reactors are supplied also with a chilled solution of catalyst, which is mixed rapidly and thoroughly with the cold, blended feed. This catalyst solution is prepared by dissolving anhydrous aluminium chloride in methyl chloride of high purity.

The polymerization reaction is exothermic and almost instantaneous. The polymer emerges from the reactor as a slurry and passes into a considerable volume of hot water. A small quantity of zinc stearate (under one per cent, based on the weight of polymer) is injected into the hot-water tank to prevent the agglomeration of the butyl, and a very small amount of an antioxidant is generally introduced to stabilize the polymer and prevent deterioration during finishing and subsequent storage. After removal of unreacted components, a wet polymer crumb is isolated by rotary vacuum filters or vibrating screens. This product is then dried at 200° to 350°F.

Various grades of butyl are available commercially. All are polymers of isobutylene and isoprene, and the differences between the grades represent varying degrees of unsaturation and different ranges of molecular weights. The degree of unsaturation depends on the proportion of isoprene used, and determines the rate of cure.

Manufacture of Polysulphide Rubbers

The basic reaction in the preparation of polysulphide rubbers is the condensation of an aliphatic dihalide and sodium polysulphide. The dihalide is added slowly, with vigorous agitation, to an aqueous solution of sodium polysulphide, which may be made from caustic soda and sulphur. The specific gravity of the polysulphide solution is adjusted to approximately the density of the halide. It is desirable to employ a dispersing agent (magnesium hydroxide) to facilitate reaction and, if latex is desired as the final product, to assist dispersion. Excess sodium polysulphide is used. The reaction is exothermic, requires from two to six hours, and is best carried out at about 70°C. At the end of the reaction, the suspension is allowed to settle and the product is washed free from sodium chloride and excess sodium polysulphide.

Fisher *et al.* (1954) summarized the available information regarding the various types of polysulphide rubber that were or had been produced commercially. Variables that may be involved in producing different types of polysulphides were listed as, (1) the nature of the dihalide, (2) the use of a mixture of dihalides, (3) the 'rank' of the sodium polysulphide, (4) the inclusion of a small proportion of a trihalide in order to cross-link the polymer chains, and (5) controlled scission of the disulphide bonds in the initially produced polymer in order to adjust its molecular weight. Most of the polysulphide rubbers produced in the United States are designated as thiokols, although Fisher *et al.* note that one of these, thiokol RD, is a nitrile rubber rather than a polysulphide. In Japan, the names thionite, hydrite, and hikatol are used for polysulphide rubbers; in Belgium, the name ethanite is used, and, in Russia, resinite.

Acrylic Rubbers

The acrylic esters polymerize readily under the influence of light, heat, and peroxide-type catalysts such as hydrogen peroxide, benzoyl peroxide, cumene hydroperoxide, ammonium persulphate, and sodium perborate. In general, the preparation of acrylic rubbers is much simpler than that of the diene rubbers. The emulsion polymerization of acrylic esters is complete in about three hours; auxiliary agents such as regulators and short-stops are not used. The operation is conducted at atmospheric pressures, and over 90 per cent of the monomer mixture is converted into polymer.

Acrylic rubbers have been produced under the names Lactoprene and Hycar. The B. F. Goodrich Chemical Company produces a large range of products in their Hycar series.

The Fluorocarbons

The 250 types of dry and latex rubbers listed above (Table XV) from the pages of *Rubber Age* are those that have reached commercial production and have then survived for present-day availability. Many other types are being tested or are in the laboratory stage. Whereas it seemed, not long ago, that an end-point was being reached in the search for new elastomers, the view ahead is now almost unlimited and there seem to be many possibilities of new polymers.

An interesting new group of rubbers are the fluorocarbons, typified by the kel-F elastomers, which were announced in June 1954 and discussed in a series of papers presented before the Division of Rubber Chemistry of the American Chemical Society at meetings in New York in September 1954. The kel-F elastomer contains 50 per cent of fluorine by weight and also, within the polymeric chain, the following chemical groups: CF_2, CFCl, and CH_2. The raw material is tough and does not break down even with prolonged milling. This rubber cannot be vulcanized with sulphur, but Griffis & Montermoso (1955) reported that a good cure for resistance to petroleum-base fuels was achieved with methylene bis-(4-phenylisocyanate) (MDI), zinc oxide, and hexamethylene tetramine.

Synthetic Polyisoprene

Late in 1954, The B. F. Goodrich Company announced the successful synthesis of a new rubber approximately duplicating the natural rubber molecule. It was claimed that this new rubber was sufficiently like natural rubber to be used as a replacement in all respects. At the 68th meeting of the Division of Rubber Chemistry of the American Chemical Society that was held in Philadelphia, 2 to 4 November 1955, details were given of the new compound in three companion papers by Horne *et al.* (1955), Wilson (1955), and Reinhart & Wilson (1955). These papers were presented by F. K. Schoenfeld and were later published as a group paper by Horne *et al.* (1956).

The new rubber was called Ameripol SN. It was shown to be a *cis*-polyisoprene on the basis of infra-red absorption spectra and the X-ray diffraction pattern. It had a Mooney viscosity in the 50 to 75 range, indicating a lower molecular weight than natural rubber. Its slow rate of cure was attributed to a lack of non-rubber constituents characteristic of natural rubber.

At the same meeting in Philadelphia, Stavely (1955), of the Firestone Tire and Rubber Company, announced 'coral rubber', another polyisoprene. It was stated that 'Coral rubber is a *cis*-1,4 polyisoprene containing up to 93·8 per cent of *cis*-1,4; 6·1 per cent of 3,4; and no *trans*-1,4 or 1,2 structure'. This paper was later published under the authorship of Stavely & co-workers (1956).

Similar synthetic polyisoprenes were announced by the Goodyear Tire & Rubber Company under the name Natsyn, and by Subbotin *et al.* (1956) in Russia under the name SKI.

Synthetic Polybutadiene

The Phillips Petroleum Company has announced the successful polymerization of butadiene to substances having qualities that are useful in the field of synthetic rubber. Unlike polyisoprene, the polybutadienes are both *cis* and *trans*, and both of these forms occur in the same rubbers. Kraus *et al.* (1957) reported on the effect of differing proportions of *cis* and *trans* forms on the quality of the rubber. They stated that all 1,4-polybutadienes containing over 15 per cent of *cis* polymers were completely rubbery at all reasonable temperatures. There was little change in important physical properties with changes between 25 and 80 per cent *cis* content. Polybutadienes of 93 per cent *trans* content yield tough, leathery, crystalline vulcanizates.

Urethane Rubbers

The di-isocyanate-linked condensation rubbers have been mentioned among the special-purpose rubbers. These include the Vulcaprenes developed in England and the Vulcollanes of Germany. The urethanes are of the di-isocyanate group and are formed by the reaction of di-isocyanates with the diols such as glycol. The urethanes differ from the di-isocyanate condensation products in that they can be vulcanized with sulphur and are more nearly like natural, or SBR, rubber in their processing characteristics. Ogden (1957), in describing one of the urethane rubbers, states: 'The properties of Adiprene C immediately suggest its use as a tire elastomer.' He expresses the opinion that, though tyres are expected to constitute its largest single market, it should find use in a variety of mechanical goods such as conveyor-belt covers, oil-well supplies, seals, and gaskets. This polyurethane rubber has superior abrasion resistance coupled with good heat ageing and resistance to oxygen, ozone, and oil.

XIV

RUBBER AS AN INDUSTRIAL PRODUCT

Rubber Usage Prior to Goodyear

There was a flourishing trade in rubber before the discovery of vulcanization. Uses for the unvulcanized rubber available prior to Goodyear's discovery (cf. p. 23) included rollers and printer's blankets, carding machines, driving belts, billiard-table cushions, fire hoses, flexible tubing, erasers, and surgical instruments. Waterproof shoes and capes were in common use and the coating of fabrics with solutions of rubber had been the basis for the formation of commercial companies whose total consumption of rubber ran into many tons annually.

Use of Solvents

Search for a Suitable Solvent. Early explorers reported that rubber was obtained from the tree by the natives of Brazil as a substance resembling milk. In its preparation in the shape of bottles, the natives took advantage of its liquid properties, painting several coats of the 'milk' on lumps of dirt or clay. After the rubber dried, the dirt or clay was washed away with water, leaving a hollow, bottle-shaped piece of rubber. As it was not possible to ship the latex to Europe without spoilage, there was interest in finding a solvent to facilitate the preparation of rubber articles on forms, as was done by the Brazilian natives.

In 1763, two French investigators, L. A. P. Herissant and P. J. Macquer, suggested the use of turpentine as a solvent for rubber and, some five years later, Macquer found that purified ether was even better. Turpentine was an excellent solvent, but the films made by spraying the solution onto wax moulds were sticky. When the ether solution was sprayed on wax moulds, the thin films produced were dry and free from the adhesiveness characteristic of films produced from turpentine solutions of rubber.

The first English rubber patent was issued to Samuel Peal and covered means of rendering leather, fabrics, paper, and wood waterproof. Peal favoured the use of turpentine as a solvent, but also noted that 'the gum may be used with equal advantage in its native fluid state'. G. V. M. Fabbroni, in Italy, found that rectified petroleum dissolved rubber. M. Grossart, in France, suggested that in the manufacture of tubing or other articles for surgical use, the rubber need not be entirely dissolved but might be softened and then pressed together in the desired shape.

Naphtha as a Solvent. Charles Macintosh found that a purified naphtha from coal tar was a good solvent for rubber. Whereas there was no commercial source of the petroleum that Fabbroni in Italy had found to be a good source of solvent, the newly developed use of coal-gas illumination in England opened up a large supply of waste tars from which Macintosh's solvent could be obtained. The naphtha was purified by redistillation and the resulting solvent was found to be effective. It evaporated quickly and did not leave the rubber as sticky as did turpentine.

Macintosh pressed two coated fabrics together and produced a very satisfactory waterproofed fabric that could be made into raincoats. A patent was issued for the process in 1823 and the Charles Macintosh Company was formed in 1824 to take over the flourishing business that Macintosh had developed. In English-speaking parts of the world, waterproof raincoats are still widely referred to as 'macintoshes' or 'macks'.

Early Machinery

The development of rubber usage in the United States lagged behind that in England, where the first compounding of rubber was accomplished by Thomas Hancock who had established the first rubber factory in England for the manufacture of elastic fastenings for various articles of clothing.

Hancock's Masticator. Hancock became concerned as to how to make use of the scraps that resulted when the desired forms were cut from rubber sheet. He thought that if he could shred the scraps they could be pressed together and re-used. Cutting the scrap up by hand proved to be a slow and tedious process and he tried to speed it up by using a toothed cylinder. Instead of being shredded, however, the rubber formed itself into a ball.

Hancock found that rubber which had been treated in his toothed cylinder could be put into solution in Macintosh's solvent much more readily than the raw rubber scraps. After obtaining from Macintosh a licence for the use of the solvent, he was much more successful in preparing a concentrated solution of rubber from the scraps. Hancock was thus the first to develop a masticator for rubber. Its success in the handling of scrap led to experiments in its use for the addition of non-rubber materials to the rubber, and thus Hancock became the first rubber compounder.

Mixing Rolls. Early rubber trade in the United States was based on the importation of rubber shoes from Brazil. The first importations were sold readily, and American lasts were sent to Brazil to improve the appearance of the shoes. Later, the manufacture of the rubber shoes was started in the United States. The first rubber company in the United States was formed in 1832 'for the purpose of manufacturing . . .

india-rubber cloth and leather and other india-rubber goods'. It manufactured shoes, life-preservers, coats, caps, wagon covers, and carriage traces.

Edwin M. Chaffee was the guiding spirit in this company, and was the inventor of two machines that marked the beginning of the industrial use of rubber. Instead of the internal mixer patented by Hancock, Chaffee developed mixing rolls consisting of steam-heated rolls turning at different speeds. The combined rolling and slipping action softened the rubber so that it formed a smooth sheet on the roll and allowed the colouring materials and other mixing ingedients to be incorporated into the rubber. Chaffee's machine has been enlarged and made more powerful and efficient, but the principle has remained the same.

Calenders. The second major machinery invention contributed by Chaffee was the forerunner of the calender that is still used in rubber factories. This was a coating machine for impregnating fabrics with rubber. Prior to the invention of this coating machine, rubber-proofing of fabric had been by dripping a solution of rubber and lamp-black onto the fabric as it was unwound from a roll. The coated fabric had then to be festooned the full length of the building to dry. This drying took several days and often eight to ten coats were required. Chaffee's new coating machine consisted of four steam-heated rolls in vertical alignment. The second roll from the top moved much more slowly than the others, to give a rubbing action between itself and the first and third rolls. In practice, the fabric to be coated was passed between the two middle rolls and then down and around the bottom one. The rubber compound was passed between the two top rolls and, as it came into contact with the fabric, was wiped into this from the roll.

Deficiencies of Unvulcanized Rubber

The pre-Goodyear, unvulcanized rubber filled a place in industrial development and had no competition in the field of resilience and resistance to rain. It softened in the summer heat, however, and became brittle in winter. Its very obvious good qualities were masked by its limitations with respect to light, temperature, and oxidation. The discovery of vulcanization resulted from the attempt to alter rubber chemically or physically by the addition of non-rubber materials that would overcome the deteriorating influence of temperature changes.

From the Discovery of Vulcanization to 1900

Early Difficulties

The discovery of vulcanization established rubber as an industrial material, but many failures were suffered before it was possible to produce vulcanized rubber articles that would give satisfactory service. An early shipment of mail bags that were waterproofed and vulcanized by Goodyear proved a total loss and threw that persistent inventor into bankruptcy—a condition to which he, unfortunately, was not unaccustomed. Yet, the art of rubber compounding and vulcanization went ahead at an accelerated pace, and the use of rubber increased amazingly.

The Invention of the Pneumatic Tyre. Early in the nineteenth century, solid rubber tyres were applied to wheels successfully. Pneumatic tyres were patented and manufactured in England from 1845 to 1847 by a young civil engineer, Robert William Thompson, of Middlesex County. The public was slow to accept Thompson's pneumatics and he resumed the manufacture of solid tyres. Forty years later, a veterinarian of Belfast, Ireland, J. C. Dunlop, made the first commercially successful pneumatic tyre. He obtained a patent for this tyre in 1888. Dunlop succeeded where Thompson had failed, because of the rise in popularity of the bicycle. He had an immediate market that was lacking in 1847 when Thompson discontinued the manufacture of pneumatics.

Dunlop's first pneumatic tyre was made by forming sheet rubber into tubing, making an air inlet out of a baby's feeding-bottle nipple, and fastening the tubing to the rim of his son's tricycle. A fabric covering was placed over the rubber tube to assist in controlling the amount of inflation. The tube was blown up and the end of the nipple tied off to prevent the loss of air. The tyre was effective, and the son outdistanced competitors in local racing. Applied to bicycles, the tyres gave greatly increased speeds. The day of the pneumatic tyre had arrived. When the French manufacturers, Michelin and Company, first applied pneumatic tyres to motor vehicles, they furnished the ferment that was to expand the rubber industry into its present gigantic proportions.

Periods of Development

To borrow phraseology from a popular American television programme, rubber technology reached its first 'plateau' when the art of vulcanization was discovered. The second plateau was reached when the pneumatic tyre was developed. There is no doubt that the attainment of the first plateau can be dated as of 1837, when Goodyear's patent was issued. It would not be true to date the second plateau as of 1845 when Thompson began the manufacture of pneumatic tyres. Without detracting from the recognition due to Thompson, the second plateau actually was not reached until forty years later, when Dunlop rediscovered the principle of the pneumatic tyre. Successful manufacture of the pneumatic tyre dated from the work of Dunlop rather than from that of Thompson. Rubber technology's second plateau was reached, therefore, in 1888.

Dunlop's invention was followed immediately by improvements in the methods of making and attaching pneumatic tyres to bicycles, and the bicycle industry developed rapidly as a result of the new invention. The next significant contribution to the use of rubber in transportation was made in France, when Michelin and Company fitted pneumatic tyres to motor cars.

So many factors have entered into the success of the motor car that it is not possible to select any one as the thing that made motoring possible as we know it today. Rubber (and chiefly the pneumatic tyre) certainly made a significant contribution to the development of the automotive industry. It is doubtful if the phenomenal development of the automobile industry would have been possible without rubber. From the attainment of its second plateau to the present time, the industrial usage of rubber has been linked to the development of automotive transportation, and the biggest prospective usages of the future are still so linked—including that of rubber in road surfacings.

Rubber as an Industrial Product in 1900

Before pneumatic tyres came to dominate the world market for rubber, important uses had developed for the vulcanized product. The manufacture and use of boots and shoes made of rubber outdistanced that of all other rubber products and continued to do so into the twentieth century. By 1900, world consumption had increased to 52,500 long tons a year and consisted essentially of five general classes of products:

1. Boots and shoes.

2. Mechanical rubber goods. Rubber pontoons had been important in the Mexican War. Packings for engines and similar uses for rubber had become a multi-million dollar industry. Rubber tyres for bicycles and carriages were also in demand.

3. Waterproof clothing other than boots and shoes had assumed great importance in the Mexican War through the manufacture of rubberized ponchos. The American Civil War created a great demand for rubber raincoats and capes.

4. The manufacture and sale of drug sundries had become an important part of the rubber manufacturing industry. Outstanding products were syringes, hot-water bottles, bandages, airpillows and cushions, and atomizers.

5. The manufacture of hard-rubber goods had also become important. This marked a real advance that was traceable directly to the invention of vulcanization which made it possible for the first time to use rubber in the field of non-rubber materials. After nearly four centuries of recorded knowledge of rubber, usages were found for it that were not dependent on its special qualities of resilience and elasticity.

Economic Fluctuations of Rubber in the Nineteenth Century

Between the discovery of vulcanization and the development of the pneumatic tyre to a dominant position in rubber manufacture, rubber had gone through the first of the economic gyrations that have since characterized the commercial life of this product. The American Civil War brought about the first rubber boom and its first decline, whilst the Mexican War had first demonstrated the usefulness of waterproof clothing in the protection of armies in the field. Outfitting of large armies in the American Civil War brought about a tremendous expansion in the use of rubber, which resulted in a period of great profit in the Amazon River region of Brazil. Rubber brokers and gatherers went through a period of prosperity such as the river area had never known before.

The ending of the war brought about the first recession in the demand for rubber. Rubber manufacturers, dealers, shippers, and gatherers knew for the first time the impact of a bursting boom, and the rubber trade has since been subjected to a regular succession of burstings of over-inflated markets. Fluctuations in the price of rubber have followed not only world and national trends in economic fluctuation, but have reacted to special trends induced in the rubber industry itself by the development of motor cars, the competition between wild and plantation rubber, the restriction of rubber production on plantations by governmental action, and the competition between natural and synthetic rubber.

Rubber Usage in the Twentieth Century

The expansion of rubber usage in the twentieth century has paralleled that of other industrial materials and, in 1957, nearly sixty times as much rubber was used as in 1900. The consumption of rubber in the manufacture of tyres and other items associated with automotive transportation has overshadowed all other applications, and accounts for more than two-thirds of all rubber consumed. The non-automotive uses, however, alone represent a tremendous extension of demand over the world's total usage at the beginning of the century.

McPherson & Klemin (1956) furnish detailed information on present-day engineering uses of rubber, showing that it now has important applications in civil, chemical, and electrical engineering, in automobile and aviation transportation, in belt conveyors of materials, and in escalators. These authors detail the particular qualities that make rubber useful, and the art of compounding that makes it possible to provide rubber with particular qualities to meet special requirements.

Industrial Applications

In its industrial applications, rubber might be likened to the art of ju-jitsu as developed in Japan. The ability of rubber to resist wear and deterioration is measured in large degree by its ability to yield to a deforming force and then to resume its former size and shape when the deforming force is removed. All of its dominant characteristics—elasticity, abrasion resistance, flexibility, and compressibility—are derived directly from its ability to 'give' rather than resist, and thus make it possible for rubber to survive where rigid materials perish. Yet it differs from plastics that also yield to superior force without permanent deformation. The ability of rubber to resume its original size and shape quickly and forcibly, differentiates it from all other pliable materials. Utilization of these special qualities is made possible by rubber's peculiar ability, in its raw state, of accepting deformation, but of assuming after vulcanization its final shape and characteristic resistance to further deformation.

Rubber has other industrial applications in which non-elastic characteristics come into play—such as adhesiveness, resistance to oil, acids, and alkalies, and the ability of thin films to resist the passage of moisture and gases. Excessive quantities of sulphur in vulcanization transform rubber into hard rubber—a most unrubbery material, stiff and unyielding, with a considerable degree of structural strength.

Manufacture of Rubber Goods

In general, the manufacture of rubber goods follows more or less standardized patterns. There are many special techniques that must be applied in the use of the various types of speciality rubbers, and the compounding formulae need to be adjusted to meet particular requirements. Not many years ago, these adjustments were made by the individual compounders who had developed encyclopaedic knowledge of the grades of rubber available, of the compounding ingredients available, and of the best way of combining them to obtain desired characteristics in the resulting product. These formulations were highly-regarded and closely-guarded secrets of the manufacturing companies. The utmost in surreptitious effort was resorted to in the attempt to discover the secrets of rival companies and to guard their own. So complete was the inter-company rivalry and espionage that it is unlikely that any of the major secrets remained long unknown to other companies, though many factory managers with quite accurate information regarding the formulae of their rivals were quite confident of the secrecy of their own.

Expanding and exacting scientific controls of rubber compounding and manufacture have now forced a greater exchange of information, and the entry of other industrial organizations into the field of rubber has widened the sphere of knowledge and need for knowledge, as well as the interdependence of the components of the rubber industry. Rubber manufacturers no longer deal only in finished goods but are engaged in the manufacture and sale of synthetic rubber. This requires that they impart information on compounding in the course of their commercial operations.

Rubber Compounding

When natural rubber is received at the factory, it is stiff and difficult to manipulate. There is now a greater uniformity in the different grades of rubber than existed in the past but, particularly in the market grades of natural rubber, it is necessary to mix rubber from many lots of the selected grades to ensure maximum uniformity of the product. This mixing, with certain ancillary operations and the addition of other desirable ingredients, is called compounding. The synthetic rubbers are prepared in much greater uniformity than has ever been possible in the preparation of plantation rubber.

Mastication. The first operation in compounding involves not only the mixing of large amounts of rubber to obtain maximum uniformity, but a mechanical manipulation of the rubber to soften it and make it possible to mix in the other compounding ingredients. This initial manipulation involves a 'break-down' of the rubber, which loses its tough, rubbery consistency and assumes a doughy, semi-plastic character. This change involves both oxidation and a scission of the long-chain molecules, so that the mean molecular weight of the rubber is greatly reduced.

This break-down is accomplished either on mixing rolls or in an internal mixer. The mixing rolls (Plate 56(*a*)) are heavy, parallel rolls turning at unequal speeds to give a tearing action to the rubber as it passes between the rolls. These rolls are comparable with the sheeting rolls on the plantations, but are of much heavier construction and are placed in parallel horizontally—rather than vertically as the plantation rolls are located. The rolls may be equipped with heating and cooling devices for the control of temperature. As the rubber softens, it tends to sheet out on the roll, and so the operator is provided with a sharp knife with which he cuts the sheet and then folds the rubber back into the mix. The type and direction of these cuts are standardized to give maximum efficiency and uniformity. All gears are enclosed, and a safety-bar is provided to stop the machine instantly should the operator's hand or clothing be caught between the rolls.

The internal mixer in common use bears little resemblance to that originated by Hancock. It is equipped with helicoidal rolls that macerate the rubber without the necessity of human assistance. The casing of the mill holds the rubber in contact with the rolls, and their irregular shape prevents the rubber from adhering to them.

That the break-down of the rubber involves some oxidation has been demonstrated by the use of an oxygen-free environment in an internal mixer. Under such conditions, the rubber remains tough and the normal break-down fails to take place. Otherwise, Mooney viscosity measurements are reduced from 100 or higher for raw, unmilled rubber to as low as 35 for rubber that has received the break-down milling—indicating that the molecular scission is an important factor in the break-down.

Compounding Ingredients. After a sufficient degree of break-down has been attained, the vulcanizing agents and other compounding ingredients are added to the rubber. Sulphur is the chief vulcanizing agent, though other chemicals are also used and some of the synthetic rubbers cannot be vulcanized with sulphur. It is not possible, in a short space, to list and describe the multitude of compounding ingredients that are in use. It is best, therefore, to treat them by categories, with the understanding that there are many specialized ingredients in each category and that only the better-known ingredients can be mentioned.

Softeners: As the name implies, these materials are used to plasticize, or soften, the rubber, and they are usually added during the initial milling period, to hasten break-down and reduce the time and power required. Generally, the softeners include mineral and vegetable oils, waxes, tars, pitches, and resins. Formerly, African rubbers were added to *Hevea* rubber as softeners, and guayule rubber from Mexico also found use for this purpose. Some of these materials are used merely to plasticize the rubber, while others also impart tackiness—so that the rubber will stick better to fabric or other surfaces. Others appear to act as internal lubricants of the rubber, reducing internal friction rather than actually softening the mixture.

In addition to shortening the time and reducing the cost of the break-down, the softeners are useful in rubbers that must be made into tubing by being forced through the orifice of an extruding machine, or that must be forced into moulds in the fabrication of moulded goods in which the flow quality of the mix is important in encouraging even penetration to all parts of the mould.

In some compounds that must have a softener added to facilitate extrusion or increase plastic flow, it is often desirable to add a stiffener such as benzidene or litharge. These compounds are useful in reducing sagging or flow after forming and during vulcanization.

Accelerators: The reaction between rubber and sulphur is usually quite slow, and it is necessary to speed up the vulcanization to make optimum use of the factory facilities and speed up the manufacturing process. A great many organic accelerators have been developed for use with natural rubber, and additional accelerators have been developed for use with individual types of synthetic rubber. To control the activity of the accelerators, classes of chemicals known as accelerator activators and accelerator retarders have been developed. These materials must be suited to the requirements of the individual compound, and are affected not only by the character of the rubber used but also by the other ingredients of the mix. Some of the accelerators that have found use are derivatives of benzothiazole, thiuram sulphides, salts of dithio acids, guanadine derivatives, and aldehydeamines.

Antioxidants: To a considerable degree, the lasting qualities of rubber compounds are dependent on their resistance to oxidation. Surface cracking and hardening are due primarily to oxidation. It is possible to increase the useful life of many rubber articles by the addition of small quantities of antioxidants to the compound at the time of manufacture. In many areas, excessive concentrations of ozone in the air make it essential that all rubber articles which must be exposed to the local atmospheric conditions in the presence of light be given extra protection, or that compounds incorporating types of rubber resistant to oxidation be used. Many of the antioxidants have a tendency to discolour white or light-coloured articles, and it is necessary to use special non-staining anti-oxidants in forming compounds for the manufacture of such articles.

Fillers: Fillers are added to many compounds to increase the bulk and weight and thus lower the cost of products in which they can be used without unduly lowering the quality. Some of the fillers are useful in giving stiffness, hardness, and weight to types of mechanical goods in which these qualities are desirable. Such fillers are considered inert and include various types of whiting, infusorial earth, clay, barytes, slate flour, and other minerals. Asbestos is added to rubber compounded for use in heat-resistant articles such as brake linings and some packings.

Some of the fillers strengthen or reinforce the rubber: chief among these are the carbon blacks that increase the tensile strength and give high abrasion- and tear-resistance. If the product must not be black, zinc oxide, magnesium carbonate, or certain clays, may be substituted for the carbon black. The size of the individual particles of the filler is of great influence on the resulting product. With the carbon blacks, the particle size determines the degree of reinforcement and, with other materials, determines whether the filler reinforces the rubber or merely acts as an inert additive.

Other ingredients: Other ingredients that may be added include pigments which are introduced as fillers but are designed to impart colour to the finished article, colours added as dyes, and odorants added in minute quantities to impart a particular odour or overcome the characteristic odour of rubber. Abrasive agents may be added in making erasers or grinding wheels. Blowing agents may be added to form gas during vulcanization in the formation of sponge rubber. While rubber is valued as a non-conductor of electricity and thus finds an important usage as an insulating covering for electrical wires and fixtures, it can be compounded to have a high degree of conductivity for use where elasticity combined with abrasion-resistance is desirable, as in grounds for static electricity for moving vehicles.

Rubber: The rubber is, of course, the most important component of the compound, and in many formulae is designated as 100—so that the percentage relationship of the other ingredients to the rubber is at once apparent. In many articles, such as that known as 'pure gum' stock, rubber is the predominant material in the compound. In other articles, however, rubber may be, on a weight basis, only a minor constituent. An article may have as little as 10 per cent of rubber by weight and still exhibit a rubbery aspect. In general, the proportion of rubber in the compound is directly related to its degree of pliability and elasticity, although these qualities are also affected by the proportions of other ingredients. Hard ebonite may contain a high proportion of rubber, with a still higher relative proportion of sulphur.

Davis & Blake (1937), in listing products that are formed with different percentages of rubber, included in those with 80 to 96 per cent of rubber by weight pure gum stocks, sheet gum, elastic thread, transparent rubber, rubber bands, electrician's and surgeon's gloves, surgical goods, and toy balloons. In articles made with 50 to 80 per cent of rubber by weight these authors included automobile and truck tyres, inner tubes, household gloves, footwear, sponge rubber, balloon cloth, printer's rolls, and high-grade ebonite. They included in the articles made with 30 to 50 per cent of rubber: printer's blankets, various types of hose, water bottles, druggist's sundries, white hospital sheeting, heels, hollow balls, soles and soling, tubing, tank linings, dolls and other toys, and footwear. As articles that could be made with only 10 to 30 per cent of rubber by weight, they included code-wire insulation, jar rings, steam or air or hydraulic packing, floor covers (mats, matting), bibb washers, gaskets, brake lining, tiling, and cheap battery-boxes. Items shown in more than one category would represent different grades of product with, in general, the higher grade having the larger proportion of rubber.

Fabrication of Rubber Goods

Rubber articles are fabricated from the compounded rubber in several ways which include extrusion, moulding, dipping, etc. In general, hose, tubing, and insulated wire are made by extruding the compounded rubber from the orifice of an extruder under pressure. From there, it goes to the vulcanization chamber where the reaction of the rubber and sulphur is brought about by subjecting the article to an elevated temperature.

Moulded articles are formed by forcing the rubber compound into moulds of suitable shape and carrying out the vulcanization in the moulds at a predetermined elevated temperature and time. Suitable gas pressure may be needed to force the compound into the smaller parts of the mould. In making automobile tyres, the tyre is formed on wheels and only the final tread is formed in the mould that is used for the vulcanization of the tyre. Air bags are used inside the tyre to force the tread compound into the mould configuration.

Dipped goods are made by dipping special forms into a solution of rubber and compounding ingredients, or into latex in which the compounding ingredients have been suspended by suitable means. After repeated dippings to build up the desired thickness of rubber, the dipped goods are vulcanized on the forms by transferring them to a heated chamber.

Rubberized fabric, such as that which forms the plies in fabricating automobile tyres, is made by passing the materials through multi-roller machines that are known as calenders. In these machines, the rolls are mounted vertically in parallel and the rolls that carry the rubber compound are run somewhat faster than the rolls carrying the fabric. The compound is wiped onto the fabric and forced into it.

Basic Machinery

The basic equipment of a rubber factory includes mixing rolls, internal mixers, calenders, extrusion machines, and vulcanizing chambers or presses (Plate 56(*b*)). As thousands of articles are produced by rubber manufacturers, the list of special equipment is extremely diverse. A tyre factory must have special equipment for the building of tyres. The manufacturer of dipped goods requires dipping tanks for holding the rubber solution or latex, and suitable mechanical means for holding the forms during the dipping process. There is a need for automatic devices for transferring materials, parts, and equipment from place to place, and automatic weighing and metering devices for dispensing the raw materials. Safety devices are required to avoid injury to personnel operating the machinery. These devices protect workers against injury from the machinery and reduce the hazard from dust and solvents such as benzol.

The control laboratory constitutes a small factory, with equipment and facilities to perform, on a small scale, nearly all the operations of the factory. It must have small mixing rolls and vulcanizing presses and, in addition, tensile testing machines, machines for the determination of viscosity, for accelerated ageing tests, and for quality control of all products manufactured in the factory. It must be prepared to evaluate not only all of the rubbers that come to the factory but also all of the other ingredients, and to furnish formulations for new products that may be produced in the factory. It must maintain controls on all of the processes at all times, so that chance deviations from specifications will not occur.

Product Control and Testing

Throughout the manufacturing process, a rigid system of control is maintained to ensure that the product is of the correct quality. This checking is exercised from the control laboratory which tests all materials before they are used, makes periodic tests of the compounds, and finally examines the completed product to determine whether it is up to specifications. These tests are determined by the nature of the compound and the type of article being manufactured. The simpler and more standardized tests include:

Tensile strength: This is the force needed to break a test piece and is expressed in pounds per square inch (lb./in.^{2}) or in kilograms per square centimetre (kg./cm.^{2}) at the time of break.

Elongation: This is the total elongation of the test piece at the time of break. It is measured by the increase in the distance between two lines placed on the test piece before the stretching process is started.

Modulus: This measurement is comparable to those both of tensile strength and of elongation. However, the former measurements are taken at the time the test specimen breaks, while the modulus measures the force exerted by a sample at a given percentage elongation.

Viscosity: Rubber has the appearance of a solid; but before vulcanization it exhibits many of the characteristics of a liquid, including plastic flow, freezing and melting, and a variable viscosity. It has been possible to measure the viscosity of raw rubber by means of the Mooney plastometer, and to demonstrate that this viscosity is related to the molecular weight of the rubber.

Accelerated ageing: Rubber is durable and is particularly valuable because of its resistance to chemicals. Many of the failures of rubber, however, are traceable to oxidation. The durability of rubber makes the testing of its resistance to oxidation difficult, because of the time-element. Accelerated ageing tests, in which the rubber is subjected to oxygen or ozone at advanced temperatures and pressures, have been developed and are useful in establishing a basis for estimating how well the compound or rubber will withstand oxidation in actual use.

Other tests: Suitable standardized tests are available for determining the amount of swelling in various solvents, the freezing and melting points, the maximum temperature at which any particular rubber will retain its rubbery qualities, the characteristics of the stress-strain curve, abrasion resistance, total recovery after stretching, fatigue, and other characteristics that may be needed to meet particular requirements.

The testing of rubber is a technical operation requiring a basic understanding of the molecular structure involved, and of the reaction of the molecules of great length to physical force at varying temperatures. In the field of rubber, there are now substances with molecular weights ranging from a few thousands to over a million-and-a-half. Intrinsically, this makes the comparison of the different polymers extremely difficult and it is necessary, for product control, to select for testing only those properties that have some direct bearing on the qualities of the product. Many of the basic tests are performed in the research laboratory which develops the routine tests performed in the control laboratory.

The Industrial and Commercial Status of Rubber in the Twentieth Century

Rubber manufacturing is now a multi-billion dollar industry closely linked with world prosperity. It has been subjected to more of the ups and downs of economic variability than most commodities, but bears signs of having reached economic maturity and a stability assured by a significant volume of synthetic production that can be expanded or contracted to meet demands, and to balance the less easily controlled fluctuations in the production of natural rubber.

The production of rubber products is now a leading industry in China, England, France, Germany, Italy, Japan, Russia, and the United States. Other countries have important rubber manufacturing industries, and still others have an expanding need for rubber goods.

Rubber is essential to the automobile industry and to the entire field of transportation—on land, on sea, and in the air. It is important in many other industries requiring elastic, flexible, or resilient materials.

XV

THE RELATIONSHIP OF NATURAL RUBBERS

SAMENESS OF NATURAL RUBBERS

RUBBER has been obtained commercially from dozens of different plants and has been reported in thousands of other plants that have not served as commercial sources of rubber. So far as is known, the rubber molecule in all of these rubber-containing plants is identical in its unit structure. Differences in the rubbers result from two variables: the molecular weight of the rubber, and the non-rubber materials that are associated with the rubber as it appears on the market. Some of the non-rubber materials are associated with the rubber in the plant and are collected along with the rubber. Others are impurities that are added to the rubber either accidentally or intentionally. These consist of dirt, stones, trash, bark shavings, and similar materials. Only the non-rubber constituents of the latex that were associated with the rubber in the plant introduce identifiable differences between the natural rubbers.

THE RUBBER MOLECULE

Chemical Structure of Rubber and Gutta

It has been noted previously that rubber is a polymer of isoprene and that a second polyisoprene is also found in plants and is known as gutta. Structurally, rubber and gutta differ only in the atomic arrangement before and after the double bonds. In rubber, the *cis* arrangement is found, the approach and continuation of the molecular chain being both on the same side of the plane of the double bond, whereas in gutta the *trans* arrangement obtains, the approach and continuation being on opposite sides. This can be shown diagrammatically as follows:

```
C     C         C

 C : C           C : C

                      C
    cis           trans
```

This angular arrangement can best be understood by realizing that in the long-chain molecule the successive atoms (carbon atoms only are in the chain) are not in alignment in a single plane, but that there is considerable latitude for directional rotation at each union of the atoms in the chain. As a result, the molecule at rest has been likened to a crumpled piece of string which, under tension, becomes more and more linear as the tension is increased.

Molecular Weight Variation in Rubber

Structurally, both rubber and gutta consist of long, unbranched molecules. In rubber, the lengths of the individual molecules vary within rather wide limits. As there are no side chains, the molecular weight of rubber is directly related to the length of the molecule. The molecular weight of the rubber from different sources varies greatly and is a characteristic difference between these rubbers. However, no sample of rubber is made up of molecules of a single size, and the observed differences result from the mean molecular weight of the individual sample of rubber and from the molecular weight distribution within the sample.

Rubber of low molecular weight is more soluble than is that of high molecular weight, and it is possible to fractionate the rubber by this differential solubility, to relate the various fractions to molecular weight, and to compare different rubbers on the basis of mean molecular weight and molecular weight distribution.

The Fractionation of Rubber. The separation of rubber into portions according to differential solubility can be accomplished in two ways. The separate fractions can be obtained by segregation on a time basis as the rubber is dissolved, or by differential precipitation from a solution. In the first case, the use of a relatively poor solvent increases the time to complete solution, and thus the ability to separate the individual fractions more precisely. The percentage relationships of the various fractions are determined firstly by the rate of solution and, secondly, by the amount precipitated by increasing amounts of the precipitant. In either case, it is possible to estimate the molecular weight of the individual fractions by determining the viscosity of the solution.

Wood (1954) gives the following formula as the one most commonly used in recent years for converting intrinsic viscosity measurements of high polymers into molecular weight:

$$V = KM^a$$

where V is viscosity, M is molecular weight, and K and a are constants to be determined for the particular polymer system involved.

For rubber dissolved in toluene, Wood gives, from Carter *et al.* (1946), the value of 0·667 ± 0·007 for a and 5·02 ± 0·04 for K. Molecular weights given by Wood for natural rubbers range from 420 to a high of 1,500,000.

Molecular Weight Distribution in 'Cryptostegia', Guayule, and 'Hevea' Rubbers. Hauser & le Beau (1946) investigated the molecular weight distribution in samples of guayule and *Cryptostegia* rubber in comparison with that from *Hevea*. These authors were particularly interested in the low-molecular-weight fractions of the rubbers, and used hexane as a solvent because it was a 'poor' one. After exhaustive extraction with acetone to remove as much as possible of the resin-content, the samples were dried in a vacuum and then treated with hexane. The hexane solution was removed at intervals and fresh hexane added. The viscosity of each fraction was determined, using Arrhenius's equation for conversion of the viscosity to molecular weight.

Hauser & le Beau investigated only the hexane-soluble fractions of *Cryptostegia* and guayule rubbers, comparing these fractions with those from *Hevea* rubber fractionated under identical conditions. They found outstanding differences between the molecular-weight distributions of these rubbers. Both *Hevea* and *Cryptostegia* rubbers contained appreciable fractions that were insoluble in hexane. Guayule rubber, on the other hand, was entirely soluble in hexane both before and after milling.

The *Cryptostegia* sample had a large fraction with a mean molecular weight of around 78,800, while the modal fraction from guayule had a mean molecular weight of around 95,000. However, the hexane-insoluble fraction of *Cryptostegia* rubber made it comparable with that of *Hevea*, both having a higher mean molecular weight than guayule rubber which was entirely soluble in hexane.

While the *Cryptostegia* and *Hevea* rubbers covered the same general range of molecular weights, their molecular-weight distributions were decidedly dissimilar. *Hevea* rubber did not exhibit the outstanding modal fraction that *Cryptostegia* showed at 78,800. This fraction in *Cryptostegia* contained 13·44 per cent of the entire sample, while no fraction of the hexane-soluble portion of *Hevea* contained more than 5·6 per cent of the entire sample. Only 52 per cent of the *Cryptostegia* sample was soluble in hexane, but 57 per cent of the *Hevea* sample was soluble in hexane in 192 hours, although the authors stated that the extraction of *Hevea* was not complete at that time.

Even though the hexane-insoluble fraction of *Cryptostegia* rubber was higher than that of *Hevea*, the mean molecular weight of the *Hevea* rubber was higher than that found for *Cryptostegia*. Compared on the basis of solubility–time relationship, the comparable fractions from *Cryptostegia* rubber always had a lower molecular weight than the comparable fractions from *Hevea* rubber.

Molecular Weight Distribution in Rubber from Various Parts of Guayule. Benedict *et al.* (1950) showed that there is a variation in the molecular weight of the rubber extracted chemically from roots, stems, branches, and tips of cultivated guayule plants. Fractionation was accomplished by differential precipitation of the rubber from a benzene solution, methyl alcohol being used as the precipitant. Each fraction of rubber was redissolved in benzene and its viscosity measured in an Ostwald viscosimeter. Using the Staudinger and Heuer relationships of viscosity and molecular weights, as given by Davis & Blake (1937), the authors calculated molecular weights of from 20,000 to over 200,000.

Benedict *et al.* found that the rubber in the roots of guayule had the highest molecular weight, that of the stems having next to the highest, followed by that of the branches, while that of the tips had the lowest. About 50 per cent of the rubber from the tips was contained in the first fraction (high molecular weight), compared with over 70 per cent of that in the roots and stems. The viscosity of the rubber solution of the first fractions from the roots and stems was slightly higher than that from the tips, but the higher mean molecular weight resulted from the unequal distribution of the six fractions in the rubber from the different plant parts.

LATEX

Latex is a milky fluid that is found in many plants. It is, in general, associated with the presence of rubber or gutta; however, certain plants such as the *Mammillaria* cactus have latex but no rubber, as is also true of species of lily that have a milky latex in the bulb. The 'milk' of some plants, such as the cow-tree (*Brosimum* spp.) and the massaranduba (*Mimusops excelsa*) of Brazil, has been reported to have been used for food, and there is record of the latter source having served as cream in coffee. The synthetic emulsion of synthetic rubbers is also known as latex and, for practical purposes, latex is considered, industrially, as a suspension in water of rubber together with non-rubber emulsifiers, stabilizers, antioxidants, and a large variety of other non-rubber substances including sugars, proteins, fats, organic acids and their salts, and minerals.

The latex-vessel system of *Hevea* has been described (cf. p. 68), as have the latex-vessel systems in other rubber-bearing plants (cf. pp. 102, 144, 156, 263) and the isolated latex-storage cells of guayule (cf. p. 106). In all of the more important rubber-bearing plants, the rubber is found in the form of latex but, in goldenrod and in the leaf parenchyma of *Cryptostegia*, rubber is found associated with the chloroplasts in the individual cells rather than separated in a specialized structure. No demonstration has been made that the gutta globule is contained in *Eucommia ulmoides* in the form of latex. When a fresh leaf is broken and the two parts are stretched apart, the strand of gutta stretches out immediately in solid form. This strand appears to act like rubber, stretching and retracting as force is applied and relaxed. However, under magnification, the gutta fibres can be seen to act like finely coiled springs, recoiling after extension rather than exhibiting elasticity.

Latex Particles

Fresh latex, as it exudes from different plants, varies in consistency from thin and watery to thick and creamy. The concentration of solids in the latex varies from plant to plant and, in individual species, varies from season to season or even at different times of day. When latex is rubbed between the fingers, that from different plants reacts quite differently. *Hevea* latex agglomerates quickly and forms a small lump of rubber that comes cleanly from the fingers. In other types of latex, no agglomeration takes place and the latex gradually dries on the fingers, leaving a sticky residue that is difficult to remove. Such latices are used as bird-limes for the catching of birds by adhesion.

Botanical Differences in Latex Particles. When viewed under the microscope, all latices have physical characteristics that serve to differentiate the general types. Most characteristic of the rubber-containing latices is the physical aspect of the rubber globules or particles. Under the microscope, these particles can be detected in an active state of Brownian movement. The shape and size of these particles are characteristic of latex from various sources. In most types of latex, the particles are spherical and differ only in size and concentration. In *Hevea* latex, however, the particles are pear-shaped, often having a distinct tail, though as not all are orientated in the same plane, the characteristic appearance of the particles varies from spherical to pear-shaped. The particles in *Manihot* latex are rod-shaped.

Particle Size and Brownian Movement. The rubber particles in different latices vary in diameter from submicroscopic to several microns. These particles are in colloidal suspension, and their erratic Brownian movement is related in rate to particle size, the larger particles being slow and sluggish in their movements, and the smaller particles moving more rapidly. Henri (1907) has estimated that there are 50,000,000 particles in 1 cubic cm. of *Hevea* latex having a concentration of 8·7 per cent of rubber. On the basis of moving pictures of the latex particles in a very dilute latex, Henri (1908) calculated a speed of 0·62 microns in one-twentieth of a second.

The ultramicroscope and the electron microscope reveal that the characteristic particles of all rubber latices are made up of masses of smaller and probably spherical particles. It is reasonable to speculate that the physical characteristics of the particles, as revealed by the microscope, are a function both of the concentration of the rubber particles and of the nature and concentration of the non-rubber constituents of the latex. Noble (1936) explains the creaming of *Hevea* latex that results from the addition of organic colloids such as karaya gum, locust-bean gum, gum tragacanth, Iceland moss, alkali solutions of alginic acid, and similar materials, as resulting from the enlargement of the particles by adsorption of the gums on the surface of the latex particles, thus stopping the Brownian movement and allowing the particles to rise to the top—because of the difference in specific gravity of the particles and the aqueous medium.

Hauser (1930) states that in young trees of *Hevea brasiliensis*, or in the green portions of old trees, the rubber particles seldom have a diameter of more than 1 micron. Trees from ten to fifteen years of age have particles with diameters of 0·5 to 3·0 microns, and also large numbers of particles with diameters below 0·5 microns that are thus not visible except to the ultramicroscope. The larger particles have lengths of 4 to 5 microns, a few being 6 or more microns long. Particles from old trees have distinct tails, but these were not found in the latex from young trees. When trees are tapped after a long rest, the particles are at first relatively large. They diminish in size with successive tappings and reach a minimum after about eight tappings. They then increase in size and reach a constant size after another eight tappings.

Primary Particles. Schoon & Phoa (1956) studied latex particles in latex from seven different species of plants, including a gutta-yielding plant. Microscopical studies were made under dark-field illumination. Chemical studies included the hydrolysis of the latex with NaOH, bromination, and soaking the brominated samples in toluene or other solvents to increase the size of the particles.

These authors concluded that the primary particles of all latices are probably spherical, and that the characteristic sizes and shapes of the particles which have been described are due to an agglomeration of these primary particles. There is no cohesion in this agglomeration and, when the particles are swollen by bromine or by the use of solvents, the discrete nature of the individual particles in the agglomerate is apparent.

General Comparison of Latex Particles. Information published by Spence (1908), Tobler (1914), Hauser (1930), Stevens & Stevens (1940), and Schoon & Phoa (1956), on the measurement and characteristics of the particles in the latex from various plants that produce rubber or gutta, is given in Table XVI.

Latex Stability

There is great variation in the stability of the latex from different plants. The latex of *Manihot* coagulates spontaneously and is difficult to collect, as it coagulates on the tree before reaching the cup. It is necessary to add a preservative to the latex of *Hevea* if it is to be kept for any appreciable time. Spontaneous coagulation is not rapid but lump formation starts in the latex of some trees, and particularly in the latex of young buddings, even before the flow of latex has stopped.

Sealed containers of *Castilla* and *Funtumia* latex can be kept for long periods without the need for any preservative. Both of these latices coagulate spontaneously in the open but are far more stable than *Hevea* latex.

TABLE XVI

LATEX-PARTICLE CHARACTERISTICS IN VARIOUS LATICES

Plant	Particle size	Particle shape and characteristics	Investigator
Castilla sp.		Spherical and spheroidal.	Stevens & Stevens
		Spherical liquid droplets with definite shell structure. Do not fuse together when water is evaporated.	Hauser
C. nicoyensis	1·0–3·5 microns	After bromination, a secondary structure becomes visible, particularly in a sample treated with NaOH, brominated, and swollen in toluene.	Schoon & Phoa
Cryptostegia grandiflora	0·1–1·0 micron	Bromination has a coagulating effect but does not lead to swelling. No secondary structure observed.	Schoon & Phoa
Ficus sp.	5 microns, max.	— — — — — — —	Spence
		Spherical and liquid-like drops of oil. Fuse completely in coagulation.	Stevens & Stevens
F. elastica	0·2–3·0 microns	Bromination causes a doubling in size and shows almost all visible particles to be made of smaller spheres. This showed up more clearly after swelling brominated particles in solvents. Authors suggest that smallest visible particles are made up of six primary particles and have at least twice the diameter of the primary particle.	Schoon & Phoa
F. nekbuda		Little difference in latex particles of different species of *Ficus*. Bromination much more effective after hydrolysis, and swelling of brominated sample has no great influence.	Schoon & Phoa
Funtumia sp.		Both pear-shaped and spherical particles.	Stevens & Stevens
Hevea brasiliensis	Less than 0·5 micron to 3·0 microns diam. and 4–6 microns long	Particles from old trees have distinct tails that are not found in latex from young trees.	Hauser
	Less than 0·2 to 3·0 microns	Bromination makes the secondary structure clearly visible. Swelling in toluene causes the primary particles to separate from each other. The primary particles seem to be invisible in ordinary light.	Schoon & Phoa
Lucuma lastiocarpa		The particles are half-way between those of *Hevea* and those of *Ficus*. They are neither pear-shaped and solid as in *Hevea*, nor spherical and liquid as in *Ficus*.	Stevens & Stevens
Manihot sp.		Rod-shaped.	Stevens & Stevens
		Both rod-shaped and spherical.	Tobler

TABLE XVI (*Continued*)

Plant	Particle size	Particle shape and characteristics	Investigator
Manihot sp. (contd.)	10 microns long, ultramicroscopic in width	They consist of a homogeneous sticky mass with low extensibility. On coagulation, the rods form clumps without orientation and finally fuse to a homogeneous mass.	Hauser
M. dichotoma		After bromination, the rod-like particles were shown to be composed of small primary particles in linear arrangement. In flocculates, the linear (rod-like) structure disappears and only the spherical primary particles are important.	Schoon & Phoa
Manilkara balata	0·2 to over 3·0 microns	By hydrolysis with NaOH, the secondary structure becomes more pronounced. The swelling from bromination is not more than 20 per cent. No further swelling in toluene. Gutta rather than rubber.	Schoon & Phoa
Mimusops balata	0·5–3·5 microns	Shell structure. Very viscous liquid centre surrounded by a thin but exceedingly tough membrane.	Hauser
Palaquium gutta	2–4 microns	Approximately spherical. Homogeneous and nearly solid. Particles from 'gutta neatok' and 'gutta sundik' have a liquid interior surrounded by a very tough membrane.	Hauser

Latex Coagulation

The variation in the natural stability of latices from different botanical sources is matched by comparable differences in the means required to bring about coagulation. All latices can be coagulated with an excess of alcohol. Some can be coagulated by the addition of fruit or mineral acids. Others, such as that of *Cryptostegia*, are best coagulated by raising the pH. *Poinsettia* latex is coagulated by the addition of ammonia.

Coagulation is related to the nature of the latex particles, to the concentration and character of the non-rubber stabilizing substances in the aqueous medium, and to the character of the adsorbed layer, or sheath, that surrounds the particle mass. Seifriz (1945) states that this sheath is considered by most authorities to be a protein, but that his studies led to the conclusion that it is a composite of protein and hydrocarbon.

Non-rubber Constituents of Latex

Much information is available concerning the nature of the non-rubber constituents of various latices—particularly on those that affect the stability of the latex, its preservation or coagulation, or the quality of the rubber. When rubber latex is coagulated, a major portion of the non-rubber constituents may be retained in the serum that is discarded. Taysum (1957) found that the serum from *Hevea* latex may have a by-product value for use in the preparation of culture media for bacteria and possibly for fungi in the production of antibiotics and growth substances. After giving directions for the production of the media, Taysum points out that such media contain '. . . a wide variety of amino-acids principally alanine, valine, tyrosine and proline, carbohydrates mainly the polyhydric alcohols myo-inosotol and quebrachitol (methyl-1-inosotol), an exceedingly diverse series of proteins of widely varying molecular weights probably extending to the nuclear proteins, and various plant growth factors.'

The non-rubber constituents that have been reported in natural latex are extremely varied. Those listed by Hauser (1930) include proteins, sugars, waxes, resins, gums, tannins, glucose, pectin, starches, inosite; the proteolytic enzyme, papain; lipase, amylase, protease, oxydase, lupeol; cinnamic and acetic esters; formic, acetic, and malic acids; the calcium, potassium, and magnesium salts of malic acid; calcium phosphate, aluminium oxide, silica; and iron, magnesium, calcium, potassium, nitrogen, and chlorine, all in bound forms. Most of these substances are not included in the rubber after coagulation and have no effect on compounding. Many latices contain only minor quantities of rubber. Most species of *Euphorbia* contain euphorbon, sometimes in considerable amounts. This material has never been reported from plants of any other genus.

Altman (1939, 1940, 1941, 1941*a*) and Altman & Kraay (1940), in a series of papers, announced the separation from *Hevea* latex and identification of the following amino-acids: proline, oxyproline, tyrosine, aspartic acid, leucine, isoleucine, dioxyphenylalanine, phenylalanine, glutamic acid, valine, histidine, cystine, ornithine, glycocol, and alanine. In addition, they reported lecithins composed of glycerophosphoric acid, choleine, and the fatty acids palmitic, stearic, arachic, oleic, and linolic; stachydrine, trigonelline, turcine of betonicine, and choline; also alkaloids.

Wild Rubbers

Dissimilarity of Natural Rubbers

The dissimilarities of natural rubbers stem partly from the constituents of the latex from which the rubber is prepared and partly from the methods of preparation. Differences in the methods of preparation may be due to the character of the plant that furnishes the rubber, to the character of the latex, or to particular local conditions that influence the gathering of the latex or rubber.

Wild 'Hevea' Rubber. The preparation of *Hevea* rubber in the form of smoked balls was standard practice in the Amazon Valley when Wickham collected the *Hevea* seeds that resulted in transferring the rubber-producing industry to the East. These smoked balls are still being produced, though giving way to the production of concentrated latex. The balls weigh from 50 to 100 lb. each, are hollow in the centre, black on the outside, and whitish to dark yellow or brown on the inside. As they are produced by dripping successive amounts of latex on a core formed of a wooden paddle revolved over a smoky fire, they have, when cut open, the appearance of a gigantic onion. The inside of the ball may be either fairly dry or filled with a watery fluid, which may occur both in the hollow centre and between some of the layers. The ball may be relatively free from odour or may be foul-smelling, but is never as bad in this respect as chilte and other rubbers that contain higher percentages of proteins. Brazilian smoked ball is the most uniform in quality of all types of wild rubbers, because *Hevea* latex has a smaller proportion of non-rubber constituents than any other type of natural rubber.

Market Grades in 1917. In a glossary of the terms used in the rubber industry in 1917, Dannerth (1917) listed the grades of *Hevea* rubber appearing on the American market:

1. *Fine Para Rubber:* This material is obtained from the wild *Hevea brasiliensis* trees found along the Amazon and its tributaries in Brazil. It appears on the market in about twenty-five grades and varieties which vary in (1) tensile strength, (2) water-content, and (3) percentage of dirt. The grades are named after the several tributary rivers of the Amazon and after the port of shipment. Some of these grades (mentioned in the order of their quality) are: (1) Beni or Beni Bolivian; (2) Madeira; (3) Solimoes, Javary, Jurua, Purus, Acre; (4) Mollendo, Angustura, Xingu; (5) Tapajos; (6) Matto Grosso, Caviana, Peruvian, Islands, Tocantins.

2. *Medium Para Rubber:* This material, prepared from the latex of *Hevea brasiliensis*, is next to fine Para rubber in commercial value. It is recognized by the appearance of the 'ham'* when viewed in cross-section. Curds and globules of imperfectly coagulated 'milk' are seen between the layers. These uncured spots and badly smoked spots may be only as large as a sixpence, or they may constitute as much as 25 to 50 per cent of the whole ham. The price per pound is in consequence 34 cents below that of fine Para rubber.

3. *Coarse Para Rubber:* This is *Hevea* scrap rubber prepared from the residue left in the latex cups. 'Up-river coarse Para' is distinguished from 'Islands coarse Para' by being drier and harder, and having the spheres or pelles smaller. 'Islands coarse Para' appears on the market in irregular balls about seven inches in diameter. This grade shrinks from 35 to 50 per cent, while 'up-river coarse Para' loses 20 to 25 per cent when it is washed and dried.

Wild 'Castilla' Rubber. Next to *Hevea*, the largest quantities of wild rubber have come from *Castilla* spp.—as caucho from the Amazon and

* The smoked ball of rubber bears a superficial resemblance to a ham and often has an odour reminiscent of a heavily smoked ham. It is often, therefore, referred to as a 'ham'.

as castilloa sheet or slab from other parts of the Americas. In many areas, coagulation was by natural fermentation—mostly in holes in the ground. This rubber was black, dirty, and foul-smelling. In some areas, the *Castilla* latex was coagulated by the addition of a decoction of moon vine. Sometimes the coagulum was washed and roughly sheeted on crude rolls, but more often it was only roughly pressed and allowed to dry. It was black, and somewhat less odorous than that prepared by natural coagulation; but it still required to be washed before being used in the manufacture of rubber goods.

Schurz *et al.* (1925) stated that in the Amazon Valley caucho came under the general classification of 'fine', and on the Para and Manaos markets was subdivided into two general classifications, *sernamby de caucho* (caucho ball) and *caucho prancha* (slab). The caucho ball was made by stripping off the ribbons of rubber that coagulate in the cuts on the tree and rolling them into balls or bundles (Plate 57(*a*)). The *caucho prancha* was rubber that had been made from latex which had been allowed to coagulate naturally, or with the aid of soap or vines, in a hole in the ground. It was dirty, and had a fetid odour and a poor appearance. It was sometimes pressed into blocks and then cut into strips and wound into balls.

Wild Ceara Rubber. Manicoba or Ceara rubber was produced from species of *Manihot*, chiefly *M. glaziovii* and *M. dichotoma*, in Brazil. It was obtained by spontaneous coagulation, or by the addition of water to the latex, and appeared on the market in the form of lumps having a light tan to amber colour. This was usually a high grade of rubber and Dannerth (1917) stated: 'Since 1910 this rubber has become popular in America for the manufacture of high-grade products.'

The African Rubbers. As was shown previously, there are many rubber-bearing trees and climbers in Africa. All of these produced soft rubbers that became known generally as 'Africans'. Dannerth (1917) stated:

> The principal 'Africans' which were offered on the American market are, in the order of their value: (1) Lopori, (2) Upper Congo, (3) Rio Nunez, (4) Conakry, (5) Massai, (6) Soudan, (7) Kamerun, (8) Benguela, (9) Accra. All these rubbers are obtained from various species of *Landolphia* and are therefore sometimes designated 'vine rubbers'. Accra rubber is also obtained from *Funtumia* and from *Clitandra*; while rubber from the Herman colony of Sud Kamerun is obtained principally from *Funtumia* plants.
>
> When purchasing these rubbers, the buyer judges them mostly by weight and general appearance. If they are dirty and full of sand, they will be obviously heavy. The loss on washing and drying these rubbers is considerable. Accra lumps may lose from 40 to 50 per cent of their weight. On the other hand Upper Congo balls may lose only 15 per cent of their weight.

Pearson (1921) listed many grades and types of African rubbers in 1921, giving the native names, botanical sources, and geographical origins.

He showed that the rubber was produced in dozens of different shapes and sizes, and varied in quality from excellent to bad. All had to be washed before use, and the loss in washing shown by Pearson ran from 7 to 60 per cent of the crude weight of the rubber.

African rubbers were produced and exported in appreciable quantities until after the end of World War I. They were of particular value as softeners for *Hevea* rubber, but their use decreased quickly in favour of cheaper materials.

Jelutong. A very resinous rubber known as Jelutong or Pontianak was produced in Borneo and Sumatra from species of *Alstonia* and *Dyera*. This rubber appeared on the market as dirty, blackish slabs, but found some use in the rubber industry and, later, in the manufacture of chewing gum. Dannerth (1917) states:

> *Pontianak.*—A gum prepared from the milk of *Dyera costulata* and related species in Borneo and Sumatra. The latex is coagulated by means of kerosene together with acidic salts (such as alum). This gum is known in England as Jelutong, but here it is universally sold as Pontianak, the name of the port on the Island of Borneo from which it is shipped. The dried gum contains about 75 per cent resins, a fact which makes it of especial value for the preparation of 'friction' compounds in the manufacture of mechanical goods.

Plantation Rubber

Market Grades

Plantation rubber is graded on appearance and cleanliness and sold in commodity transactions on this classification. Grades have been established for crepes and for ribbed smoked sheet (RSS or R.S.S.). Both International and R.M.A. (Rubber Manufacturer's Association) standards have been established and can be used for buying and selling. Quotations may be by either standard and, in general, the values of the rubbers are directly related to the grades. International grades 1 to 3 for crepe and smoked sheet denote increasing amounts of imperfections, as do R.M.A. grades 1 to 5. The brown and blanket crepes also vary in grade according to the assigned numbers, which represent increasing amounts of dirt.

While, in general, the grade designation indicates the relative value of the rubber, demand for particular grades may result in lower grades being actually quoted temporarily at higher rates than some of the better grades, or may result in the higher grades being tendered at the lower grade quotation. In general, rubber quotations are given as those for RSS 1 (first-quality ribbed smoked sheet).

Technically Classified Rubber

The variability of wild rubber was accepted as a natural condition arising from differences in a multitude of botanical sources. In compounding, it was necessary to take into account the variability of dozens of grades and types of rubber, and so to blend the rubbers from different sources that uniform products were obtained. The desirability of producing standard grades of plantation rubber has been recognized, and a large measure of uniformity has been accomplished. Complete standardization has, however, not been attained. The processing characteristics of the rubber vary from place to place, from clone to clone, and from season to season. Manufacturers of rubber goods must still blend rubber from several to many lots to produce uniform products.

Synthetic rubber, on the other hand, is produced in standard grades that can be used without the necessity of blending. The uniformity of competing grades of synthetic rubber forced a review of the variability of plantation rubber. Here, rigid adherence to market grades was not sufficient for standardization of the product, as there is a significant variation in the processing characteristics of different lots that is not encompassed in the classification.

French scientists of the Institut des Recherches sur le Caoutchouc en Indochine suggested the marketing of rubber with predetermined processing characteristics. At a general conference at the Rubber Research Institute of Malaya, Kuala Lumpur, agreement was reached for the production of rubber classified at the point of origin with regard to its processing characteristics.

R. G. Newton *et al.* (1951) studied and tabulated the type and source of the variation of plantation rubbers, and thus indicated the tremendous natural obstacles to standardization through control of plantation processes. Mann & Newton (1950) and de Hann-Homans (1949) showed the advantages of determining and marking the rubber according to its processing characteristics as a means of facilitating the use of plantation rubbers to meet specification demands, without the necessity of mixing many lots of rubber to maintain a uniformity of compound at the factory.

Under the French plan as adopted for general use, the rubber was to be classified for hardness on the basis of Mooney plasticity tests, and for the rate of cure on the basis of tensile strain tests. There were to be three categories of each, making nine classifications in all. The hardness of the rubber was to be indicated by placing a cross, circle, or line on two sides of the bale. The cross represented a stiff rubber, the circle a medium rubber, and the line a soft rubber. The curing characteristics of the rubber were to be indicated by the colour of the markings. A blue cross, circle, or line indicated a fast-curing rubber. If the marking was yellow, the rubber was medium-curing and, if the colour was red, the rubber was slow-curing.

It was soon realized that changes in the rubber in shipment and storage are sufficient to invalidate plasticity measurements made at the point of origin. Rubber manufacturers did not find the hardness markings useful in the classification of the rubber at the factory, and so these were discontinued.

The colour marking to indicate the relative rate of cure has continued, being applied in the form of a circle. The rate of cure is determined on the basis of a standard mix and cure. The stress is measured in kilograms per square centimetre at an elongation of 600 per cent. The higher the stress, the faster is considered the cure. The rubber from a given farm or plantation is carefully tested, and markings are assigned that may be used if a standardized processing system is followed. The marked rubbers enter the market on the basis of the standard grades, and a prime tenet of the backers of the classification is that rubber so marked should not sell at a premium. The markings are informational only, and it is hoped that they can be used to guide the assembling of the rubber into groups with uniform processing characteristics.

Consideration has also been given to the advisability of classifying the rubber on the basis of cleanliness. The Indonesian Rubber Research Institute (INIRO) proposed three grades:

I. Super-clean rubber
Content of harmful dirt less than 0·05 per cent.

II. Clean rubber
Content of harmful dirt less than 0·15 per cent.

III. General-purpose rubber
Maximum dirt-content 0·30 per cent.

Note: Harmful dirt is that consisting of particles which do not pass a 325-mesh screen.

Vervloet & Noothout (1954), on the basis of the INIRO tentative standards, studied the dirt-content of rubber classified in the following R.M.A. (*see* p. 311) grades:

RSS 1, 2, and 3
Crepe 1, 2, and 3
Brown crepe 1x, 2x, and 3x

The investigation covered twenty estates of seven different companies. Dirt was measured by plasticizing a sample of rubber on a warm mill (about 70°C.) for six minutes. Then 10 gm. of the rubber were dissolved in zylene and the solution was filtered through a 325-mesh screen, carefully washed out, dried at 105° to 110°C., and weighed. Nearly all of the rubbers studied had less than 0·15 per cent of harmful dirt, and 70 per cent were classified as super-clean. Brown crepe, representing only a few per cent of the total rubber, was the only grade with a wide range of harmful dirt.

Superior Processing Rubber

Superior processing rubber, as described by the Rubber Research Institute of Malaya (1957*a*), is the name given to a form of natural rubber prepared in accordance with British Patent Application 7770/54, in which a portion of the raw rubber is vulcanized before coagulation. This material can be prepared either in the form of crepe or as sheet, and is considered of particular value in the manufacture of goods by extrusion, because of its smoother and easier workability.

This rubber is prepared by vulcanizing fresh ammoniated latex with a suspension of vulcanizing agents made up in accordance with the following formula:

	lb.
Sulphur	20·0
Zinc oxide	7·5
Zinc diethyldithiocarbamate	2·0
Mercaptobenzthiazole	4·0
Dispersol	0·4
Water	48·1
Total	82·0

This amount of suspension is sufficient to treat latex containing 1,000 lb. of rubber which, when diluted with untreated latex, will give 5,000 lb. of Superior Processing Rubber.

Strained latex is ammoniated to 0·3 per cent and a suspension of the vulcanizing agents, made according to the above formula, is added in the proportion of 8·2 per cent of the weight of the rubber in the latex. The temperature of the latex is then raised to 180°F. by the injection of live steam at a rate to bring the latex to the desired temperature in one hour. The temperature is then maintained at between 180° and 185°F. for about two hours until the reaction is complete. The treated latex is next blended with diluted field latex in a proportion to give five parts of rubber in the blend to one part of treated rubber. The blended latex is finally poured into coagulating tanks and processed through to the bale in the same manner as would be done with normal field latex.

The Rubber Research Institute of Malaya has found that, in a suitable plant, the extra cost of the partial vulcanization amounts to 1·35 cents (Malayan) per pound of rubber—including amortization of the extra factory costs amounting to $15,000 to $23,000 (Malayan). In 1957, the rubber was sold to users at a premium of 1d. Sterling (3·5 cents Malayan) above the equivalent grades of crepe or sheet. At that time, the demand for Superior Processing Rubber exceeded the capacity for its production.

Skim Rubber

In the concentration of latex by centrifuging, the skim may contain from 2·5 to 10 per cent of rubber. It can be coagulated spontaneously in open pits or by the use of sulphuric acid. A combination of formic acid and calcium chloride is sometimes used. The coagulum is prepared in the form of sheet or crepe and, according to the Rubber Research Institute of Malaya (1957*b*), contains between 70 and 85 per cent of rubber, between 5 and 10 per cent of fatty material, and between 9 and 18 per cent of protein—compared with average figures for ribbed smoked sheet of 95 per cent of rubber, 3 per cent of fats, and 2 per cent of protein.

The Firestone Tire and Rubber Company has a patented process for the production of skim rubber that is substantially equal to standard smoked sheet. In this process, the skim latex is clarified and then allowed to coagulate spontaneously. The coagulum is reduced to a finely divided state and treated first with lime water and then with caustic soda solution. A conventional antioxidant is added and the rubber is washed, dried, and pressed into bales. During the treatment, both the high protein and high fat-contents of the original skim rubber are reduced, but the rubber has a higher-than-normal ash content.

The Dunlop Rubber Company, Ltd., has a patented process for preparing a skim rubber by the use of a proteolytic enzyme. As described by Barnwell (1957), an 8 per cent solution of trypsin is added to the latex in a proportion suited to the proteolytic activity of the particular trypsin used, and the mixture is allowed to stand for twenty-four hours for deproteinization. The ammonia content is reduced to 0·1 per cent by stirring and surface aeration, and the treated skim is run into coagulating tanks containing a solution of sodium meta-bisulphite sufficient to give a concentration of 0·05 per cent on the basis of the skim. Sufficient diluted formic acid is then added gradually, and with constant stirring, to effect coagulation. When coagulation is complete, the coagulum is cut into strips, soaked for four hours, creped with a plentiful supply of water, and dried.

Barnwell furnished the following comparison of rubber prepared by the Dunlop process and RSS 1:

	Skim rubber per cent	RSS 1 per cent
Moisture	0·41	0·30
Protein (calculated from nitrogen content)	2·75	2·50
Acetone extract	5·48	2·50
Ash	0·23	0·20
Dirt content (325-mesh screen)	0·01	0·025
Rubber hydrocarbon	91·13	94·45
Copper	7 p.p.m.	4 p.p.m.

The Rubber Research Institute of Malaya (1957*b*) points out that 100 lb. of normal skim rubber with a hydrocarbon content of 75 per cent will be equivalent to about 82 lb. of Dunlop improved skim containing 91·5 per cent of rubber, or 79 lb. of Firestone skim containing 94 per cent of rubber. It is necessary to take into account this loss in weight in determining whetherit is profitable to prepare and market the skim rubber purified by either process

Untreated skim rubber is useful in some products. A brown sole crepe made from skim and estate scrap has better properties than one made from scrap alone: the ageing characteristics are improved and the sole crepe is harder. The skim rubbers are fast-curing and some discrimination must be exercised in the choice of accelerator. Harder, stiffer compounds are usually obtained when skim rubber is used to replace standard grades of rubber in compounding for vulcanization. Skim rubbers cannot be marketed under standard grades but must be sold on the basis of samples.

Rubber Powders

The use of rubber in the surfacing of roadways has resulted in the development of interest in preparing crude rubber in a form to facilitate the mixing of the rubber into the heated asphalt used in the surfacing. A suitable form has been found to be a powder, as the rubber can then be safeguarded from agglomeration in coagulation, by treatment to remove the adhesiveness of the rubber particles. A product that has proved successful is known as mealorub, and is prepared from fresh ammoniated field latex by heating the latex with sulphur, zinc oxide, and an accelerator. Van Dalfsen (1940) gives a detailed outline for the production of mealorub.

Modified Rubbers

Considerable effort has been put into the modification of the rubber molecule by the addition of monomers or other chemical substances that might be expected to unite with the rubber to alter its molecular structure, and impart some of the special properties in which synthetic rubbers have proved to be superior to natural rubber. Koolhaas *et al.* (1950) reported on tests carried out in Indonesia on the use of ethylenic derivatives to modify the rubber in fresh latex. Bacon & Farmer (1938), Compagnon & Le Bras (1941), Compagnon & Bonnet (1942), Le Bras (1942*a*), Compagnon & Delalande (1943), and Le Bras & Compagnon (1944), have reported on various studies on modifying the natural rubber molecule. Natural rubber, which is the standard for all general-purpose rubbers, may also become important in the field of special-purpose rubber as a result of these experiments.

XVI

COMPARISON OF NATURAL AND SYNTHETIC RUBBERS

Introduction

In the discussion of the various types of natural rubber, we have been concerned with the same basic material. Variations are found in the mean size of the molecules and in molecular weight distribution; but any particular molecular weight, either high or low, is not, except in a very general sense, a characteristic of any botanical source of rubber. All plants that produce rubber contain high- and low-molecular weight rubber, and the proportions of high- and low-molecular weight rubber vary even in different parts of the same plant. Variability in molecular weight is characteristic of all natural rubbers.

Non-rubber impurities, both those normally associated with the rubber in the plants and those that are mixed with the rubber in obtaining it from the plants and preparing it for market, are characteristic of various types of rubber as they appear on the market. It is possible to differentiate between natural rubbers largely on the basis of the non-rubber constituents.

When the field of comparison is widened to include synthetic rubber, there is no longer a common denominator of molecular structure, and the only non-rubber impurities are antioxidants and similar materials that are added deliberately in very small amounts. We are no longer concerned only with polyisoprene, nor even only with polymers of closely related monomers such as butadiene. The rubbers include not only polymers of individual monomers but co-polymers, condensation products, silicones, and other chemical entities with a great diversity of chemical structure. There is, however, a common denominator for all rubbers, both natural and synthetic—namely elasticity, the quality that differentiates rubber from other materials.

To the degree that elasticity means only the ability to return to a normal shape and size when a deforming force is removed, rubber shares this quality with many other materials. Even gases submit to deformation in the form of compression, but return to their former state when the original conditions of pressure and temperature are restored. Metals often exhibit elasticity when subjected to forces less than those required for permanent deformation. The tuning fork is vocal in its response to deformation, reacting forcibly but, in relation to total deformation, is slow in assuming its former state, lacking the dampening effect of rubber. On the other hand rubber, under tension, exhibits vibratory reaction to deformation similar to that of the tuning fork.

Wood (1957) states: 'Rubbers, natural and synthetic, are unique in their high extensibility and forcible quick retraction. These two properties, in suitable quantitative terms, serve as the modern definition of rubber —independent of any mention of chemical structure.' The ability to stretch to several lengths and then return to the original length quickly and forcibly when the stretching medium is relaxed is characteristic of all rubbers, and it is this great elasticity that differentiates rubber from other materials that exhibit some degree of elasticity.

The rubbers are not equally elastic, and they share the characteristic of having their tensile strength and elasticity improved by vulcanization. The elastic response varies with the type of rubber and how it is compounded and vulcanized. The elasticity of any rubber and of any compound varies with the temperature, the other conditions under which the rubber performs, and the rate of deformation and recovery.

Elasticity

The measurement of elasticity in rubbers requires the assessment of many characteristics and reactions. One's first thought regarding an elastic material is 'How far will it stretch?' The first measurement of elasticity is, therefore, the total elongation, in relation to its original length, at the time the sample breaks—followed by a measurement of the force exerted by the sample at the breaking point. These measurements are known as total elongation and tensile strength.

There is an unequal relationship of elongation to the force applied to the sample. At first, there is almost a straight-line relationship between the force applied and elongation; but increasing force must be applied to obtain additional elongation. Finally, the approximately straight-line relationship is resumed, but the rate of elongation with additional force is much reduced. This relationship is characteristic of all rubbers, but the specific relationship of force (or load, as it is more commonly expressed) to elongation at different stresses and strains varies with different rubbers and different compounds. The total relationship, as expressed visually, is known as the stress-strain curve. The force exerted by rubbers at a given elongation, say 400 per cent, is termed the modulus and is the most commonly used element of the stress-strain curve. It is necessary to state the selected elongation and the unit of measurement, i.e. pounds per square inch of cross-section, in expressing this measurement.

Tensile Strength

The Formula. Before being tested, a rubber must be mixed with other materials and vulcanized. The formula is a recipe giving the proportionate amounts of rubber and other ingredients to be used in making up the compound to be tested. Standardized formulae must be used for routine tests and for facilitating the comparison of results obtained in different laboratories. However, the same formula does not give equally informative results with all types of natural rubber. Formulae designed to give optimum cures with natural rubbers, do not serve to give comparable results with synthetic rubbers, and the formulae must be varied for optimum performance of different types of synthetics. Optimum tensile properties can only be obtained by suiting the formula to the type of rubber under test. Deviations in formula are difficult to balance in evaluating tests comparing different rubbers and, for that reason, basic comparisons of different rubbers must be made on the basis of a common formula and cure, recognizing that the chosen formula may not be optimum for one or more of the rubbers. Comparisons of a particular rubber are made by suiting the formula to the type of performance desired.

Time and Temperature of Vulcanization. The terms 'vulcanization' and 'cure' are often used almost interchangeably to express the final step in the transformation of raw rubber into the finished product, though actually, vulcanization is the chemical reaction, and cure applies to the heat and time given to the reaction. The optimum cure is not uniform for all rubbers, nor for all mixes of the same rubber. In the compounding and manufacture of rubber goods, it is necessary to suit the time and temperature of vulcanization to the type of goods being manufactured and to the performance specifications. There is a large variation in the rate of cure of natural rubbers and an even greater variation among synthetic rubbers.

The Test Piece. After vulcanization, the sample is stretched to the breaking point in specialized equipment that measures the total load applied and permits the operator to record the total elongation. The test piece may be in the form of a ring that can be placed over standard projections on the stationary and moving portions of the tester, or it may be a dumb-bell shaped piece with broadened ends that are gripped in the jaws of the machine. A typical dumb-bell test piece is $4\frac{3}{8}$ in. long, with broadened ends 1 in. wide and the centre portion $\frac{1}{4}$ in. wide. These test pieces are cut from sheets that have been vulcanized in presses with a standard depression of 0·075 in. but, for the purpose of calculating cross-section for expressing the stress, the actual thickness of the individual test piece is measured by the use of a special micrometer that is designed to exert uniform standard pressure on the sample, for the utmost precision of measurement.

Temperature of Test. The temperature of the test affects materially the performance of the rubber. Both tensile strength and elongation are decreased as the temperature of the test is increased. Not only is the measured tensile strength of any given rubber dependent on the temperature of the test, but no two rubbers act alike, and variation with temperature is dependent on the type of compound as well as on the type of rubber. Vervloet (1953), together with Arentzen & Zeehuizen (1953), has shown that the testing of natural rubber in the tropics is usually done at room temperature, and that the results are fairly standardized as it is not difficult to maintain a uniform temperature of around 82°F. in the tropics. Normally, optimum results are obtained at temperatures of 68° to 70°F., and such a range is maintained in the controlled-temperature rooms in Europe and the United States. Many of the tests, however, are done in laboratories not equipped with controlled temperatures. Boonstra (1949) found it possible to convert to a common base the tensile properties determined at various temperatures, and he has supplied tables giving the variation in tensile strength and elongation over a wide range of temperatures for both gum and tread stocks of the principal rubbers.

Speed of Stretch. The speed of stretch may be expressed either in terms of the distance between the jaws of the tensile machine or in terms of the increase in length of the specimen. The standard rate of stretching in the United States is 20 in. per minute and refers to the jaw separation of the tensile machine. The R. T. Vanderbilt Company (1948) has reported that no difference was found in five samples of natural rubber when the jaw separation was increased from 20 in. per minute to 40 in. per minute. At higher rates of elongation, differences have been found in the tensile strength and elongation and, even though for natural rubber an increase in rate of elongation to double that of the standard appears to make little difference in the results, it is recognized that this change would alter the reading with some types of rubber and that, even for natural rubber, it is necessary to use only the standard rate of extension in determining compliance with specifications.

Modulus

The tensile strength and total elongation of rubber involve only some of its elastic properties. The stress-strain relationship covering the entire period of stretch gives additional important information regarding its elastic behaviour. A stress-strain curve can be plotted for a test specimen that will show the force exerted by the rubber at different percentages of elongation or, conversely, the total load needed to stretch the rubber to an indicated percentage elongation. Here again the time relationship is important. If the specimen is held at any given percentage elongation, the force exerted by the rubber gradually decreases—rapidly at first and then more slowly. If the load is held at a given figure, the length of the sample increases in the same manner as above—rapidly at first, and then more and more slowly. The decrease in force due to prolonged holding of the rubber at a given elongation is called 'stress relaxation', and the increase in length due to prolonged holding at a given load is called 'creep'. Both stress relaxation and creep are important characteristics of rubber, and the amount of each is influenced by the type of rubber, the mix, and the cure.

Martin *et al.* (1956) demonstrated that the time required by rubber for complete recovery from a sustained stress is appreciable, and may be as much as a week after it has been held under a stress of 4 kg. per square cm. for 1,440 hours.

There are many relationships of the stress-strain curve that may be used advantageously to demonstrate or measure differences in rubbers and in rubber compounds. The most common term other than 'tensile strength' or 'total elongation' is 'modulus' which, in rubber testing, measures the stress in load per unit of cross-section at a given strain expressed in percentage elongation. In the classification of rubber in producing areas in the East, the modulus at 600 per cent elongation is used. The optimum strain point varies with the different rubbers and compounds and with the use for which the individual compound is intended.

Hysteresis

Wood (1957) points out that when a sample of rubber is stretched at a controlled speed and then allowed to retract at the same rate, the stress at any given percentage elongation is less during retraction than it had been during the initial stretching. The specimen exerts less force at each elongation on return than it did while being stretched. In the example given by Wood, GR-S rubber was stretched and allowed to retract at a constant speed of about 200 per cent of original elongation per minute. In a second cycle of stretching and retraction that was started about three minutes after the completion of the first cycle, the stress data during extension were considerably below those for the first cycle but almost coincided with those for the first cycle during retraction.

These reductions in stress during the individual cycles are explained by Wood as due to an irrecoverable loss of energy in the form of heat—in exact analogy with the hysteresis losses in magnetic materials. Wood states:

> The loss shown by GR-S synthetic rubber is much larger than is obtained with natural rubber under the same conditions in the absence of crystallization. The loss manifests itself in heat, of course, and causes GR-S tires to develop higher temperatures than natural rubber tires in operation.

Wood continues:

> The loss shown by GR-I or Butyl rubber (commonly used in inner tubes) is normally much greater than that shown by GR-S synthetic rubber, particularly if the cycle is traversed rapidly. Dropped from a height of 6 ft., a natural rubber ball is deformed in a period of the order of milliseconds and rebounds, giving back about 80 per cent of its original energy; about 20 per cent is lost in hysteresis. A Butyl rubber ball dropped under the same conditions gives back about 8 per cent of its original energy; about 92 per cent is lost in hysteresis.

Resistance to Abrasion

The ability to yield to deformation, but to continue resistance, is an essential quality of elasticity, and is also essential to optimum resistance to abrasion. The ability of a rubber to combine with, and hold, reinforcing and abrasive agents, is also an important factor in resistance to abrasion. In abrading wheels in which rubber is used to unite the constituents of the compound, the cementing or holding ability of the rubber is important, but its continued ability to yield makes it superior to non-yielding cements with higher holding capacity.

Zapp (1956) showed that, with 20 per cent slippage, the rate of loss of rubber was nearly twice that of steel, while with only 8 per cent slip, the loss of steel was three times that of rubber. The rate of loss of the steel at 8 per cent slip was less than a sixth of that at 20 per cent slippage. The rubber used in this test was a butyl tyre compound, and illustrates the high resistance of that rubber to abrasion under conditions of low slippage in normal wear—together with high drag when there is high slippage, such as would be experienced in braking.

Zapp compared butyl rubbers of varying degrees of unsaturation and of molecular weights ranging from 310,000 to 900,000, and concluded that resistance to abrasion is related both to toughness and to softness, stating: 'In simple terms, what is needed for best resistance is the softest, toughest material.'

Resistance to abrasion is measured in the laboratory by subjecting the rubber to various types of abrasion under different pressures, speeds, and temperatures. The abrading devices consist of abrading wheels, or of discs, wheels, or endless belts covered with abrasive coatings. The rubber may be held static, all abrasion resulting from the movement of the abrading device, or the abrading device may be static when the movement of the rubber creates the friction. The load may be constant, or the variable contact between tyre and road surface may be simulated.

No laboratory test of tyre compounds has been devised that can take the place of tests under actual operating conditions. The road tests, however, are time-consuming even with overloading and underinflation. The laboratory tests do much to reduce the number of road tests needed, and also have values that cannot be obtained in road tests. In the laboratory, all conditions of the test can be controlled precisely—the character of the abrading surface, the speed of abrasion, the force of contact, the amount and character of the contact between the sample and the abrading device, the allowable slippage, and the temperature of test. Precise recordings can be made of these and other factors for evaluation of the tests. These measurements have not been perfected to present an accelerated wear test, but they are useful for the basic comparison of rubbers and rubber compounds.

Hardness

Hardness in rubber refers specifically to its surface characteristics and is measured by its resistance to indentation by various types of rounded points. Several types of instruments are used to measure hardness, but most have ball-shaped indentors. The Shore A Durometer has an indentor shaped like a segment of a cone. The diameters of the indentors vary from that of a hemisphere from 1/16 to ¼ in.in diameter, to that of a segment of a cone 3/64 in. in diameter at the base and 1/32 in. in diameter at the tip. The indentor is pressed into the sample either by means of a dead weight or by spring pressure. The depth of penetration is the measure of hardness. The loading varies with the type of instrument—from 2 to 29 oz. in the Shore A Durometer, to over 3 lb. at total load in some types. To avoid errors due to the character of the bench on which the sample is resting or to an unsupported edge of the sample, it is necessary to have the sample at least ½ in. thick and the test point at least ½ in. from the edge of the sample. The difference in the indentors and loads in the various instruments makes it necessary to specify the particular instrument in giving hardness measurements—for instance Shore hardness. The dead-weight loading avoids the use of springs and is considered more accurate, but the spring pressure instruments are more portable and are preferred for routine tests.

Numerous hardness meters have been devised and used in the attempt to obtain a standardized measurement of the surface hardness of rubber. Some gauges measure the depth of indentation directly and thus give an indirect measurement of the hardness, or resistance to penetration. Others reverse the scale in order to provide a direct measurement of resistance to penetration, the higher numbers on the gauge representing low penetration (high resistance to penetration) and the lower numbers representing deep penetration (lack of resistance to penetration). The depth of penetration may be measured in thousandths of an inch or hundredths of a millimeter. Some meters are provided with special feet to equalize the pressure on the sample of rubber. It is necessary, therefore, to specify the type of meter or gauge in giving the results of hardness tests.

Elastic Properties of Natural and Synthetic Rubbers

The primary comparison of rubbers is on the basis of their elastic behaviour, the character that differentiates the rubbers as a group from other materials. To a large degree, such comparisons are often artificial, since the high elasticity measured is seldom a requirement of the service to which the material is to be submitted. As *Hevea* rubber is highly elastic, other rubbers, both natural and synthetic, have been compared with it on the basis of elasticity.

Few commodities have received such generalized designations of quality, running from poor to excellent, with as little relation to actual performance in use, as has rubber. The usage of rubber covers such a wide range of products that it is not possible to designate a rubber as good or poor without some indication of the use for which it is being classified. A general-purpose rubber suitable for the manufacture of tyres is not necessarily the best for tubing, and an excellent rubber for tubing might be quite unsatisfactory for cements. Even within the rubbers suitable for cements, there is a large difference in qualities depending on the particular use of the cement.

In each rubber, the expression of the various facets of elasticity can be varied from high to low by changes in compounding and cure. Within any given class of synthetic rubbers, changes can be made in the formulation during manufacture that will alter the performance of the rubber with respect to specific performance tests, and the development of 'Heveaplus', and of other branch polymers of natural rubber, opens the way to the production of special-purpose rubbers based on a natural rubber base. No synthetic rubber has yet been found to have tensile properties equal to those of 100 per cent clean *Hevea* rubber prepared with the utmost care to exclude all traces of sand and dirt. The best grades of commercial natural rubber contain traces of foreign matter that reduce their tensile strength; but *Hevea* rubber is still pre-eminent among rubbers. New synthetic polymers such as Ameripol, Coral, Natsyn, or SKI, simulate the natural rubber molecule and may eventually rival *Hevea* rubber in tensile properties, but the need for such high elasticity is extremely limited.

For any specific modulus within the normal range of commercial requirements, and for resistance to abrasion, high degree of hardness, and plasticity, it is possible to produce a synthetic rubber that will equal or better the performance of natural rubber. The superiority of synthetic rubbers is evidenced most when the elasticity must be combined with other characteristics such as oil-resistance, resistance to oxidation, lack of permeability to gases, and similar requirements of consumer needs. No synthetic rubber has as great a range of usefulness as natural rubber; but, for special uses where a combination of elasticity with one or more special qualities is needed for optimum performance, some of the synthetics are able to combine adequate elasticity with superior accessory performance.

The hysteresis of natural rubber is superior to that of synthetic rubbers that have sufficient resistance to abrasion for use in tyres. The heat that is built up in the rapid flexing of a tyre, is a prime cause of failure of the fabric that makes up the plies which give the tyre its basic strength. High heats, particularly those built up in tyres of large cross-section, are a significant factor in the rate of abrasion of the tyre under road conditions. The lower hysteresis of natural rubber gives it a pre-eminence in the demand for rubber for use in superior-quality tyres, or for use in tyres with a large cross-section, where the greater amount of flexing causes a greater degree of heat build-up.

Plasticity

Elasticity has been described as the common denominator of all rubbers. Yet, all rubbers must also have a plastic state in which they can be manipulated, mixed with compounding ingredients, and made into useful products. The use of plasticity measurements in determining the molecular weight of natural rubber, and in the comparison of processing characteristics of various types of natural rubber, has been discussed. Plasticity measurements facilitate the comparison of natural and synthetic rubbers with respect to molecular weights and processing characteristics.

The plasticity of rubber can be measured by several methods. In the compression method, the sample of rubber is compressed between two parallel plates and the flattening of the rubber is measured with regard to temperature, load, and time. In the extrusion method, the amount of rubber extruded through a given orifice in a given time is recorded with respect to temperature and pressure. In the shearing-disk method, described by Mooney (1934), a sample of rubber of definite volume and at constant temperature is sheared between the surfaces of a rotating disk and a stationary chamber surrounding the disk. To prevent slippage, the rubber is maintained under a confining pressure and the surfaces that shear it are roughened. The volume is controlled by the space between the walls of the chamber and the surface of the rotor. The temperature is controlled from heated plates above and below the rubber. The resistance that the rubber offers to the turning of the rotor is transmitted to a calibrated spring, and the deflection of this spring gives a measure of the shearing force. This shearing force is proportional to the intrinsic viscosity of the rubber and thus may be used in estimating the molecular weight of natural and synthetic rubbers, as well as in providing a measure of their processing characteristics.

Resistance to Oils and Chemicals

Many uses of rubber bring it into contact with oils and chemicals. The ability of rubber to resist the action of oils and chemicals and still retain elasticity and pliability has been an important factor in its use for the manufacture of hosing for the handling of corrosive liquids and the transmission of fuels, in insulation subjected to oil and gas, in gaskets and couplings in fuel, oil, or chemical lines, and in similar usage where some degree of resistance to such materials is necessary. The use of rubber for such purposes did not start with the development of synthetic materials; but the utility of rubber in this respect was greatly increased by the invention and manufacture of new synthetics with superior resistance to oils and chemicals.

Before the invention of these new synthetics, a rubber with increased resistance to oils for use in fuel hosing, or in other applications where resistance to oils is essential, was made by combining a large proportion of reclaimed rubber in the compound. Natural rubber swells when it is subjected to the action of oils or solvents. In fuel hosing, this may cause complete obstruction and necessitate early replacement. The use of reclaimed rubber greatly increased the life of rubber articles subjected to the action of fuels and oils.

The discovery of oil-resistant synthetic rubbers, particularly Neoprene (at first called Duprene) and Thiokol, greatly increased the utility of rubber in fuel lines, gaskets, insulation, and similar uses where the rubber is in contact with oil or oil derivatives that swell or dissolve natural rubber.

Swelling is measured by suspending the sample in the fluid involved and measuring the amount of swelling by total volume, or the increase in weight of the sample. The time of immersion, the temperature of the fluid, the size and shape of the specimen, the volume-ratio of the liquid to the specimen, and the type of fluid, all affect the results of the test. In these tests, many types of synthetic rubber have been found to be superior to natural rubber and these receive preference, irrespective of supply or cost.

Permeability

The permeability of rubbers to gases is an important characteristic. Many of the uses of rubber involve both elasticity and the ability to contain or exclude air, hydrogen, helium, water vapour, or other gases. Most important from a volume standpoint has been the use of rubber for inner tubes in motor-car tyres. Other important uses include balloons, both large and small, and the packaging of fresh materials (particularly foodstuffs) to prevent drying. Comparisons are made on the basis of permeability, rate of diffusion, and solubility of the gas in the rubber. Permeability and rate of diffusion are related to the area of rubber exposed and to the differential in pressure between the gas on the two sides of the rubber.

Amerongen (1946) compared the permeability at 25° C. and 43° C., the diffusion, and the solubility, of natural rubber, Buna S, Perbunan, Neoprene G, and polyisobutylene (Oppanol B-200), to hydrogen, nitrogen, and oxygen. He found that permeability and the rate of diffusion increased sharply with temperature, and are influenced greatly by the nature of the gas and of the rubber. In this test, natural rubber was relatively high in permeability to hydrogen, but relatively low in permeability to nitrogen and oxygen. All three gases are comparatively soluble in natural rubber.

Resistance to Oxidation

Oxidation enters into most of the chemical changes associated with the ageing and wear of rubber. Antioxidants must be added to minimize the oxidation of compounded rubber and to preserve synthetic rubbers prior to fabrication. *Hevea* rubber contains a natural antioxidant that preserves it adequately before fabrication, at least under normal conditions. This antioxidant can be extracted with acetone and used to protect other types of rubber. In compounding, additional antioxidants must be used and, under severe conditions, it is difficult to protect rubber goods adequately from oxidation. Conditions that are inimical to rubber and that encourage oxidation involve light-intensity, temperature, and atmospheric conditions—particularly in areas where there is a high incidence of smog, and the resultant build-up of an abnormally high atmospheric content of ozone, the measurement of which is used as an index of the severity of the smog.

The choice of rubbers for use in areas of smog is an important consideration, and it has been found that the correct selection of the rubber is more important than the selection of an antioxidant. Gaughan (1956) attributes the resistance, to oxidation by ozone in smog areas, of certain types of rubber to the degree of unsaturation of the rubber. Butyl, thiokol, and silicone rubbers are completely saturated and show the highest resistance to oxidation. Neoprene is unsaturated but has a chlorine atom next to the double bond, and Gaughan attributes its relatively high resistance to oxidation to this fact. Natural rubber has a high degree of unsaturation and a low resistance to oxidation. Butadiene-styrene rubbers and butadiene-acrylonitrile rubbers derive partial resistance from the saturation of the co-polymers that are included in the synthesis together with the butadiene.

Resistance to Extremes of Temperature

When rubber first found commercial use, it was fabricated and used in the unvulcanized state, and suffered greatly from softness and stickiness in summer and from stiffness in winter. After the art of vulcanization was discovered, the resistance of rubber to the vagaries of the weather was greatly increased and it could be compounded and vulcanized to meet all of the normal needs of man for an elastic material.

Advancing technology and widening uses for rubber have broadened the field in which rubber products find application. Part of this usefulness is due to the new types of rubber that have come into use, and part to the developing needs of an expanding technology. Particularly, the use of rubber has increased at temperatures above and below those at which it had previously been found satisfactory. Demands were made for rubbers that would not stiffen at arctic temperatures, and that would not soften in advanced temperatures in engine rooms where insulation and elastic gaskets failed.

New techniques, new rubbers, new compounding ingredients, and new test methods had to be developed to meet these new requirements.

The first necessity was to define the requirements and the qualities in the rubbers available, as well as their deficiencies.

Brittle Point

Vulcanized rubber loses its elasticity and becomes brittle when subjected to extremely low temperatures. The rubber can then be shattered by a sharp blow and is no longer useful in tyres or in other applications requiring resilience. The brittle point of rubber first became important when ships, automotive equipment, airplanes, and rubber-equipped apparatus, had to be operated at temperatures far below freezing in the polar regions and at high elevations above the world. The development of materials that will continue to be resilient under arctic extremes of temperature is an important field in the study of rubbers and rubber compounds.

At present, the performance of natural rubber at low temperatures, down to 62°C. below zero, is superior to that of the synthetic rubbers. Special compounding of some synthetics serves to impart qualities equal to those of natural rubber at low temperatures, but this performance is gained at the expense of the quality of performance at higher temperatures. At temperatures below minus 65°C., natural rubber and all synthetic rubbers, other than certain silicone rubber compounds, become brittle. Silicone rubber can be compounded to reduce its brittle point to minus 100°F. (about 73°C. below zero) and, at the present time, has the lowest brittle point of any of the known rubbers.

Resistance to Elevated Temperatures

At the other end of the allowable temperature range, almost the same relationship exists. As the temperature is increased, the performance of natural rubber is increasingly superior to that of synthetic rubbers. At temperatures of 150° to 250°C., however, silicone rubber can be compounded to retain superior elasticity as measured by flex life (indicated by its ability to take repeated bends of 180° over a $\frac{3}{8}$-in. mandrel before breaking) and hardness. Thus, the versatility of natural rubber at both elevated and reduced temperatures is outstanding; but, at extremes of temperature, silicone rubbers can be compounded to retain useful degrees of plasticity and resilience beyond the range either of natural rubber or of other synthetic rubbers. The silicone rubbers that are superior to natural rubber at extremes of temperature have utility at less extreme temperatures only as special-purpose rubbers, and thus lack the versatility of natural rubber.

NATURAL *v.* SYNTHETIC RUBBERS

It is not possible in a short space to compare the performance of natural and synthetic rubbers in detail. There are dozens of important tests of rubber that have not been mentioned, and many of these reveal outstanding differences between natural and synthetic rubbers and between the various types of synthetics. For present purposes, it has seemed best to select a few of the more important characteristics of rubber and to point out the chief differences between the rubbers that are available on the market.

It has not seemed desirable to make detailed comparisons between the various types of synthetic rubber, as most types can be compounded in a variety of ways to give a range of values, and it would be far beyond the space available to make such detailed comparisons.

Some years ago, it was stated that there were usages for which synthetic rubbers were to be preferred and would be chosen without regard to cost, and that there was also a field of use for which natural rubber was essential and could not be replaced by synthetic rubber. This, of course, left an intermediate field of competition for which either might be used and in which the choice of rubber to be used would rest entirely on availability and cost. An early estimate was that this relationship was 25-50-25 (natural-either-synthetic). Improved technology of production and compounding, together with the discovery and manufacture of new types of synthetics, have latterly increased the utility of synthetic rubbers, the area of free competition having correspondingly narrowed.

Phelps (1957), after a careful comparison of the competitive position of natural and synthetic rubbers, stated: 'From the point of view of preference alone, in part divorced from price, there appeared to be a consensus in 1952 that natural rubber would constitute 30 to 35 per cent of the total consumption, that synthetic rubbers would constitute 25 to 35 per cent, and that for the remaining 40 per cent price would be the controlling factor.' Phelps considered it reasonable to assume that developments in technology would increase the applicability of various types of synthetic rubber in applications for which natural rubber was preferred in 1952, and noted that more recent data on preference indicated a gain for synthetics.

It would be difficult to determine just how much of such preference is based on technical superiority and innate quality, and how much is based on unwillingness to alter manufacturing routine and use materials that require some adjustment of machinery and compounds. As has been pointed out, there are some basic differences between natural and synthetic rubbers. In some respects, such as low hysteresis, low crack-growth, adaptability to temperature fluctuations, and over-all versatility, natural rubber is superior. Synthetic rubbers may be chosen that are superior to the natural product in resistance to oxidation and ozonation, that are less permeable to gases, and that surpass any compound of natural rubber in resistance to oils and chemicals.

In few uses is it possible to select a rubber on the basis of its optimum performance with regard to a single property. In his autobiography, Benjamin Franklin confessed that he lost ground on those qualities he had already attained when he attempted to attain perfection by concentrating on a single good quality at a time. That is also true of rubbers of all types. The qualities and uses of rubber are not unidirectional. Optimum development of each quality is often at the expense of another. It is commonly necessary to compromise with something less than the best in a given character in order to attain adequate performance in another respect.

XVII

VULCANIZATION

Background

Plasticity to Elasticity

ELASTICITY is the common characteristic pertaining to all rubbers, both natural and synthetic. Plasticity also is a quality of all rubbers that is necessary to enable them to be formed into usable shapes. Vulcanization is the chemical process that transforms the plastic (raw) condition into the elastic (finished) condition. These two conditions, as has been pointed out previously, are not mutually exclusive, and there is considerable elasticity in the raw state of rubber and considerable plastic flow in the finished condition. However, the plastic condition must be of such character before vulcanization that the rubber can be moulded, extruded, or otherwise shaped. After vulcanization, the rubber must resist further change in shape and exhibit only a minimum yield to permanent deformation.

Goodyear's discovery of the interaction of rubber and sulphur under the influence of heat increased the usefulness of rubber, particularly with regard to its stability at high and low temperatures. This chemical and physical stability, resulting from the reaction of rubber and sulphur, made possible the use of rubber for many purposes for which the raw rubber was unsatisfactory, and was the basis for tremendous expansion of its commercial utilization.

Semantic Origin and Development of Vulcanization

Goodyear's discovery of the reaction between rubber and sulphur resulted from a mixture of the two being 'carelessly' subjected to the high heat of the stove top. From an experimental standpoint, the mixing of rubber and sulphur was neither new nor unique with Goodyear; only the use of great heat was new. The effect of heat was therefore the basic discovery made by Goodyear who later, at the suggestion of a friend, called the process vulcanization in reference to the effect of heat rather than the use of sulphur. Later, Alexander Parkes found that thin films of rubber could be changed from the plastic to the elastic state by the use of sulphur monochloride, and that this change could be accomplished without heat. The process, therefore, brought about the same result as hot vulcanization in that the plasticity of the rubber was reduced, elasticity was increased, and the physical characteristics of the rubber were stabilized. This process, which was carried out at room temperature, became known as 'cold vulcanization', and constituted a recognition that heat was no longer an essential of vulcanization.

The basic connotation of both the terms rubber and vulcanization now hinges on broad physical characteristics, on physical similarities, and on comparable physical changes, rather than on narrowly restricted material identifications. Each represents the growth of a term to cover a developing concept rather than the expanding of language by the adoption of new terms to meet the needs of new concepts. The eraser evolved into any highly elastic material, and heat treatment of rubber in the presence of sulphur evolved into treatment of any rubber or rubber-like material to make it less plastic, more elastic, and more stable in its reaction to temperature and solvents.

Early Studies of the Nature of Vulcanization

The discovery of cold vulcanization of rubber by sulphur monochloride was made by Parkes in 1846 and no further advancement was made in the theory of vulcanization for over half a century. During that time, the use of sulphur and heat predominated in the vulcanization of rubber, and the process was considered as essentially a reaction between rubber and sulphur. Meanwhile, great advances were made in the art of compounding and vulcanization, without any appreciable advance in the knowledge of the basic nature of vulcanization.

Weber (1902) made a scientific study of vulcanization and came to the conclusion that it was a chemical process. The summary of his conclusions may be translated as follows:

1. The rubber hydrocarbon, 'polyprene', combines with sulphur without the evolution of sulphuretted hydrogen. The vulcanization process is thus an addition reaction.

2. The vulcanization process consists in the formation of a continuous series of addition products of sulphur and polyprene. The upper limit of this series is represented by the compound $C_{100}H_{160}S_{20}$, and the lower limit by the compound $C_{100}H_{160}S$. This series is characterized, physically, by a decrease in extensibility and an increase in tensile strength, as it progresses from the lower to the higher numbers. Which member of the series is present in predominant amount in any individual case, in other words what degree of vulcanization has been reached, depends upon the temperature and duration of the vulcanization as well as upon the amount of sulphur present.

3. Vulcanization, considered as a chemical reaction, is unaffected by the physical condition of the rubber colloid, but this latter factor does have an influence upon the physical constants of the vulcanized rubber produced.

What is Vulcanization?

Definition of Vulcanization in 1922

Early scientific attempts to determine the nature of vulcanization were based entirely upon explaining the reaction of rubber and sulphur. Weber (1902) believed that vulcanization involved an additive reaction, while Ostwald (1910) summarized the work on vulcanization and attributed the interaction to adsorption of the sulphur by the rubber. The use of accelerators of vulcanization had become general, and it was recognized that compounding ingredients other than sulphur affected not only the quality of the finished rubber but also the character of the vulcanization reaction. Schidrowitz (1922) summarized contemporaneous thought on the meaning of vulcanization when he defined it as 'A process consisting in reaction between rubber and sulphur, whereby the thermal and physical properties of the rubber are considerably modified and improved'.

The definition given by Schidrowitz involved two concepts, (1) that vulcanization is a reaction between sulphur and rubber, and (2) that the essential effect of vulcanization is an improvement in the physical and thermal qualities of the rubber. Concept number 1 has been greatly modified by increasing technical advancement since then, but there has been little change in concept number 2 other than in the choice of words for its expression.

Definition of Vulcanization in 1935

Dawson & Porritt (1935) gave the following definition of vulcanization: 'Any process which converts raw rubber into a product insoluble in most solvents, less sensitive to temperature changes, and of increased elastic and less plastic properties. For technical purposes vulcanization is almost always carried out (*a*) by heating mixtures of rubber and sulphur, or (*b*) by treating rubber with sulphur chloride.' These authors defined hot vulcanization as resulting from heating a mixture of rubber and sulphur at temperatures ranging from 110 to 160° C., the proportion of sulphur varying from 2 to 5 per cent for soft rubber goods and the length of vulcanization time being determined by the temperature and composition of the mix. Cold vulcanization they defined as resulting from the treatment of raw rubber with dilute sulphur chloride at normal, or only slightly raised, temperatures, the process being suitable only for thin sheets or thin articles of rubber.

These authors, therefore, projected one step farther the definition of vulcanization as given by Schidrowitz. To the thermal and physical terminology used by Schidrowitz they added a reference to a decrease in solubility in most solvents, and they left the door open for the inclusion, in the broad concept of vulcanization, of processes other than the reaction of rubber and sulphur. That this was a recognition of advancing scientific knowledge, rather than the specific inclusion of processes other than the reaction of rubber and sulphur, is evidenced by their restricting the definition, for technical purposes, to the reaction of rubber and sulphur under the influence of heat or to the reaction of rubber and sulphur chloride.

Vulcanization without Sulphur

Ostromislensky (1915, 1915*a*) found it possible to vulcanize rubber without the use of sulphur. He reported that the changes attributed to vulcanization could be brought about by a treatment of rubber with certain nitro-compounds, organic peroxides, or selenium. According to Davis & Blake (1937), M.G. Shepard continued the work of Ostromislensky and discovered the vulcanizing effect of benzaldehyde and mercury oxide in 1919. Neither of these chemicals was effective alone.

The work of Ostromislensky led to a general recognition that the changes attributed to vulcanization could be brought about without sulphur, just as Parkes had shown that they could be accomplished without heat. The definition of vulcanization given by Schidrowitz (1922) still based the meaning on the interaction of rubber and sulphur. Dawson & Porritt (1935), however, recognized that there might be other processes that would bring about vulcanization but stated that, for all technical purposes, vulcanization consisted in the reaction of rubber under heat with sulphur or at normal temperatures with sulphur chloride. It is to be noted that the work of Ostromislensky and Shepard preceded both the definition given by Schidrowitz in 1922 and that given by Dawson & Porritt in 1935.

Vulcanization without Curing Agents

The development of synthetic rubbers necessitated intensified consideration of vulcanization. Some of the synthetic rubbers could not be vulcanized with sulphur. Some were saturated and had no double bonds to explain the addition of sulphur or other agents of vulcanization. As the number and diversity of rubbers increased, the difficulty of explaining vulcanization on the basis of a common reaction increased.

Carothers *et al.* (1931) found that *a*-polychloroprene could be vulcanized by heat alone, without need for the addition of any special vulcanizing agent. Davis & Blake (1937) mention the use of ultra-violet or cathode rays to vulcanize rubber without the use of heat or special vulcanizing agents. The use of radiation, since the development of nuclear fission, has become a more and more important scientific method of inducing vulcanization, and may become commercially useful as sources of radiation become available and cheap.

Definition of Vulcanization in 1957

It is no longer possible to restrict the changes characteristic of vulcanization to the reaction or interaction of any chemical with rubber, in

Photographs by permission of [illegible]

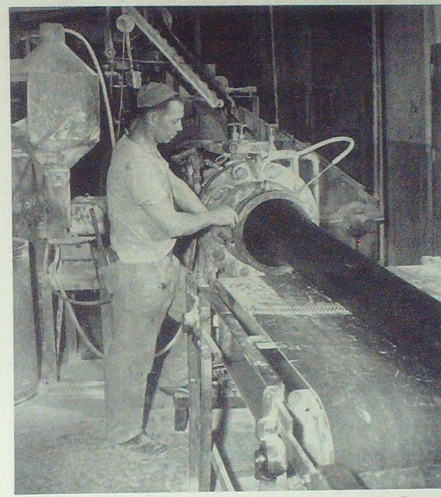
(*a*) Balls being taken to the river.

(*b*) [illegible] for shipment.

[illegible] *prepared from the leaves of* [illegible]

Photograph by permission of Goodyear Tire and Rubber Company

(*a*) Motor-car tyre being removed from the mould in which it has been vulcanized.



Photograph by permission of United States Rubber Company

(*b*) Large rubber tube being extruded.

view of the effect of irradiation without the addition of curing agents. When he was asked to supply a modern definition of vulcanization, L. A. Wood, of the United States National Bureau of Standards, suggested that such a definition might be a 'chemical reaction in which the physical properties of a rubber are changed in the direction of decreased plastic flow, less surface tackiness, and increased tensile strength by reacting it with sulphur or other suitable agents'.

The Nature of Vulcanization

Known Factors in Vulcanization

The 'before' and 'after' pictures of vulcanization are much better understood than the precise chemical reaction or reactions that bring about the change. It may be of some help to summarize the available information regarding vulcanization, the conditions under which it occurs, and such other pertinent facts as may be useful in understanding the process. What, then, are the known facts?

1. Natural rubber and most synthetic rubbers can be vulcanized with sulphur. This is the oldest and most basic concept of vulcanization. However, some of the synthetic rubbers that otherwise have all the basic characteristics of rubber, including specifically the ability to be vulcanized, cannot be vulcanized with sulphur which, therefore, does not constitute the common factor that is involved in the vulcanization of all rubbers.

2. Comparatively high heat is required to bring about the reaction between rubber and sulphur, and the heat must be continued for a considerable period of time. Heat and time are also important with curing agents other than sulphur, such as the peroxides. Heat requirements may be reduced by the addition of accelerators or by increasing the time. The use of accelerators increases the reaction speed, often accomplishing in a matter of minutes vulcanization reactions that formerly had been measured in hours. Rubber, however, can be vulcanized in the cold (room temperature) by the use of sulphur monochloride as a curing agent. Because of the rapidity of the reaction, this method of curing is limited to thin articles; but it shows that heat and time are relative and not, in themselves, essential conditions of vulcanization, even though they are highly important in specific vulcanization reactions.

3. Vulcanization of natural rubber has been explained as an additive reaction, there being no evidence of the evolution of gas and its release in the form of hydrogen sulphide. Natural rubber, being unsaturated, can conceivably add sulphur at the double bonds; but some of the synthetic rubbers, such as butyl, are fully saturated before vulcanization. There is, therefore, no simple chemical addition or substitution that is common to all vulcanization.

4. Both natural and synthetic rubbers can be vulcanized with curing agents other than sulphur, including agents that do not contain sulphur even in bound form; so sulphur is not essential in any form.

5. A neoprene rubber, *a*-polychloroprene, can be vulcanized by heat alone. Vulcanization of natural rubber has been brought about by ultra-violet and cathode rays. Vulcanization of natural rubber, and many synthetic rubbers, can be induced by irradiation. It is apparent, therefore, that vulcanization can be brought about without curing agents and that no common characteristic of curing agents can be a common factor of vulcanization.

6. There is an optimum 'cure', but vulcanization is progressive rather than determinate and normally depends on heat, time, amount of vulcanization agent present, and also on the amount and character of the non-rubber constituents of the compound. Vulcanization is not, therefore, a specific chemical reaction characterized by a finite completion.

7. When maximum combination of natural rubber and sulphur takes place, ebonite is formed, enough sulphur having been incorporated to satisfy all the double bonds that existed in the raw rubber. Yet, the double bonds are not all satisfied and the resulting ebonite is unsaturated. The sulphur must be added, therefore, at points in the rubber molecule other than the double bonds or in polysulphide units.

8. In addition to the plastic→elastic effect of vulcanization, note has been made of the decrease, in both solubility and surface tackiness, that is characteristic of vulcanization. It has also been noted that, in the beginning, an increase in molecular weight can be detected. Increasing insolubility has made it difficult to follow this increase in molecular weight through the full range of vulcanization; but it has been established that the increase in molecular weight is characteristic of vulcanization. When rubber is broken down on the mill prior to compounding, its molecular weight is greatly reduced. Gain in molecular weight in vulcanization has been partially explained as a reunion of the broken chain units.

The Basis for the Theory of Cross-linking

In addition to the end-to-end reunion of molecular units to reconstitute the molecules split during breakdown, it was recognized that increase in molecular weight might also result from the cross-linking of adjacent molecules to form larger molecules during vulcanization. Weber (1902) had explained vulcanization as an additive reaction, and suggested that the range of vulcanization products would be from $C_{100}H_{160}S$ (partial saturation) to $C_{100}H_{160}S_{20}$ (total saturation). When saturated synthetic rubbers were found capable of being vulcanized by chemical agents, it was apparent that the simple addition of sulphur was not the explanation of vulcanization. Vulcanization by irradiation indicated that vulcanization did not consist of chemical reaction with any particular agent or agents.

The physical characteristics imparted by vulcanization could be measured and evaluated, but the chemical changes were difficult to explain—except on the basis of union of the molecules into larger molecules. These changes appeared to be more logically explained on the basis of cross-linking of adjacent molecules into a molecular network, rather than end-to-end union—which might explain vulcanization without curing agents, but not that involving the incorporation of sulphur or some other vulcanizing agent.

The theory of cross-linking of adjacent molecules provided an explanation of the plastic→elastic change in rubbers of diverse origin and composition, and the cognate improvement in tensile strength, resistance to solvents, and chemical stability. Though cross-linking has now been accepted generally as the basic change in vulcanization, there is not such general agreement either as to how this cross-linking is brought about, or precisely what the cross-linking mechanism is. The curing agent may provide a chemical 'bridge' to unite adjacent molecules and bring about cross-linking; but when irradiation is the vulcanizing force, the bridging mechanism must be supplied by the rubber itself, or there must be direct cross-linking without a bridge.

A concept of vulcanization may be gained by a comparison of the cross-linking of a rubber with a high degree of unsaturation and a rubber that is fully saturated. As natural rubber is the best known of the rubbers that are characterized by unsaturation, and has received a preponderant share of research effort, it seems desirable to use it as the type of similar rubbers with unsaturated double-bonds. A simple structural arrangement found in the saturated rubbers is that of dimethyl silicone rubber. The chain of this rubber is composed of alternating silicon and oxygen atoms, and there are two methyl side-groups attached to each silicon atom. A general understanding of these two types of rubber may provide a basis for the understanding of cross-linking in other rubbers and, thus, a recognition of some of the ways by which vulcanization occurs.

Vulcanization of Silicone Rubbers

The vulcanization of silicone rubbers can be brought about either by the use of peroxides as described by Harper *et al.* (1958), or by irradiation as described by Epstein & Marans (1958). In both cases, the reaction is between the adjacent molecules of the silicone—rather than by the vulcanizing agent entering into the rubber network as a bridging unit.

Vulcanization with Peroxides. The molecular structure of dimethyl silicone rubber, consisting of alternate silicon and oxygen atoms with two methyl groups attached to each silicon atom, can be indicated as follows:

$$\begin{array}{ccccccccc} & & CH_3 & & CH_3 & & CH_3 & & \\ & & | & & | & & | & & \\ (-O- & & Si & -O- & Si & -O- & Si & -O-)_n & \\ & & | & & | & & | & & \\ & & CH_3 & & CH_3 & & CH_3 & & \end{array}$$

Dimethyl silicone

The vulcanization rate of dimethyl silicone can be increased by substituting a small proportion of vinyl groups ($CH_2 : CH$) for some of the methyl (CH_3) groups, to form methyl vinyl silicone.

Harper *et al.* (1958) state that the peroxide vulcanization of silicone rubber proceeds by a free-radical mechanism. The reaction starts with decomposition of the peroxide, forming free radicals. These free radicals extract hydrogen from the organic side-groups of the silicone polymer. The activated side-groups then proceed to combine with each other, forming cross-linkages.

Harper *et al.* studied the vulcanization of dimethyl and methyl silicone with nine different peroxides, and found that no one vulcanizing agent could vulcanize silicone rubbers to suit all purposes. They found that benzoyl peroxide, dichlorobenzoyl peroxide, and tertiary butyl perbenzoate, all function well with both dimethyl and methyl vinyl polymers. The physical properties of the vulcanizates are good when correct amounts of the peroxides are used. Dichlorobenzoyl peroxide exhibits the best over-all characteristics, but care must be taken to avoid scorching.

Ditertiary butyl peroxide has excellent vulcanizing characteristics with methyl vinyl polymers, particularly for thick sections, carbon black-filled stocks, and when minimum-compression set is desired. It is very volatile and evaporates quite rapidly from the compounded stocks.

The optimum amount of peroxide to use for a desired application is fairly critical, though there is some latitude in using dicumyl peroxide or ditertiary butyl peroxide. The optimum amount depends on the particular application of the vulcanizate, as well as on the vulcanizing agent involved.

Many factors thus enter into the vulcanization of the silicone rubbers by peroxides. The quality of the vulcanizate depends not only on the structural characteristics of the individual polymer, but also on the type and amount of peroxide present, the temperature of decomposition of the peroxide, and the relative reactivity of the free radicals resulting from this decomposition. The vulcanization reaction is affected by the characteristics of the compounding ingredients, and the final performance of the vulcanizate is affected both by the effect of the peroxide in vulcanization and by the character of the by-products of the vulcanization reaction.

Vulcanization by Irradiation. Vulcanization of the silicones by peroxides requires high heat and long curing-time. These factors and the effects of the by-products can be avoided by bringing about the cross-linking by means of irradiation. Epstein & Marans (1958) discuss in some detail the effect of irradiating dimethyl silicone. Sources of radiation that may be used in the treatment of rubber include nuclear reactors, particle accelerators, and radioactive isotopes. Of these, the nuclear reactors are the most difficult to control with regard to the type of radiation and the total energy absorbed by the rubber. In the nuclear reactor, the rubber is exposed to fast and slow neutrons, to electrons (beta particles), and to gamma rays. The measurement of the radiant energy absorbed and the control of the temperature are both difficult; moreover the rubber, together with its container, may become radioactive.

Particle accelerators give a considerable degree of flexibility in treating rubber. They may be adapted to the production of electrons, protons, deuterons, and other rays and particles.

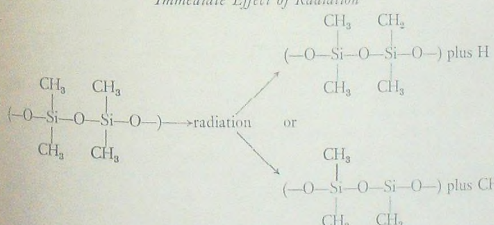
Radioactive isotopes that can be used include cobalt 60 (which emits gamma rays), other isotopes produced in nuclear reactors, and spent fuel from nuclear reactors. Most of the work on radiation processing of rubber has been done either with electron accelerators or with cobalt 60. The electron accelerator is characterized by high dose-rates and moderate penetration, while the cobalt 60 usually gives low dose-rates and deep penetration.

The effect of the radiation is to split off hydrogen atoms from the methyl groups or to split off entire methyl groups, or both. These hydrogen and methyl groups immediately recombine to give a mixture of hydrogen, methane, and ethane. The silicon molecules that have been deprived of hydrogen or methyl groups, then unite and thus establish cross-linkage at the points from which the hydrogen or methyl groups have been split off. This is a direct cross-linking, and no substance derived from the vulcanizing agent and foreign to the original silicone molecule is required to form the bridge.

In irradiation, the number of cross-links formed is roughly proportional to the energy absorbed from the radiation source by the rubber. For lower polymers, it has been calculated that 4·5 cross-links are formed per 100 electron volts of radiant energy absorbed. The relationship of energy to cross-linking has not been determined for silicone rubber, but it bears a definite relationship that makes the control of cross-linking by irradiation much more specific than with cross-linking induced by peroxides.

The structural changes caused by irradiation, and the recombination to give gases and cross-linkage, are shown below in general accordance with the presentation of Epstein & Marans (1958).

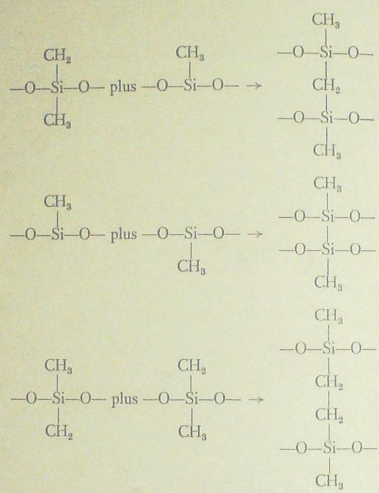
Immediate Effect of Radiation



Formation of Gaseous Products

H plus H→H_2 = hydrogen.
H plus CH_3→CH_4 = methane.
CH_3 plus CH_3→C_2H_6 = ethane.

Formation of Cross-links



Among the advantages listed by Epstein & Marans (1958) for the radiation curing of dimethyl silicone rubbers, are (1) the absence of by-products, (2) rapid curing, (3) low-temperature curing, (4) good control of the extent of the cure, (5) elimination of the need for chemical introduction of vinyl or other groups to aid the cure, and (6) little or no effect of non-rubber compounding ingredients.

Vulcanization of Other Rubbers by Irradiation

Irradiation has also proved a useful tool for the study of vulcanization in other rubbers. With all rubbers that can be effectively cross-linked by irradiation, this is an effective manner of bringing about the plastic→elastic change without the addition of any chemical to complicate the interpretation of the results. Irradiation, however, instead of bringing about cross-linking of certain rubbers, has an opposite effect on them, resulting in disintegration of the chemical structure.

Charlesby & Groves (1954) studied the cross-linking of natural and various synthetic rubbers by irradiation. The treatment of the rubber was accomplished in an atomic pile, where a unit dose of slow neutrons plus the associated fast neutrons and gamma radiation in the centre of the pile were equivalent to a gamma dose of about 45 million Roentgen. After irradiation, the amount of cross-linking of the rubber was measured by changes in solubility and swelling. The authors report that in rubber, and in other long-chain polymers, an insoluble gel may be formed after an exposure of about one million Roentgen. Changes in viscosity may be observed in the soluble polymers after only a few minutes' exposure in the pile. This initial increase in viscosity, indicating an increase of molecular weight due to the cross-linking of adjacent molecules, is followed by more and more cross-linking, which results in the formation of a molecular network of such high molecular weight that it becomes an insoluble gel. There continues to be a sol fraction but, with continued irradiation, the gel portion tends toward 100 per cent. As in the case of the silicone rubbers, the radiant energy absorbed, rather than the type of ray, appears to govern the amount of cross-linking that results from irradiation. Charlesby & Groves (1954) remark: 'Although no definite statement can yet be made, existing evidence indicates that the effects produced by high-energy radiation depend mainly on the total energy absorbed, and not its nature—neutrons, electrons, X-rays, and gamma rays, or alpha particles.'

These authors found that while some rubbers were cross-linked, and thus made less soluble, by irradiation, other rubbers were degraded. Polyisobutylene, particularly, was degraded by main-chain fracture and converted into a viscous liquid after only a few units of radiation. *Hevea* and guayule natural rubbers were cross-linked readily by irradiation, as was polychloroprene. Polybutadiene was found to be slightly cross-linked initially, and to be cross-linked further on irradiation. Thiokol was cross-linked by irradiation, but the change was difficult to follow because of the lack of initial solubility of this rubber.

Most concepts of vulcanization are based on the reaction of rubber and sulphur. The plastic→elastic transformation reaches its highest value in this vulcanization reaction. Technologically, other curing reactions are of great value and, for particular purposes, those of some of the speciality rubbers may be of even greater importance than the rubber-sulphur reaction of natural rubber. The more complex structure of natural rubber makes it more difficult to demonstrate a specific vulcanization reaction than is possible with the silicone rubbers that have a molecular structure composed of a relatively simple repetition of basic units.

Technologically, natural rubber is not a pure chemical. The synthetic rubbers also contain impurities, but these are not comparable with the complex mixture of non-rubber components that have been identified in natural rubber. The antioxidants, minor ingredients, and resinous materials in natural rubber have affected the development of vulcanization and must be accounted for in compounding formulae. These adjustments to meet the requirements of individual samples of rubber have complicated the interpretation of the basic reaction in vulcanization, and less is known regarding the basic reaction of natural rubber than about that of the synthetic rubbers which have received far less attention.

Vulcanization of Natural Rubber by Irradiation

E. B. Newton (1933) first announced the successful vulcanization of natural rubber by irradiation. He was issued a patent in 1933 on the basis of his claim to vulcanize rubber by short exposure to 250-kV cathode rays. Gehman & Auerbach (1956) state:

> Polymer science teaches that the essential or general feature of all vulcanizing reactions is that they bring about a crosslinking or interconnection of the long, flexible rubber molecules into a network structure. . . . The number of crosslinks required for good technical vulcanization is relatively small, of the order of one crosslink per hundred monomer units. Too many crosslinks destroy the property of high elasticity, too few give excessive plastic flow and permanent set.

Jackson & Hale (1955), in introducing a report on the vulcanization of rubber by irradiation with cobalt 60, stated:

> In accordance with most widely accepted theories, vulcanization is primarily a cross-linking process. This cross-linking is stated to occur at points in the rubber molecule which are reactive to such known vulcanizing agents and accelerators as sulphur, sulphur derivatives, metallic oxides, amines, etc., under the reaction conditions involving heat, time, amount and type of agent.

These authors found that the use of gamma radiation from cobalt 60 was particularly desirable in the treatment of rubber because:

(1) High-energy gamma rays have great penetrating power and, hence, the elastomers are vulcanized uniformly.

(2) The utilization of cobalt 60 with proper shielding greatly reduces radiation hazards.

(3) No residual radioactivity is imparted to the treated elastomer.

(4) After initial installation of the source, together with the proper shielding, maintenance problems are limited as compared with those encountered with X-ray equipment or particle accelerators.

Jackson & Hale (1955) state:

> It has been found through this study, that uncured vulcanizable elastomers may be cross-linked in the absence of vulcanizing agents and without the use of high curing temperatures. The products obtained closely resemble the chemical vulcanizates in many respects, and offer considerable promise

in developing elastomers for specialized uses. By subjecting the otherwise compounded base polymer to the action of a high-energy gamma radiation source, not only can the elastomer be cross-linked or vulcanized, but the extent of the change produced can be controlled directly by adjustment of the radiation dosage.

The course of the changes in physical properties induced by irradiation of natural rubber has been studied with respect to changes in solubility, increase in viscosity, and improvement in performance tests. In general, the vulcanizates are comparable with similar vulcanizates resulting from the reaction of rubber and sulphur under heat. The identical nature of the chemical vulcanization with that accomplished by irradiation has been established, and the belief that both consist in a cross-linking of the molecules is accepted.

The probability has been established in the case of silicone rubber that both hydrogen and entire methyl groups are split off from the rubber by the irradiation. Epstein & Marans (1958) expressed the belief that splitting of the carbon-silicon bond (as in splitting off the methyl group) predominates over the splitting at the carbon-hydrogen bond (as in splitting a hydrogen atom from a methyl group). Three types of splitting are possible in natural rubber: (1) hydrogen from a methyl side-group, (2) hydrogen from a carbon atom in the chain, and (3) a methyl group from a carbon atom in the chain.

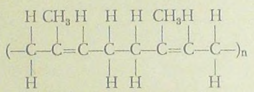
Vulcanization of Natural Rubber with Sulphur

It has appeared probable that, in the vulcanization of silicone with peroxides, the vulcanization reaction is similar to, or identical with, that in which vulcanization is brought about by irradiation. No portion of the peroxide molecule becomes a part of the 'vulcan' bridge. Rather, the peroxide serves only the same purpose as the radiation source—to induce cleavage in the silicone structure. The silicone molecules become highly reactive at the points of cleavage, adjacent molecules become attached at these points, and a network structure results.

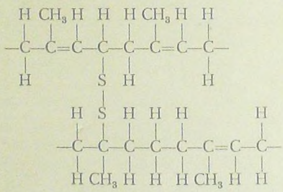
It is probable that irradiation of natural rubber results in a similar cleavage, and that the adjacent molecules unite in a network comparable with that postulated for silicone rubber. In the vulcanization of natural rubber with sulphur, however, a union of the sulphur and the rubber takes place and the resulting vulcan bridge is made up of sulphur atoms. It has been postulated that the accelerators in this case act in a manner similar to that of peroxides in the vulcanization of silicones, and that thermal decomposition of the accelerator results in highly reactive free radicals. These radicals induce cleavage of hydrogen from the rubber molecules, and the sulphur forms vulcan bridges that unite adjacent molecules of rubber at the reactive points of cleavage.

Natural rubber also differs from silicone rubber in having a double bond for each monomer unit. It is no longer believed that sulphur unites with rubber only at the double bond, nor even that the union of the sulphur at the double bond is the major factor in the cross-linking of the individual molecules with their neighbours. The double bonds do exist, however, and the possibility cannot be disregarded that they assume an important role in vulcanization.

Gehman & Auerbach (1956) have presented a hypothetical chemical structure for a disulphide cross-linking of natural rubber that involves union—both at the double bond and at a cleavage point resulting from the splitting off of a hydrogen atom from a chain carbon. For comparison, a structural arrangement for unvulcanized natural rubber is given first and then the hypothetical linking of two molecules is shown. It is possible, of course, by repetition of the monomer units, to project the molecular arrangement of the unvulcanized natural rubber into a sizeable molecule. It is not possible to project the hypothetical arrangement of the vulcanized rubber molecule by direct repetition, as the number of cross-links is relatively small, being estimated by Gehman & Auerbach as of the order of one cross-link per hundred monomer units. The precise number of cross-links and their relative frequency at any level of cure have not been determined.



Unvulcanized natural rubber



Hypothetical chemical structure of vulcanized natural rubber showing one sulphur cross-link

The hypothetical structure presented by Gehman & Auerbach shows not only the addition of sulphur to form the bridge in the vulcanized rubber, but also shows the hydrogen split from one molecule united to the companion molecule in partial saturation of the double bond. On the assumption of 1 per cent of the monomer units being cross-linked with bisulphide bridges, the sulphur would represent 0·94 per cent of the weight of the vulcanized rubber.

Bresler *et al.* (1954) and Bresler *et al.* (1954*a*), in companion articles, reported on experiments in which radioactive sulphur was used to trace the mechanism of vulcanization. They studied the vulcanization of rubber both with and without an accelerator. These authors added new concepts to the theory of the mechanism of vulcanization and the character of the resulting bridge. Their studies led them to the conclusion that the bridge formed in the vulcanization of rubber was a polysulphide containing from ten to twenty sulphur atoms. In tracing the diffusion of free sulphur in rubber, they also found that the bound sulphur retained a high degree of mobility, and that there was a reversible dissociation and recombination of the sulphur molecules. Free sulphur was found in the form of the very stable S_8.

Any given quantity of bound sulphur could be accounted for under the polysulphide-bridge theory of Bresler *et al.* with fewer cross-linkages than under the bisulphide-bridge theory of Gehman & Auerbach (1956). In both hypotheses, the bridge structure would be solely of sulphur. The migration of the bridge units, according to the hypothesis of Bresler *et al.*, is difficult to understand in view of the great stability of vulcanized rubber and the difficulty of separating the bound sulphur from the rubber in reclaiming.

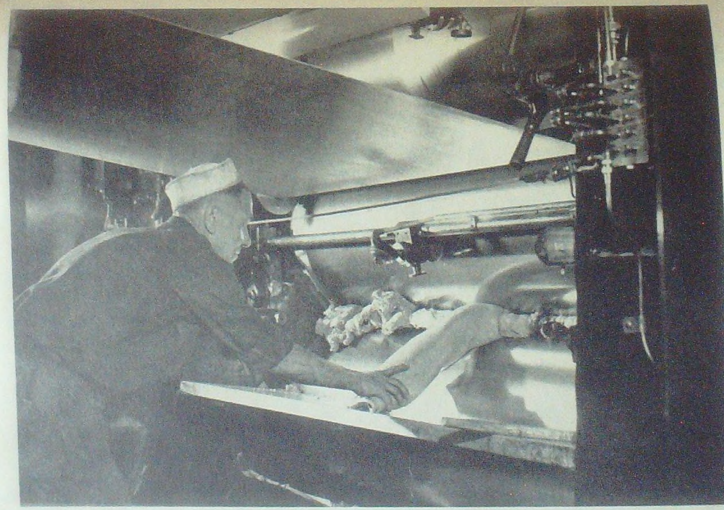
The Mechanism of Vulcanization

The theories given previously regarding changes in chemical structure of natural rubber during vulcanization have been put forward by their proponents more as hypotheses than as established chemical changes. From a mechanical standpoint, they serve to establish a basis for understanding how the known physical changes in the properties of the rubber can result from changes in the basic molecular structure of the rubber.

That cross-linking does occur, and that this cross-linking is basic to the physical changes that have been observed, is generally accepted. The relative amounts of cleavage and of joining at the double bond are less clear, as is the ultimate size of the network structure of the vulcanized rubber molecule. That there is an optimum cure has been established by the measurable physical characteristics of the rubber, which improve up to a certain point and thereafter exhibit evidence of over-cure. Even before this point, the resistance of the rubber to solvents complicates the study of molecular weight, and it is difficult to determine whether the decrease in physical properties after optimum cure is due to giganticism or to molecular breakdown.

Vulcanization is characteristic of all rubber, natural and synthetic, and is beyond question the most important chemical and physical change that takes place in the production and utilization of rubber. Its plastic→elastic effect, and the physical changes in tensile strength, surface tackiness, solubility, and resistance to permanent deformation, have been well established for each of the known rubbers. Less is known regarding the changes in chemical structure, except that there is a general agreement that vulcanization is characterized by a cross-linking of adjacent molecules —either by direct union under suitable conditions (*see* p. 340), or by the addition of a bridge consisting of particles from the vulcanizing agent (*see* p. 344).

It has not been the purpose of this discussion to develop a general theory of vulcanization on the basis of an extremely limited survey of the known facts. It has seemed, however, that a short comparison of a rubber with a relatively simple polymer structure (such as silicone rubber), and a rubber with a relatively complex structure (such as natural rubber), would serve a useful purpose in illustrating to the non-specialist in this field the chemical changes in structure that accompany the plastic→elastic change caused by vulcanization.



Photograph by permission of United States Rubber Company

Photograph by permission of Goodyear Aircraft Corporation

Inflated aeroplane, the Inflatoplane.

PLATE 60

XVIII

RUBBER IN INDUSTRY AND TRANSPORTATION

Industrial Uses of Rubber

TENSILE strength, toughness, quick response to pressure (both in yielding and in recoiling), resilience, pliability, and similar attributes of elasticity, are the chief qualities for which rubber finds industrial use.

Rubber also has other characteristics that, alone or in conjunction with its elasticity, make it particularly useful. Resistance to the passage of gases has made rubber useful for the manufacture of diaphragms for the control of gases, and for balloons, air bags, inner tubes, and comparable inflated or inflatable articles. The resistance of rubber to fuels, acids, and other chemicals, has made it important in the manufacture of battery boxes, flexible hosing, and flexible fittings needed for such hosing. The ability to impart a usable degree of tack has made rubber useful in the manufacture of pliable cements. The film-forming characteristics of rubber when compounded chemically, have been utilized in the manufacture of packaging materials and in paints.

The synthetic rubbers have contributed qualities that natural rubber does not have, and have thus added versatility to rubber as a whole. Many purposes that were not fulfilled by natural rubber, and some that were fulfilled less adequately, can now be handled by synthetics or mixtures of natural rubber and synthetics. This expanded usefulness of rubber has been particularly evidenced in superior resistance to oils and chemicals, resistance to oxidation and ozonation, and resistance to abrasion.

Structural Qualities of Rubber

Rubber serves as an engineering material on the basis of several of its characteristics in which it is unique among the available materials. Outstanding is, of course, the degree of elasticity, pliability, resilience, resistance to permanent deformation, toughness, and resistance to abrasion.

Tensile Strength. Rubber can be compounded to have a tensile strength of up to 5,000 lb. per square in. of cross-section. Natural rubber prepared with the utmost care to eliminate the possibility of even a trace of foreign particles, has been compounded to give a tensile strength of 8,000 lb. per square in.; but the range up to 5,000 lb. per square in. is the practical limit of present usefulness of rubber. This tensile strength compares with that of the weaker metals. Cast or drawn lead has a tensile strength of 2,600 to 3,300 lb. per square in.; cast or drawn tin, a tensile strength of 4,000 to 5,000 lb.; and cast zinc, a strength of 7,000 to 13,000 lb. Wool, the weakest of the commercial fibres listed by Mauersberger (1947), has a tensile strength of 17,000 to 25,000 lb. per square in.—far higher than that of rubber; and cotton, listed as 40,000 to 111,000 lb. per square in., has even greater tensile strength.

Elongation. No other material has a degree of elongation comparable with that of rubber, in which maximum elongation under stress may be over 1,000 per cent. Recovery of rubber is relatively quick when the stretching force is relaxed. Most materials have some ability to stretch, and will then resume their original dimensions when the stretching force is relaxed—provided the limit of elasticity has not been exceeded. However, in materials other than rubber, elongation is limited to fractional increase in length. Mauersberger (1947) gives the elongation at break of wool as up to 60 per cent, while the elongation at break of viscose rayon is up to 40 per cent.

Rubber is entirely unique in its multiple elongation and elastic recovery. In combination with other useful characters, this multiple elongation and quick recovery constitute the value of rubber in applications in which stronger, but less elastic, materials are unable to compete.

Toughness. Toughness is a quality in which rubber is outstanding, both because of its surface resistance to penetration and because of its lack of rigidity, together with its ability to resist and recover from deformation. Rigid materials of great strength may be abraded by the impact of fine particles in water or air—that would result in only minor, temporary indentation of rubber. Metallurgical advance has resulted in tough, durable metals with great resistance to the impact of fine particles, but the required structural strength and rigidity of the metals often make them less durable than the softer rubber.

Resistance to Abrasion. Resistance to abrasion involves toughness but is not identical with it. Toughness is primarily a surface phenomenon involving the ability of a material to resist the penetration of foreign objects. Resistance to abrasion is the ability to resist erosion by friction with a roughened abrasive surface. As in the case of toughness, rubber has an advantage over rigid, non-yielding materials in that the subsurface structure is able to assist in the resistance to abrasion by allowing the surface layer to deform momentarily before the eroding force.

Resilience. Resilience permits rubber to adjust to adjacent structural members, to make a tight seal between structural parts, and to maintain that seal when the parts are subjected to stress as a result of movement, or when there is an increase or decrease in size due to changes in temperature. It allows the rubber to accept compression but to adjust its volume to balance any loss in compression thereafter. It is also the quality that allows rubber to accept and absorb vibration and shield structural members from the vibration of moving machine parts. Resilience makes it possible for rubber buffers to shield machine parts or structural members from moving objects, allowing the rubber to resist the force and absorb the energy without injury to the machine part or structural member.

Pliability. Pliability is the character that makes it possible to use rubber hosing for dispensing or transporting fuels and other liquids without the necessity of permanent installations of rigid piping. Combined pliability, toughness, resistance to abrasion, and chemical stability, together give rubber a wide usefulness in dredging, fuel and oil lines, pharmaceutical and laboratory hosing and fittings, water bags, ice bags, toys, and athletic goods, as well as for gloves and other articles of wearing apparel.

An important use of rubber that results from its pliability is as insulation for extension cords. As the high resistance to electrical current can be combined with a high degree of resistance to oils and chemicals, the rubber insulation has been found extremely durable under adverse conditions and hard usage. Rubber can also be compounded to have a high degree of electrical conductivity. This characteristic makes it possible to utilize rubber as an electrical connection in applications where a high degree of pliability, toughness, and resistance to abrasion are required, as in the case of ground wires to discharge static electricity from moving vehicles.

Impermeability. Resistance to the passage of gases is not related directly to elasticity but, combined with elasticity, has made rubber useful in the manufacture of balloons—both as toys and for scientific uses such as the determination of weather conditions in the upper air. Its chief value has been in the manufacture of inner tubes for pneumatic tyres for use on motor cars and trucks. Other applications include air brakes, air suspension systems, the dispensation of gases under pressure, steam lines, diaphragms for the controlled dispensation of gases, and even bubble gum that depends on small percentages of rubber for its ballooning quality.

Rubberized fabrics are also used in the manufacture of balloons and air cells. The fabrics impart a higher tensile strength than is possible with rubber alone, though extensibility is limited to that of the fabric.

Resistance to Chemicals. Resistance to fuels, oils, acids, and other chemicals, is another useful quality of rubber that is not directly related to elasticity. Similar resistance can also be found in materials with greater structural strength and durability. However, the combination of elasticity and other qualities that characterize rubber, makes its use important for purposes where lightness, portability, and convenience are the controlling factors but rigidity is not necessary.

In battery boxes and similar applications of hard rubber, superior chemical resistance is combined with lightness, cheapness, and adequate structural strength, even though the hard rubber no longer retains the attributes of elasticity.

Classification of Rubber Articles by Method of Fabrication

Raw rubber is blended and compounded in accordance with the requirements of the article being manufactured. The shaping of the finished article is done while the rubber is still plastic, before vulcanization, and is accomplished by various processes, the principal of which are moulding, extruding, dipping, and calendering.

Moulded Goods. Moulded goods may be either of hard rubber with a high percentage of sulphur, or of soft rubber—varying from pure sheet rubber, with a low percentage of sulphur and no other ingredients except the accelerators, to heel or tyre rubber, containing high percentages of inert fillers.

Battery boxes, telephones, and many types of electrical outlets and fixtures, are typical of hard rubber goods. These may be moulded direct in the finished form, or may be moulded in separate parts or in flat sheets and fabricated into the finished articles after vulcanization. The hard rubber can be cut, drilled, threaded, and otherwise manipulated in a manner similar to that used for other structural materials, and has the advantage of cheapness, durability, and chemical resistance.

Gears or gear boxes made of rubber, in addition to having resistance to acids and chemicals, do not spark and have that advantage over metal parts in the construction of pumps for the handling of inflammable liquids, or for machine parts where there is some danger of explosion.

Soft rubber articles shaped by being vulcanized in moulds include almost the entire range of materials which are apt to be thought of as rubber. They vary all the way from a flat sheet to a giant tyre containing nearly a ton of rubber. In the manufacture of tyres (Plate 58(*a*)), the rubber is forced into the moulds by means of air bags that are placed inside the prefabricated tyres and inflated when the tyres have been mounted inside the moulds. This pressure forces the rubber into the indentations of the mould, so giving the characteristic designs. Air pressure is also used to force the rubber into the recesses of the moulds used in making toys and hollow balls.

A great variety of rubber articles can be made in flat moulds in which the tight fit of the top and bottom serves to force the rubber into the indentations in the mould. Such articles include mountings for machinery, rubber pads and sheets, bottle and sink stoppers, heels and soles, and thousands of comparable articles that are needed for industrial or personal use. Flat articles may be formed by the mould used in vulcanization, or may be cut from vulcanized sheet by special dies.

An important industrial use of moulded rubber articles is in the form of vibration dampeners in the mounting of machinery. For this and similar purposes, the bonding of rubber to the metal parts of the machinery has become an essential feature of the industrial application of rubber. The most successful and common method of bonding has involved electroplating the metal part with brass, and then bonding the rubber to the brass. This method requires the utmost precision and almost one hundred per cent cleanliness both of the metal before electroplating and of the brass coating until the rubber is applied. New types of adhesives have largely replaced the electroplating and result in easier and better bonding of the rubber to the metal.

Rubber has been employed wherever there is a necessity for the absorption of vibration. It is also used in the form of bumpers to absorb shock and prevent injury to machine or structural parts. Such use is exemplified in the fitting of rubber collars to oil-well pipes, to prevent damage during shipment and storage.

Extruded Rubber Goods. Useful rubber articles are also made by forcing the rubber under pressure from the orifices of extruding machines (Plate 58(*b*)). The shape of the extruded rubber can be altered by varying the shape of the orifice, and the product may be in the form of rubber stripping, rubber tubing, or insulation on wire. The stripping may have almost any conceivable cross-section. The channel strips for the sealing of motor-car windows illustrate the type of rubber stripping produced by extruding. Another use is for sealing the adjacent edges of corrugated metal sheets, where such sealing from weather or chemicals is important.

An important use for extruded rubber is in the insulation of electrical wire. In this application, the wire is passed through the extruding machine and the rubber is formed on the outside of the wire core. For this purpose, a rubber with a high resistance to oils and chemicals is necessary, since such wire is often used as extension cords on garage or machine-shop floors, where it is dragged through oil drippings or may be exposed to battery acids or other chemicals. Such extension cords may be used both out-of-doors and indoors, being exposed, respectively, to direct sunlight or to excessive amounts of ozone where electric generators are in operation. For long life and effective service, such electric cords must resist not only oils and chemicals but also oxidation and ozonation—a requirement that necessitates the selection of the rubber and other ingredients to meet the service contemplated.

Dipped Goods. Thin articles that are to be made of pure gum rubber, or with a minimum of non-rubber ingredients, can be made by dipping forms with an outward shape like that of the finished article into rubber latex or a solution of rubber to which sulphur, accelerators, and other ingredients have been added. After dipping, the form is raised from the liquid, allowed to drip and partially dry, and then given successive dippings until a sufficient thickness of rubber has been accumulated. The dipped goods are vulcanized in heated chambers. Rubber gloves, balloons, and similar thin goods can be made in this manner. Dipped goods find extensive use in personal, pharmaceutical, and medical articles, but do not lend themselves extensively to industrial applications. The latex or rubber solution may be sprayed on the forms instead of the forms being dipped into the liquid. Vulcanization may be accomplished by the use of sulphur chloride rather than by adding vulcanizing ingredients to the liquid mix.

Calendering in the Production of Rubber Goods. The chief function of the calenders (Plate 59) is to produce rubberized fabric. This material has extensive use in rubber manufacturing processes, both in sheet form, as tarpaulins for the shedding of rain or protection from weather, and in the manufacture of tyres—also in containers for oil, fuel, and water. The choice of the fabric for the particular purpose equals in importance the choice of the particular rubber. The characteristics of the weaving are also important, particularly for use in the construction of tyres, which are constantly subjected to stresses—both those normal to the direction of travel, and cross-stresses and shocks.

New applications of calendered fabrics include storage tents that can be erected and maintained by a 5-lb. air pressure. The same principle has been used to erect and hold structural members of ready-built houses, the fabric 'balloon' serving as a temporary jack to raise and hold a roof while the supports are being put in place.

Rubber Age (1957*a*) has announced the development by the Goodyear Aircraft Corporation of the Inflatoplane (Plate 60), an aeroplane made of airmat, consisting of two walls of rubberized fabric connected by nylon threads. This new 'plane may be stored or carried in a very limited space, but can be assembled and ready for take-off in five minutes. Its air pressure is maintained by a compressor attached to the engine, and the inflation can be maintained even though the fabric is punctured by bullets. The 'plane is equipped with a 42 horse-power motor and has a top speed of 70 miles per hour.

Chemically Altered Rubber. While vulcanization is the most important chemical reaction that is involved in rubber technology, there are other chemical changes that also have proved significant industrially. These changes are most important with natural rubber and involve principally the reaction between rubber and the halogens, particularly chlorine. This is an additive reaction and appears to involve primarily the saturation of the double bonds, though some substitution of hydrogen occurs. In this reaction, there is no sign that any cross-linking takes place, and neither is there any indication of a plastic→elastic change.

Rubber hydrochloride can be precipitated in the form of a thin film that is somewhat thermoplastic, being sealed by heat and thus suitable for the packaging of many types of products, including foodstuffs. Rubber hydrochloride has also found extensive usage in the formulation of paints, to which it imparts flexibility and smoothness.

Special Uses

It is not possible in a short space even to mention each of the approximately 40,000 articles that are made of rubber. Because of the predominant use of rubber in the manufacture of tyres, the rubber industry is tied closely to the motor-car industry. Yet there are many important uses of rubber, both in the automotive and transportation fields and in industry and the home, that are not directly related to the manufacture or use of tyres.

Foam Rubber. Though of comparatively recent origin, foam rubber is now a familiar commodity to most people. It is used extensively for cushions and upholstery in the home, and for upholstery in motor cars. There is an increasing use of foam rubber in mattresses and upholstery, and a popular recognition of its usefulness and value. There is less general knowledge of the growing use of fire-resistant foams such as polyurethane, which has increasing industrial value as a rapid and effective sealant. This material is heat- and flame-resistant, and can be used for ironing-board covers and for industrial applications where other types of foam rubber are not suitable.

Power and Endless Belts. Rubber power-transmission belts are made in almost all possible sizes and are highly important in all phases of flexible mounting of engines. There has also been an important development in the field of movement of coal, crushed rock, minerals, and other bulky materials by endless belts for long distances. Rubber belts have proved particularly useful for this purpose, and belts have been designed and used for prompt transportation of human beings as well as of inanimate objects.

Rubber in the Oil Industry. In spite of its tendency to swell under the influence of oils, rubber has found a place in the oil industry, for use in packings and gaskets, because of its elastic compressibility. Under the influence of oil, parts made of natural rubber swell and must be replaced at frequent intervals. Formerly, rubber parts that were to be exposed to fuels and oils, were compounded with high percentages of reclaimed rubber that improved their performance greatly. Since the invention of oil-resistant synthetic rubbers such as neoprene and thiokol, it has been possible to replace the natural rubber with synthetic rubbers that fill the need for sealants having the elastic compressibility of natural rubber but meanwhile have greatly increased resistance to oil. This also has made it possible to replace mechanical parts subjected to abrasive materials that erode metal, with parts made of rubber. This is particularly important in the drilling industry, where gaskets, collars, and many other rubber parts, have greatly diminished the time lost in the replacement of worn-out parts. Rubber-lined valves perform satisfactorily, in spite of abrasive materials and oils that must be controlled.

Rubber Hosing. Rubber hosing can be designed for efficient transportation and dispensation of petroleum oils and fuels and for handling corrosive liquids and gases; and rubber can be prepared with sufficient rigidity for use in valves and other fittings for employment in such service. Reinforced rubber hosing is used for handling liquids and gases under high pressure, and may also be compounded to withstand both the pressure and heat of live steam.

Adhesives. From a tonnage standpoint, the use of rubber in adhesives is a minor factor in rubber consumption. From a technological standpoint, this is a major use, as it is essential in the building of tyres, where rubber must be bonded to rubber, and in comparable applications where rubber must be cemented to rubber, metals, plastics, or other materials. With increased speeds and continuous operation of motor-cars for long periods in hot desert areas and on turnpikes, ply separation is a serious problem, chiefly in the case of recapped tyres but also in original treads. Separation of rubber bonded to metal is an important source of failure, particularly in the rubber used in engine mounts. The choice of rubber for particular purposes is a highly technical decision. With the wide variety of rubbers available, it is now possible to avoid most of the separation problems that have arisen.

The various rubbers have differing values as adhesives, and the type of rubber must be chosen with regard to the conditions under which it is to be used. Sawyer (1957), in reviewing the uses of rubber in adhesives, stated that natural rubber should be used in any highly functioning part such as vibration dampers, engine and instrument mountings, and track block-pins. Styrene rubber is useful for rolls, tracks, and diaphragm compounds. Whenever reasonably good oil and ozone resistances are required, Sawyer recommended the use of Neoprene, better adhesion being obtained with Neoprene GN and W compounds than with the GRT or WRT types. Such applications as shaft seals, electric motor mountings, and solid tyres, are typical for Neoprene.

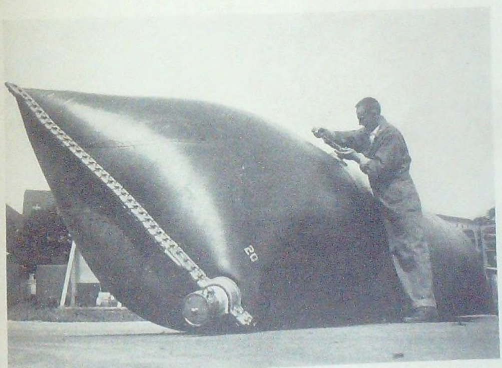
The acrylonitrile-butadiene co-polymers find their biggest use in those applications that require extremely high oil-resistance, the easy processing polyenes being best suited to adhesive work.

Rubber latex, both natural and synthetic, is also used as a binder in the manufacture of non-woven fabrics. Cotton or nylon fibres, or mixtures of the two, are pressed to form a mat. Fibre direction may be either completely aimless or the fibres may be orientated to give somewhat greater strength in one direction. The fibres are then bound by saturating, coating, or spraying them with rubber latex. Both natural and synthetic latices have been found useful for this purpose. Welch (1957) describes the manufacture of these non-woven fabrics and states that popular binders for bonding the pressed fibres include synthetic latices such as nitrile rubber, styrene rubber, polyvinyl chloride, polyvinyl acetate, and polyacrylate, as well as natural rubber latex. He cites the industrial usages of non-woven fabrics as laminated fabrics, coated fabrics, filter cloths, burial-casket linings, cheese-press cloth, pattern-marking cloth, oil-field tape, and desiccant bags.

Packaging and Shipment in Rubber. The use of rubber in packaging of foodstuffs has been mentioned. It now finds use for large as well as small shipping containers. Rubber packaging for the transport of liquids has been envisioned as an important factor in reducing the cost of

Photograph by permission of Goodyear Tire and Rubber Company

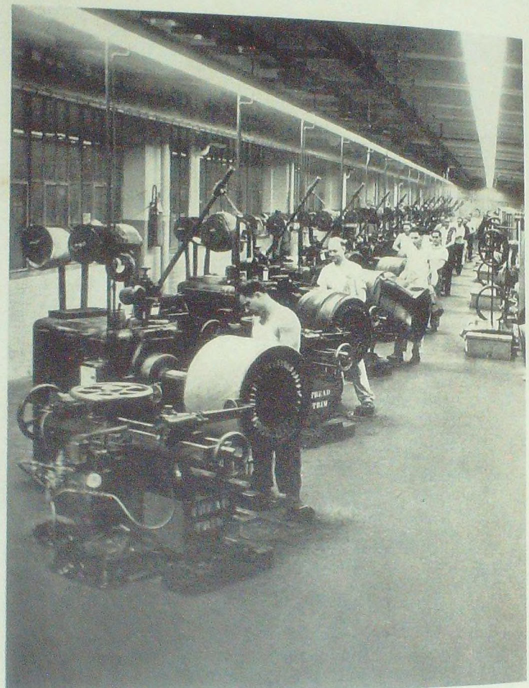
(*a*) Fuel transportation over rough terrain, the rubber tyres forming the fuel containers.



Photograph by permission of United States Rubber Company

(*b*) Sealed tank container for shipment of liquids.

PLATE 61



Photograph by permission of United States Rubber Company

Building truck and bus tyres.

PLATE 62

shipment and the return of empty containers to the point of shipment.

Rubber World (1958) describes a shipping container (Plate 61(*a*)) developed by the Goodyear Tire and Rubber Company, and manufactured by the Four Wheel Drive Auto Company, that is essentially an enormous tyre. This tyre is equipped with a hub and axle on which it can be rolled, but is itself the container for the liquid. Ten units can be drawn by a single tractor. Each unit is 5 ft. high, 3½ ft. wide, and has a capacity of 500 gallons. The axle and towing assembly for each unit has a braking system operated from the tractor. Each unit has attachments for easy filling and emptying at a rate of 50 to 100 gallons per minute. The ten units require no maintenance, and the towing and braking assemblies need only occasional lubrication and inspection. The tyre bags are said to be resistant to chemicals and to fuels of up to forty per cent aromatic content. They can be stored outside at temperatures as low as 80°F. below zero, and can be operated at temperatures of from 65°F. below zero to 125°F. above zero.

Rubber Age (1957*b*) reports the development by the United States Rubber Company of a 'Sealedtank' container (Plate 61(*b*)) that is 56 in. in diameter, 35 ft. long, and holds 3,600 gallons of liquid. The tank weighs 1,040 lb. empty and its capacity when filled with molasses, for example, is 22 tons. The Sealedtank is made of four plies of rubber-coated rayon tyre fabric moulded similarly to that for a tyre. Both ends are sealed by metal closures. The outer surface is made of neoprene for oil and weather resistance, and the inner surface can be made of any of a variety of special rubber compounds that make possible the handling of almost any type of liquid. The container can be made in any size to fit any lorry, railway truck, barge, or ship. It is placed empty on the trailer or truck and filled through a fitting at the end or top. Atmospheric pressure collapses the container when it is emptied after shipment. When empty, the container lies flat and can be rolled into a compact package for return to the shipper. A container the size of the one described above would roll into a package 25 in. in diameter and 7 ft. 4 in. in length.

Pipe, Tank, and Mill Linings. Rubber's superior resistance to abrasion has resulted in its use as lining for metal pipes, tanks, and mills that are subject to the action of highly abrasive sand and similar materials. Metal linings require frequent replacement, involving not only the cost of the new lining but also time lost in making the replacement. Replacing with rubber the metal linings of pipes used for dredging sand and comparable purposes, has increased the life of individual liners and reduced the cost of replacement. The use of synthetic rubber has materially increased the life and effectiveness of the linings that must come into contact with oils.

In tumbling mills, whether ball or pebble, the steel linings must be replaced at frequent intervals. Replacing the lining with a tough, abrasive-resistant lining made of rubber has resulted, in many cases, in a material reduction in maintenance costs.

Flooring. There is an increasing demand for rubber tiles as floor covering in both commercial and industrial buildings. The tiles are frequently compounded to have attractive colouring and patterns, whilst their resilience and toughness impart a desirable degree of resistance to wear, being conducive to long life and low maintenance costs.

Rubber in Transportation

The Wheel

One of the industrial marvels of all time was the invention of the wheel. Transportation development since that discovery has largely consisted in making use of improvements in the wheel and in methods of generating power (human, animal, motor) and applying that power to the wheel. Increased traction has been obtained by transforming the simple round wheel into a revolving track. Even in arctic and antarctic exploration, motorized equipment that moves on rolling parts or moving tracks has largely replaced the dog-sled.

The first wheels were merely rounded units hewn out of single pieces of wood. They represented a tremendous advance in moving heavy objects, and persisted in primitive transportation for many centuries. An early development in the wheel, as we know it today, was that made up of shaped parts—the axle, spokes, and felloes. This wheel was improved by the application of a rim of raw hide and later of metal. The metal rims were expanded by heat and the cooling after they were placed on the wheel made a tight fit. Drying out of the wooden wheel members caused the wheel to become loose, requiring that the rim be made smaller or that the wooden parts be enlarged by soaking in water. From long before the Roman chariots revolutionized warfare and play, until many years after the discovery of the rubber tyre that replaced the metal rim, the rimmed wooden wheel was a dominant factor in the movement of man and the transportation of his goods.

Modern Travel

Civilized man travels on rubber. On foot, he is shod with rubber heels and often with rubber soles. On all self-propelled, wheeled vehicles, tyres made of rubber transmit the driving force as well as serve as the points of contact with the road. Man-propelled methods of locomotion, such as the bicycle and roller skates, have wheels rimmed with rubber, and it is important in the operation of ships and aeroplanes, the latter depending on wheels equipped with rubber tyres for their contact with the ground in taking off and landing. From the time that the infant is pushed in the baby carriage until the hearse has performed its appointed function, civilized man depends for his movement from place to place on rubber, which has everywhere facilitated and eased that movement.

Rubber serves not only as the contact of vehicles with the road but also assists in making the operating mechanism of the vehicle effective and adding to the comfort of the passengers. Rubber is essential in many ways to the safe and effective operation of moving vehicles, whether man-propelled, self-propelled, or drawn, and whether on land, on sea, in the air, or on tracks. Rubber has even entered into the construction of the floors that man walks on and the roads on which he drives.

Rubber in Tyres

The major usage for rubber is in the construction of tyres. There has been tremendous improvement in tyres since J. C. Dunlop first constructed the crude pneumatic casing that gave his son advantage over his competitors. These improvements have come about as a result of intense competition in the rubber manufacturing industry and, during the past three-quarters of a century, have resulted in the establishment of the tyre cost, on a mileage basis, at a point below that of any other major factor of automotive cost. This has resulted from continual improvement in tyre-building techniques and from comparable improvement in the quality of the components of the tyre.

Many individuals can remember their first feeling of pride in a tyre that ran for more than 10,000 miles, probably after numerous repairs before it was replaced. Now a tyre that has been on the road for the same distance under reasonably good conditions is only slightly worn, and may triple that mileage with no occasion for repairs. Yet, this greatly improved tyre costs only a little more than did the 10,000-mile tyre at a time when commodity costs were far below their present levels.

Tyre Costs. Tyre costs have been kept down by increased factory efficiency. Automation has been called upon to aid in the transportation of materials, tyre components, and uncured tyres within the factory. Automation has also come to the vulcanization of the tyre, so that the uncured tyres can be fed to the presses, mounted, inflated, vulcanized, and released from the press without the need of human touch. The building of a tyre, however, is still a human effort, requiring the services of highly skilled tyre builders (Plate 62) whose wages have been greatly increased over the years—an increase that is more than counterbalanced by increased efficiency of tyre production and the quality of the product (Plate 63). Tyre mileage can be purchased in 1961 for a fraction of its cost in 1920; and the 1961 purchase includes increased comfort and care-free operation.

Tread Designs. Detailed research has resulted in radical revisions in the tread designs of tyres. In the beginning of large-scale manufacture of tyres, tread designs were chosen primarily to represent a trade-mark of the manufacturer. The designs were calculated to give good traction; but there was little similarity in the designs chosen by the different manufacturers. Under the guidance of research on the effectiveness of various designs with regard to traction, braking, and skidding, tyre designs have tended to become standardized. New treads have been developed that are far superior in wear, power transmission, low slippage (non-skid), and good friction in braking on both wet and dry pavements and other surfaces. Special treads with a much greater variety and depth of design have been developed for use in mud and deep snow.

Safety Factors in Tyre Design. Safety tyres have been developed that provide a high degree of protection from blowouts, including some in which the organic fabric in the plies has been replaced by steel cords (Plate 64(*a*)). Some of the safety tyres rely on extra airproof linings, and some on a soft inner lining that seals off small leaks caused by the penetration of nails and other sharp objects. Most new cars in the United States are now equipped with tubeless tyres that are mounted directly on the rim. Increased safety, dependability, and long wear of all grades of commercial tyres, have led to the optimistic belief that tyres may soon be designed to outlast the motor-car on which they are placed as original equipment. A slightly less comprehensive aim was expressed by Humphreys (1957), who gave as a principal objective of tyre research the development of a tyre of such safety and efficiency at motor-way speeds that there would no longer be a need for spare tyres on either old or new cars.

The Importance of Tyres in Rubber Usage.

In 1956, tyres, inner tubes, tyre-repair materials, and accessories, accounted for 62·45 per cent of all rubber consumed in the United States, 67·56 per cent of that consumed in Canada, 59·47 per cent of French consumption, and 54·29 per cent of all rubber used in the United Kingdom. These tyres were for motor-cars, trucks, tractors, motor-cycles, bicycles, commercial vehicles, horse-drawn vehicles, and miscellaneous small pieces of equipment. In the United States, 59·42 per cent of all rubber used in tyres was synthetic. The percentage of synthetic rubber in tyres made in Canada in 1956 was 55·8. In France and the United Kingdom, more natural rubber than synthetic rubber (81·4 and 72·8 per cent, respectively) was used in making tyres.

An important outlet for rubber for tyre use is the manufacture of re-treading compound commonly known as Camelback. Re-treading of tyres has increased greatly as the quality of the fabric and carcass of the tyre, and the efficiency of the re-treading operation, have all been improved. Tyres may even be re-treaded more than once, and their life doubled or tripled at far less cost than replacement. The development of improved adhesives has minimized tread separation, and rigid inspection can avoid the recapping of defective tyres.

Non-tyre Usage of Rubber in Transportation

Almost the entire range of rubber products finds use somewhere in the field of transportation equipment. The modern ocean liner, with complete accommodation for thousands of people in addition to the operating crew, has need for all of the rubber articles required to maintain a small town—together with those used in the extra facilities required for movement. While the aeroplane does not have need for so large an assortment of rubber articles and parts, it requires specialized equipment—de-icers, effective sealants for the openings so that the cabins may be pressurized, and rubbers that will withstand high-altitude changes in temperature and still retain resilience.

Automotive equipment needed for transportation in arctic regions, or at high altitudes where extremely low temperatures are reached, requires special rubbers that will retain sufficient rubbery qualities at the temperatures encountered to do the job for which they are designed. Articles that find use at both arctic and tropical temperatures must have rubber parts that have an extreme range of usefulness.

Rubber is also essential in parts of the automobile other than the tyres. The more important of these uses include the rubber in fuel lines, in braking systems (both in the pressure hosing and as gaskets in the master cylinder), in brakes, and as shock absorbers, spring covers, engine mountings, fan belts, grommets, gaskets, bumpers, electrical insulation, stripping for sealing wind-shields, windows, trunks, and ventilating shutters, floor mats, pedal covers, and foam rubber upholstery. Hard rubber finds an important function in the construction of battery boxes.

These articles require a wide assortment of rubbers and rubber compounds. Some require high resistance to fuel and oil, while others require a high degree of resilience and ability to function for long periods without loss of ability to absorb vibration. Much of the failure of rubber on ageing is a result of oxidation. Rubber compounds must have a high degree of resistance to oxidation for adequate performance and long life. Many of the rubber components of a motor-car are not replaced during its lifetime.

Rubber in Roads

Interest in using rubber as a paving material has existed for more than a hundred years. The British Rubber Development Board (1950) quotes a patent issued in 1844 for the use of a bitumen-rubber mixture for roads. Spectacular results were also reported for small sections of roadway that were laid with rubber blocks. The cost of solid rubber pavement has always been too high to encourage the belief that it would be feasible to make extensive use of rubber blocks in paving.

Interest in the use of rubber in conjunction with asphalt in the laying of asphalt roads has persisted, and extensive experimental pavings have been laid in Europe, America, and the Far East. Some of the tests have been rated as failures, and many have not been under observation for a sufficient time to obtain significant information. In other cases, the rubberized road has outlasted control sections laid without rubber, and has demonstrated conclusively that, under suitable conditions, the rubber will add materially to the life of the road surfacing. As a maximum of $2\frac{1}{2}$ per cent of rubber is added to the asphalt-aggregate mix, the cost of the rubber is much less than when rubber blocks were used. However, the cost of the rubber even in such circumstances is a significant factor in road costing. Should it be demonstrated that the value of the rubber addition to the asphalt coating is commensurate with the cost of the rubber and the added cost of mixing the rubber and asphalt, this could be a significant new outlook for crude rubber.

Various methods of combining the rubber with the asphalt have been tested with some success. The rubber has been added both in the form of a powder (such as Mealorub, the preparation of which has been described earlier) and in the form of latex. The preparation of the rubber-asphalt mix has been accomplished both by adding the rubber to the aggregate before the addition of the asphalt, and by combining the rubber directly with the asphalt. In the latter case, the rubber-asphalt mixture may be added to the aggregate or used only as a surface topping, being confined to the top millimetre of the road surface.

The rubber-asphalt mixture is prepared and applied hot. Some of the rubber goes into solution in the asphalt, but a portion remains undissolved. It has been postulated by some that the effect of the extremely thin layer of rubber-asphalt mixture, applied as a 1-mm. surfacing, provides an effective seal for the road surface which then not only resists the penetration of water but also gives a tough, rubbery resistance to wear. Others believe the important factor to be that the rubber swells under the influence of the asphalt, and that this swelling action results in the fixing of the lighter fractions of the asphalt which usually tend to vaporize. The rubber retains these fractions in the road surface.

In addition to its use in asphalt roads, rubber can also serve an important purpose as expansion joints in concrete roads. *Rubber Age* (1958) recently announced a new expansion joint (Plate 64(*b*)) developed by The B. F. Goodrich Company and made up of rubber bonded to metal. The metal is designed to take the vertical load, while the rubber absorbs horizontal expansion of as much as 3 in.

XIX

RUBBER IN THE HOME AND ON THE FARM

Rubber in the Home

Many uses of rubber are made daily around the home without any thought of how important this commodity has become in our normal living. No one of the household usages constitutes a major outlet; yet altogether they require a considerable amount of rubber. There are few activities involved in the operation of a modern home that do not depend to some extent on the use of rubber. Electrical fixtures and appliances, plumbing fixtures and appliances, cleaning equipment, and children's amusements, each require the use of dozens of rubber articles. In many uses, the choice of rubber or other material is determined entirely on the basis of cost. In some cases, rubber contributes to operating comfort; and in other uses, particularly if non-conductivity of electricity is necessary, rubber is essential.

Personal use of rubber is its oldest application. Outside of the crude bottles that made up the main bulk of imported raw rubber for so many years, the next important form was as crude overshoes. Rubber raincoats were an early contribution of English technologists. At the turn of the century, the manufacture of boots and shoes represented the major use of rubber. While the use of rubber in motor-cars, and particularly in tyres, has now far out-distanced all other applications, the manufacture of rubber articles for personal and home consumption requires far more rubber than was used for all purposes in 1900.

Electrical Appliances and Tubing

Many electrical appliances, including floor and table lamps, require the use of extension cords that must be flexible and reliable. Rubber is important in the insulation of these cords. The rubber insulation on appliances that depend on resistance wires and heat for their use must be resistant to elevated temperatures. Hard rubber fixtures are used in the outlet boxes for plugging in the extension cords. The terminal connectors of the cords may be either of hard rubber or of durable soft rubber with somewhat greater resistance to mechanical damage. Soft rubber grommets protect the extension cord where it enters the appliance and wherever electric cord must be insulated in penetrating a metal housing. Heating pads and electric blankets must be protected by the use of rubber insulation.

Rubber hosing finds many uses in connection with electrical appliances, and must be both heat-resistant and strong enough structurally to withstand line pressures in being used to fill washing machines, dishwashers, etc., as well as in non-appliance use in garden and lawn irrigation. Other hosing must withstand the suction of vacuum cleaners. Soft rubber hosing finds use for spraying dishes and for shower connections in the bath and, for these purposes, must have a reasonable degree of resistance to pressure. On the other hand, the soft rubber tubing used for fountain syringes must withstand mild pharmaceutical solutions and must be free from any material that might act as an allergen.

The racks in dishwashers that hold the dishes and kitchenware are made of wire covered with rubber to protect delicate tableware. The rubber must have a high degree of resistance to heat as well as to the action of soaps, detergents, and bleaches used in cleaning.

Non-electrical Appliances

Non-electrical appliances and fixtures include pails; garbage and trash cans; flexible baskets; tubs; cups, dishes, and other articles for picnic, patio, or similar use; and rubber gaskets of many types. Rubber may be combined with metal in the form of a resilient surfacing for use in dish drainers, or may be compounded with plastics to unite the best qualities of both. It has been demonstrated that fixtures of considerable strength, durability, and resistance to rust and wear, can be made of rubber-plastic mixtures. Plumbing fixtures with a sufficient range of resistance to temperature changes, good structural strength, and a high degree of resistance to rust and corrosion, have been made of such mixes. Lightness, ease of installation, and relative cheapness, indicate that such fixtures may compete with metals in permanent plumbing installations.

Rubber casters are important accessories of tea wagons and similar pieces of household equipment that must be rolled over polished floors or floor coverings. These casters are safe to use without thought of possible scarring of the floor. They may be made either of hard rubber or of heavily loaded soft rubber which preserves some softness and flexibility and, thus, gives even greater protection to polished floors.

Floor-coverings

The use of rubber tiling in floor surfacing in the home has increased greatly. Rubber tiling is durable, can be polished like other floor surfacings, and can also be compounded to have self-polishing qualities in use. Rubber tiling is easy to clean, is highly resistant to cleaning agents, and is produced in many attractive colours and patterns.

Rubber backing for rugs gives a high degree of resistance to slipping—an important factor in throw-rugs for use on polished floors. The rubber backing is usually applied in the manufacture of the rugs, but the rubber is also put up in solutions or emulsions for home application. Sheet- and foam-rubber rug pads also have found extensive use. Foam-rubber not only gives resistance to slipping but also imparts a softness and depth to the rug that adds greatly to comfort.

Stair treads are an important application of rubber in the home. These treads not only protect against accidents in going up and down stairs, but may be used to impart a decorative touch. They are more durable than carpeting and can be cleaned more easily.

Drug Sundries

Rubber's resistance to fluids and gases, and its ability to withstand washing and sterilization, make it useful in connection with the sick-room and for similar purposes for the comfort of the individual. It has been possible to include, in the rubber compound, protectants against odour-causing bacteria, moulds, and mildew, thus attaining even greater protection. These protectants, according to Sadev (1957), have been incorporated into all important types of rubber, including both latex and foam rubber and articles made by such different processes as calendering, moulding, foaming, dipping, and coating. It has been used in the manufacture of pillows, bathing caps, footwear, baby pants, hospital sheeting, crib sheets, heating pads, gloves, aprons, and coated ironing-board covers. Some eighteen rubber companies were reported by Sadev to be testing the use of protectants for other articles such as combs, toothbrushes, dolls, girdles, toys, balloons, and mattresses.

The use of rubber in personal hygiene has been an important application for many years. Hot-water bottles, ice caps, bathing caps, atomizers, rubber hose, rubber sheeting, catheters, and hard rubber fittings for douches and enemas, are familiar to the general public and represent important usages of rubber. The common requirement of these articles is that absolute sterilization be possible, and that the rubber article be resistant to the chemicals used in sterilization as well as to steam and hot water.

Softness and pliability are essential in rubber articles that come into close contact with the body. Such articles must not contain any chemical or compounding ingredient that would be irritating to the skin or to internal tissues. Natural rubber has been preferred for such uses, including applications of rubber for bodily support, comfort, or fashion.

Wearing Apparel

Because of its resistance to the passage of air and moisture, rubber is not favoured in general as a material for articles of clothing. However, it does find some use in sweat shirts and similar garments to induce perspiration and loss of weight. Its resistance to water has been applied in raincoats, overshoes, boots, gloves, aprons, baby pants, and similar protective garments.

Rubber has also been prepared in the form of thread and combined with other fibres in the manufacture of elastic garments. Only a small proportion of rubber threads need to be used to give the desired elasticity. Several processes have been used in the manufacture of the rubber thread. The original process involved preparing the rubber in thin sheets which were then cut by suitable means into thread. This was known as cut thread and had a square cross-section. Later, thread was made by extruding latex or a solution of rubber into a coagulating medium, and this is the process that is in general use today. The coagulant is adjusted to the latex or solution so as to give approximately instantaneous coagulation. The thread is dried and vulcanized, and is then combined with the other fibres on the weaving mill. The vulcanization ingredients can be added either before extrusion or in suitable baths after extrusion and coagulation.

The size of the rubber thread can be altered by the size of the orifice of the extruder, the pressure of the latex or solution, the type of coagulant, and the relationship between the level of the orifice, which is immersed in the coagulant, and the surface of the coagulant.

Fabrics containing rubber thread are used in clothing, particularly in the manufacture of supporters, elastic garters, and supporting garments such as girdles. In this usage, the elastic strength of rubber is utilized to give support, and at the same time to allow free movement and adjustment which would not be possible with less elastic materials.

Rubber gloves are useful in many household tasks and are essential in hospital and medical usage. While strength and durability are the chief requirements of rubber gloves for household use, surgeon's gloves must have maximum possible strength, thinness, and resistance to chemicals and steam used in sterilization. They are made of the finest natural rubber. Rubber gloves for household use must have good resistance to soaps, detergents, bleaches, and other chemicals and also to acids, alkalis, and other corrosive materials that find occasional use.

Foam rubber is used in padding of clothing, and this has been pointed out as a potential danger in the laundering of the clothing. *Rubber Age* (1957) states that the National Protection Association has suggested that clothing and other products padded with foam rubber should not be force-dried in home or commercial driers. The Association suggested also that such foam rubber articles be dried separately by natural means after washing, and urged that such articles be labelled 'Do not dry in driers or oven heaters' as an aid to preventing fires through spontaneous heating and ignition.

Protection from moisture is given by rubber in the form of rubber shoes, overshoes, boots, capes, raincoats, rain caps, bathing caps, and ponchos, and in waterproofed fabrics. A pioneer rubber chemist contributed his name to the first rubberized fabric raincoats that were known almost universally for many years as macintoshes, and still are so termed in many English-speaking countries.

Rubber heels have cushioned the shock of walking on modern pavements and may be credited with aiding in the adjustment of mankind to modern living. Athletic shoes made of rubber are taken for granted as necessities in efficient competition. Crepe and sponge rubber soles have received general acceptance for sports and comfort. As the use of rubber in heels has increased, the art of compounding has been improved to obtain tougher and more durable heels. A major problem has been the compounding of non-marking rubber heels that do not leave scuff-marks on flooring. As women's heels have become higher and thinner, the problem of producing a sufficiently tough tip (top-lift) has become increasingly difficult. An increasingly smaller tip was called upon to perform the same work as a broader heel had formerly done. The need for increased toughness and resistance to abrasion increased in direct proportion to the decrease in wearing surface

Wolf (1958) reported that a suitable top-lift to meet the rigid requirements for ladies' shoes could be obtained by using a carboxylic nitrile rubber reinforced with a fine-particle silica and hard clay. If desirable, other synthetic rubbers might be combined with the carboxylic nitrile rubber. He also reported success in using a relatively large amount of phenolic resin with nitrile rubber reinforced with the fine-particle-size hydrated silica.

Athletic Goods

Many articles of apparel that are made wholly or in part of rubber are designed primarily for sports wear or for use in athletic activity. Rubber has also entered into the sports field in many other ways. Footballs, medicine balls, basket balls, and all other inflated or inflatable balls, are made of rubber or have rubber bladders. Tennis balls are inflated by chemical action during vulcanization. Footballs and similar playing balls have inflatable bladders that hold the air under pressure. Golf balls are given greater 'carry' by having the core made of rubber, and the tough surface results from the incorporation of rubber in the compound.

Rubber also plays an important role in the manufacture of swimming accessories. Beach toys and swimming aids are made of rubber. Skin diving has created a considerable demand for rubber in the manufacture of breathing tubes, masks, fins, and snorkels. In skin diving, rubber is subjected to a considerable range of temperature and pressure. It must have softness for personal comfort, and also pliability, durability, and dependability to avoid dangerous failure.

Toys

Rubber is also an important constituent of toys—especially of those that are unbreakable and harmless for children. The fabrication of life-like dolls that have the characteristics of babies has developed into a large industry. The parts are made primarily by moulding, and then joined to make dolls with a high degree of adjustability as to position. Miniature nursing bottles with functioning nipples are supplied, as well as durable plastic or rubber dishes and doll furniture. Rubber has added a significant element of reality to the make-believe life of the growing child.

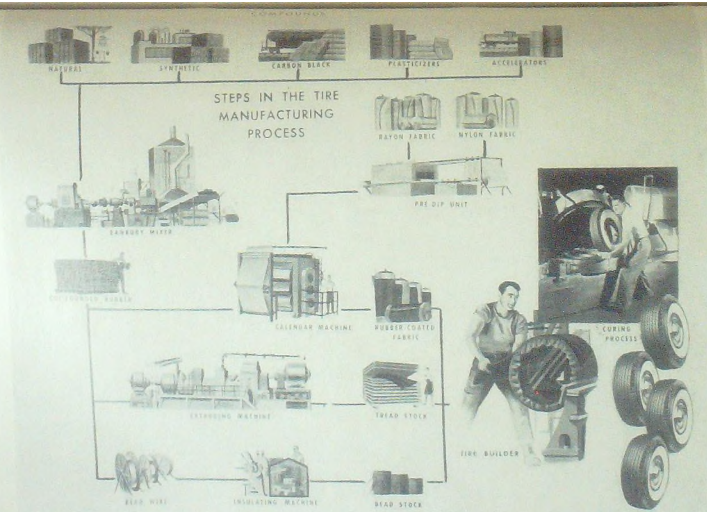
Rubber has also entered into the construction of the play-pens, building blocks, toy trains, toy cars, and many other articles designed to give respite to harassed parents and joy to the child. Indoor archery is possible with rubber-tipped, cup-shaped arrows that stick to the target by suction. While ultimate protection of the home from toys in the hands of small children could only be accomplished by constructing the home and furnishings largely of rubber, the use of rubber in the manufacture of toys has certainly been of great value in this connection.

Wheeled playthings have assumed an important place in the lives of children. The rubber tyre is applied to wheels of every size, and for use on many types of toys. In addition to serving the purpose of rolling, these rubber tyres protect the furniture and floors and give traction to spring- or rubber-propelled toys. Hard rubber wheels are of great importance in making roller skates; and rubber tyres are essential on baby carriages, both toy and practical, and on wagons, velocipedes, tricycles, and bicycles.

In the manufacture of tyres for such a variety of toys and vehicles, the versatility of rubber and rubber compounds is demonstrated. The type of mix is suited to the prospective application, and rubber finds use on toys that are designed for competition with the cheapest of other materials, or with the best. A high degree of durability is built into hard rubber wheels for roller skates and the rubber used in bicycle tyres. Toys for infants must have softness and resilience but are not required to have a durability equal to that of the bicycle tyre. Rubber tyres on toys that roll on the nursery floor do not need the toughness and resistance to abrasion of those on velocipedes that, in turn, do not require as tough a rubber as is used on bicycles.

Sponge Rubber

Sponge or foam rubber for home use is made by the same methods as are employed for the manufacture of industrial products. Uses of foam or sponge rubber in upholstery in motor-cars directly parallel its application in the home for the upholstery of furniture. The use of sponge rubber around the home requires special mention, however, because it represents a relatively new form in which rubber meets many of the household needs. From its first application in the manufacture of quality mattresses and pillows, sponge rubber has spread to every category of household need, and its use is expanding. Rubber sponges fastened to appropriate handles are used for cleaning floors, walls, toilets, bath tubs, windows, etc. Similar sponge rubber has also been put out in the form of soap dishes for holding



Photograph by permission of Goodyear Tire and Rubber Company

Flow-chart for the manufacture of modern tyres.

Photograph by permission of Goodyear Tire and Rubber Company

(*a*) Steel cords used in the manufacture of tyres.

Photograph by permission of B. F. Goodrich Company

(*b*) Improved rubber expansion-joint for roads.

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soap in the lavatory, bath, and sink. Polyurethane foam is a valuable heat-resistant rubber that has proved useful as a pad for ironing boards. Vinyl foam cushions are now being marketed in a form for being covered at home and have been compounded to be flame, moisture, mildew, and moth resistant in addition to being non-allergic, sanitary, and durable.

Sponge, foam, or cellular rubber is made by including in the mixing ingredients chemicals that will form gas during the vulcanization process. Marchionna (1933, 1937) collected and abstracted hundreds of patents issued for the preparation of sponge rubber from natural rubber latex. Later, it was found possible to make sponge rubber from synthetic latices. The internal structure of the sponge rubber can be controlled to give either small, isolated air cells or large, interconnected air passages, and the form of the mould may add further to the open internal construction.

Adhesives

Photographic adhesive pastes made with rubber have found popularity for the pasting of photographic prints, clippings, and similar materials. Rubber cements have found use for the gluing of fabrics that must remain flexible, and for application to the undersurface of rugs to keep them from slipping on polished floors. Rubber cements are used in the home for laying rubber and vinyl tile. Wherever rubber must be bonded either to other rubber or to different materials, a rubber cement is necessary as no other adhesive is satisfactory in bonding rubber. Many articles designed for household use are fabricated by the use of rubber adhesives. Foam rubber pads are bonded to metal or wooden frames or handles by rubber cements, and rubber strippings used as sealants for refrigerators are held in place by rubber adhesives.

An important outlet for rubber cements in the manufacture of articles for personal use is in making shoes. The upper parts of most shoes are cemented together with adhesives, and Blyler (1958) states that in the final process of attaching the uppers to the soles, approximately 90 per cent of all women's shoes are fastened with adhesives, as are 50 per cent of children's shoes and 25 per cent of all men's shoes. Whereas formerly nitrocellulose adhesives were used almost exclusively for this purpose, the use of rubber soles and non-leather tops during the war caused a change to various types of rubber adhesives that are necessary in the case of rubber soles. Natural rubber latex, neoprene latex, and the nitrile rubbers, have been used successfully in cementing the various parts of shoes. The nitrile rubbers have been especially useful in cementing vinyl plastic tops to rubber soles.

Rubber is an important constituent of the cement used in the manufacture of a wide variety of adhesive tapes. Rubber tape is wrapped around a soldered electrical connection to insulate it from other wires in the union box. Rubber is an ingredient in the tacky surface of various types of fabric and plastic tapes. Thumb tacks (i.e. drawing pins) have been almost entirely replaced on the drawing board by adhesive tape that is convenient to use, causes no damage to the board, and offers no obstruction to free movement of drawing instruments.

Miscellaneous Uses

Household correspondence requires the use of the two rubber items that are of almost universal application, the rubber band and the eraser. Rubber is also used in the manufacture of wall-paper cleaners that, after all, are essentially large-scale erasers.

In cosmetics, rubber has found its chief application in the manufacture of hard-rubber combs and in the soft-rubber bulbs of atomizers. The development of pressurized sprays has reduced the use of rubber for this latter purpose, but rubber bulbs are needed for perfume atomizers, droppers, and similar appliances. In the kitchen, rubber bulbs are needed for basters and, in the garage, for hydrometers for checking battery and radiator fluids.

Rubber nipples on nursing bottles represent a well-established application of rubber that has increased with human population and shows no sign of being replaced.

Gaskets represent an important household outlet for rubber. Rubber sealing rings are an essential accessory in home-canning. While the efficiency of commercial canning has tended to restrict many home-canning activities, the production and use of rubber jar rings still constitutes an important use of rubber. Heat-resistant rubber gaskets are used on pressure cookers, and rubber also finds extensive use around the home in valve gaskets, hose gaskets, and in the sealing of refrigerator doors. Rubber strips may be used around doors and windows as weather-stripping.

Rubber sheets and rubber pads are needed in every home. Crib sheets, waterproof covers, and waterproof tarpaulins, illustrate the use of rubber for waterproofing. Sink and drainboard pads represent the applications of flat rubber padding to protect glass and china tableware. Foam-rubber kneeling pads, both for use inside the home and for the home gardener, illustrate the use of rubber for making the efforts of the homemaker less arduous. Thus, sheet and pad rubber perform in the home three functions that are characteristic of the contribution of rubber—waterproofing, protection of delicate materials from injury, and adding to the comfort of the homemaker.

Rubber on the Farm

To the degree that the farm is still a place of abode as well as a farming business, the rubber uses listed above for the home are duplicated on the farm. There are, however, many uses of rubber that are peculiar to farming operations as they are conducted in this age of automation. Just as rubber has assumed a major role in the developing civilization in which the jarring bounce of the ox-cart has given way to seemingly effortless and joltless mechanized travel, and metallic clang and vibration have been silenced and deadened by the interpolation of rubber, the labour of men and animals on the farm has given way to more efficient mechanical operation. Man formerly multiplied his own labour by utilizing the efforts of beasts of burden. Now his efforts receive even greater increase by the use of machines.

The raising and care of animals continues but, in many countries, these are now the products of the farm rather than the tools for its operation. Mechanization has also been applied to the care of the animals that are still raised on the farm, and rubber has contributed greatly to this farm mechanization.

Rubber in Traction

Traction is a major need on the farm, using much power. It is needed for the operation of farming equipment, for transportation on the farm, for obtaining supplies and equipment, and for transporting the farm products to market. Primitive wooden ploughs pulled by human power were the first development in agricultural traction. Substitution of draft animals for the human power constituted a major change that motivated advance in the construction of the crude plough. Soil preparation prior to planting and cultivation of the growing crop then became more and more important concepts in agricultural operations. Even during the animal-power period of farm operation, it became evident that farm management consisted in more than just stirring up the soil. Yet ploughed and clean-weeded fields were found to lose their top-soil through wind and rain erosion. Methods of farming were accordingly devised to minimize the loss of soil, while still permitting the working of the soil to establish good tilth, and meanwhile provide sanitation and adequate control of weed plants.

It was noted, however, that the plough itself created problems. In many types of soil, a compressed layer was left at the bottom of the furrow. With 'improved' types of ploughs that allowed well-controlled depth of ploughing, this layer, the plough sole, became more or less continuous. It set up a barrier to the penetration of roots and a hindrance to the free movement of water in the soil, and became a serious problem of farm-management.

Farm mechanization started with the substitution of farm tractors for draught animals. The efficiency and speed of ploughing and cultivation were greatly increased by the substitution of untiring mechanical traction. Stops for repairs were shorter than the total rest-periods for farm animals, and the machine could be worked continuously for long hours. Speed-control and uniformity of work were much greater with the mechanical traction than had been possible with draught animals.

Substitution of machinery for draught animals introduced new problems into farm management, however. Traction created the first and most serious problem. Under normal field conditions, heavy tractor wheels with large iron cleats gave good results, but they were easily bogged down if the field was wet, and the iron lugs were prohibited from paved roads because of their destructive effect. Transportation of the tractors from field to field became a major problem, yet this transportation was essential because the efficiency of the tractor widened its use to many acres rather than to a single field. Early substitution of rubber lugs for the original steel lugs helped somewhat in the transportation of the tractors from place to place, but did not solve the problem of traction in wet fields. Substitution of tracks for the traction wheels, however, partially solved the problem.

While ploughing itself does not involve the working of very wet soil, there are many farm operations that do require the use of power equipment over wet land. Unfavourable weather often interferes with the operation of power equipment in the harvest of cereals, and the use of track-equipped machinery may not be practicable. In rice farming, the use of power machinery was not even considered as a possibility until long after the use of such equipment had become standard practice in most farming operations.

The use of power-operated equipment on wet soils, even on inundated rice land, was solved by the development of giant rubber tyres with deeply-notched tread designs, eclipsing even the heaviest of the iron and rubber lugs formerly used on the metal drive-wheels. Such tyres may contain up to three-quarters of a ton of rubber and weigh more than a ton and a half. With a height of more than 6 ft., these tyres can operate in swamps or in the dampest of farm lands without becoming clogged, and with only a minimum churning of the soil.

Not all of the farm traction needs have required such enormous tyres, but the development of heavy rubber tyres with large cross-section and deep, heavy tread design has been an important element in the adjustment of farm traction to machine operation. These tyres can be operated anywhere on the farm that mechanical traction is required, and do not damage the paved highways.

The plough sole has been mentioned as a problem in farm management. The substitution of machines for animal traction complicated this problem, for horse-drawn ploughs and other farm machinery cause little compaction of the under-soil. In addition to the plough sole that is characteristic of the ploughed land on many types of soil, the use of heavy tractors results in further compaction of the soil. This may result either in excessive surface dryness, even when subsoil moisture is adequate, or in waterlogging. Both conditions may occur in a single field, as they result from the destruction of soil capillarity by the compacting. A build-up of soil diseases inimical to the farm crops may result from the poor aeration of the soil. The more efficient transmission of power that resulted from the use of large rubber tyres has made it possible to reduce the weight of farm tractors and reduce compaction materially.

Farm Transportation

The products of the farm move to market on tyres, and fertilizers and other supplies reach the farm on vehicles equipped with rubber tyres. Tyres are also nowadays almost indispensable for the transporation of men, supplies, and equipment from point to point around the farm. The practical elimination of living horse-power has forced reliance on trucks or lorries of all sizes, and these have found use even in the transportation of tractors and heavy equipment where the distance of haul makes the greater speed of the truck advisable.

Not all of the wheels on the farm have been equipped with rubber tyres. It has been shown conclusively, however, that great economies can be made by replacing steel rims with rubber tyres wherever heavy loads have to be hauled. Over rough terrain, the advantage of the rubber is even greater than elsewhere. It has been found that rubber tyres are of great advantage on horse-drawn vehicles, and the accomplishment of oxen has been greatly increased by putting rubber tyres on ox-carts. In all phases of farm operation, it has been found that economies result from putting rubber tyres on equipment that is rolled on wheels. This replacement is particularly important in the case of wheelbarrows and similar equipment that is propelled by human power.

Power Belting

Apart from the rubber in traction and transportation equipment, power belting has been the important contribution of rubber to farm mechanization. The farm, like the factory, is capable of great mechanization, and most of the farm operations can be facilitated by the use of power. Unlike the factory, however, the farm is spread out over a large area and it is impracticable to make permanent installations to provide the power needed in so many places. Many of the farm operations can be concentrated near centralized power equipment; but it is often better to take the power to the work than to take the work to the power.

Flexible power transmission through the use of power belting has made it possible to convert tractors, trucks, or motor-cars into temporary sources of stationary power. Wood saws, thrashing machines, balers, and comparable machinery, can be operated far from the farm centre because of the possibility of converting self-propelled equipment to use as stationary engines through the temporary use of power belting.

Power belting also finds many uses in permanent power installations on the farm—machine shops, pumping installations, milking machines, electrical generators, and similar uses that make the operation of a farm comparable to that of a factory with respect to power needs.

Transplanters

As in industrial operations, rubber finds many uses on the farm because of its softness and resilience. These qualities of rubber have been utilized in the mass handling of eggs, and for similar purposes in the washing and handling of bruisable farm crops. Crops, such as potatoes, that have been dug from the ground, must often be washed to take on an attractive appearance and command the best return. Fruit and vegetable crops often have to be washed to remove any residue of insecticides or fungicides. Rubber performs an important service in the form of fingers or buffers to avoid damage to the farm crops while they are being washed or otherwise handled in packing and preparation for market.

Another very delicate operation that must be performed on many farms is the transplantation of nursery seedlings. These seedlings are fragile and easily bruised. In large-scale operations, this transplanting is done mechanically, the only human function being to carry the seedlings to the transplanter and place them, one by one, into individual pockets or fingers on the machine. The machine does the rest of the job, opening the hole in the soil, carrying the plant to the hole, inserting the plant, and firming the soil around the plant. The transplanter may even apply water to the newly transplanted seedlings at the time of planting, and rubber hosing finds use for this purpose.

The important functioning parts of the transplanter are the rubber pockets or fingers that hold the seedlings while they are being planted. These rubber appendages hold the plants firmly but softly. The non-slip surface of the rubber retains the seedlings without abrasion while they are being carried to the planting holes, but releases them instantly without tendency to stick. Little pressure is exerted on the seedlings, and there is a minimum of damage to the tender young bark or other surface.

Spraying Equipment

The protection of growing crops from diseases, insects, and weeds is an important phase of farm management. There are many devices that have proved useful in providing this protection—including the breeding of resistant or vigorous crops that are not seriously affected by the diseases, and of insects that will devour and suppress the weeds. The majority of the protective processes involve the application of fungicides, insecticides, or herbicides. These protectants are applied in the form of powders or dusts, or as emulsions or solutions.

Rubber is used extensively in connection with the chemical protection of plants from diseases, insects, and weeds. Many of the chemicals used in the protectants may be injurious to the person mixing them in preparation for application, or subjected to the fumes or sprays during application. It is often necessary to wear protective clothing while mixing the chemicals and during the time of application. Eye irritation is common from many of the dusts used as fungicides or insecticides, and it is often necessary to wear protective goggles or aspirators as well as suitable gloves and other protective clothing. Rubber is essential in the manufacture of the clothing, and in connection with the fabric of the masks or aspirators and the sealing strips that hold the goggles, masks, and aspirators to the face of the operator—to protect eyes and nose from the sprays or dusts.

Crop protectants (fungicides, insecticides, herbicides) may be applied by hand, by hand-operated equipment, by various types of power equipment on the ground, or by aeroplane. Rubber finds use in devices to control the rate of application and feed controls in all types of spray- or dust-spreading equipment. Its greatest use is in connection with hand or power equipment that sprays or dusts from the ground. In addition to its use in goggles, clothing, and other devices to protect the operator from the chemicals, rubber is found mainly in the hoses that are used to direct the spray or dust. The rubber used in these hoses must be compounded to have a high degree of resistance to the chemicals used in the spray or dust, and also must have considerable strength to resist the pressures needed to atomize the spray or dust and force it to the limit of the area being treated. As the controlling nozzle must be at the end of the hose, where it can be controlled by the operator, the hose must be designed to withstand the full force of the spraying pressure that may reach several hundred pounds per square inch. Many effective herbicides consist of oils, or of emulsions containing oils. Hoses that handle such materials must be made of oil-resistant rubber.

In addition to the hoses needed in applying sprays, dusts, or emulsions, the machines require many types of rubber washers—to seal the top of the tank, for use in connecting the hose, for sealing inlets and outlets, and in the control valves. Protectant machinery also represents an additional important use for rubber tyres to facilitate transportation over ploughed ground.

Rubber in Other Farm Equipment

Rubber is also useful in the construction of many other types of farm equipment. Cotton pickers make use of rubber, and it is also used in thrashers and combines and in suction pickers for small seed. Furthermore, rubber has been applied to protect the surface of metal parts against abrasion by sand and dust where high-pressure suction or pressure is needed in cleaning seed.

Many farms are at such distances from settlements where there is fire-fighting equipment that the farm must provide its own. This is an additional and important need for rubber. The farm is not essentially different from a factory in this respect, as the first moments of a fire often determine whether it will be controlled. In both cases, the availability of fire hosing and the necessary fittings and water outlets are essential, and so rubber is a basic material in protection against fire.

The Use of Rubber in Stock Raising

Rubber has important uses in connection with the raising of farm animals for meat and dairy products. Veterinary needs and protection against disease and insects require many of the rubber goods that find use in medical treatment of humans. Sanitation is extremely important for the health of the animals and for the character and quality of the product. Barns and pens must be washed and sprayed and kept clean by the most meticulous effort. Rubber enters into the sanitation programme in an important manner as a constituent of atomizers and similar veterinary supplies, and in the hoses and attachments used for spraying and hosing out the buildings and pens.

Farm mechanization in the handling of livestock has been effective in the milk industry. In highly competitive areas, hand milking has given way to the use of milking machines, and the simple milking machine is giving way to elaborate installations in which the milking machine empties into pipes that carry the milk to the assembly point. All operations leading to the delivery of the milk to the collecting truck are here performed mechanically, while the milking machine and all pipe lines are cleaned by forcing cleaning fluids through them under pressure.

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THE EXPANDING NEED FOR RUBBER

PREDICTION OF RUBBER CONSUMPTION

PREDICTIONS of rubber consumption are normally short-term estimates made to guide the industry in planning production schedules. At this point, however, we are concerned more with a long-term prediction, projecting rubber usage twenty years or more into the future. The planning of production schedules, or even the construction of new production facilities for synthetic rubber, can be based on annual estimates of demand; but the establishment of plantations requires a minimum of ten years for each planting. A long time is required for a major increase in plantation rubber production.

A rubber plantation can be brought into tap at the age of five to seven years and attains full yield about ten years after planting. A period of around twenty years is then required to amortize the investment. The initiation of a plantation operation involves the supposition that production will still be profitable some thirty years after the date of planting. An orderly planting or replanting schedule would serve to level off the influence of temporary economic fluctuations in demand or price, but would not protect against major trends that might involve a shift to competing products. The biological problems of planting, care, and exploitation of the plantation, create only a minimum of uncertainty covering this thirty-year period. Economic questions of continued need for natural rubber, the expanding market for rubber of all types, and the market price in the future, contribute major uncertainties.

Geographical Distribution of Usage

In 1959, as shown in Table XVII, the United States used 44·2 per cent of all the rubber consumed throughout the world. A total of 34·3 per cent of the rubber was used in Europe. A major portion of the rubber used in the United States and Canada, 65·9 and 56·4 per cent, respectively (Table XVIII), was synthetic. In England and France, natural rubber, to the extent of 69·6 and 68·1 per cent, respectively, constituted the major source of raw rubber, as it did also in all other countries.

Tyres, tubes, and tyre accessories accounted for over half of the rubber used throughout the world, including 70·1 per cent of all rubber used in Canada and 63·0 per cent of that used in the United States. The usage of

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TABLE XVII

RUBBER CONSUMPTION IN 1959 BY COUNTRY, IN PER CENT OF ESTIMATED TOTAL WORLD USAGE*

Country	Per cent	Country	Per cent
United States	44·2	Australia	1·5
United Kingdom	7·1	Brazil	1·4
France	5·4	Canada	2·8
Germany	5·9	India	1·2
Netherlands	0·8	Japan	5·2
Eastern Europe	8·5	China	4·0
Other Europe	6·6	Others	5·4

* Calculated from data in Table 23, International Rubber Study Group (1960). No account has been taken of synthetic rubber originating from Eastern Europe.

TABLE XVIII

CONSUMPTION OF RUBBER IN 1959 IN CANADA, FRANCE, THE UNITED KINGDOM, AND THE UNITED STATES, BY AMOUNT IN LONG TONS AND PERCENTAGE USED IN THE MANUFACTURE OF TYRE AND NON-TYRE PRODUCTS AND THE AMOUNT AND PERCENTAGE OF NATURAL AND SYNTHETIC RUBBERS*

Product	Canada		France †		United Kingdom		United States	
	tons	*per cent*	*tons*	*per cent*	*tons*	*per cent*	*tons*	*per cent*
Tyres	‡		§		‖		¶	
Natural	31,721	31·2	56,506	39·2	84,090	32·4	354,663	21·8
Synthetic	39,478	38·9	27,300	19·0	58,169	22·4	669,611	41·2
Total	71,199	70·1	83,806	58·2	142,259	54·8	1,024,274	63·0
Non-tyre	**		††		‡‡			
Natural	12,551	12·4	41,600	28·9	96,552	37·2	200,381	12·3
Synthetic	17,734	17·5	18,541	12·9	20,844	8·0	401,715	24·7
Total	30,285	29·9	60,141	41·8	117,396	45·2	602,096	37·0
Totals								
Natural	44,272	43·6	98,106	68·1	180,642	69·6	555,044	34·1
Synthetic	57,212	56·4	45,841	31·9	79,013	30·4	1,071,326	65·9
Grand totals	101,484	100·0	143,947	100·0	259,655	100·0	1,626,370	100·0

* Compiled from data in Tables 36, 37, 38, and 39, International Rubber Study Group (1960).

† Data included for first nine months only.

‡ Includes tyres and tubes.

§ Includes auto covers, vehicle tubes, vehicle covers, aero tubes, cycle tyres, other tyres, and repair materials.

‖ Includes new covers and tubes for tyres for: cars (tubeless and other); commercial vehicles; tractors, earth-movers, and horse-drawn vehicles; motorcycles and tricars; bicycles; and other covers as well as solid tyres, re-treads, and repair materials.

¶ Includes tyres and tyre products.

** Includes wire and cable, footwear, foamed rubber, and other products.

†† Includes technical rubber goods; hosing; belting; ebonite; footwear; soles and heels; surgicals; proofing; cement; thread; cables; and miscellaneous.

‡‡ Includes belting; cables; ebonite; footwear; hosing; proofing; cellular rubber; thread; surgical products (excluding sheeting); sport goods; sheeting; rings, seals and gaskets; tiles and flooring (other than cellular rubber); and other miscellaneous products.

rubber for other purposes was also highly important, and the United States alone used over ten times as much rubber in non-tyre products in 1959 as was used throughout the world for all purposes in 1900.

The disparity in usage between that in the United States and that in the rest of the world encourages the belief that there are great opportunities for expansion in the use of rubber. Phelps (1957), after reviewing the available information, found that the rate of increase for all other countries is now somewhat greater than for the United States, the comparative figures for the period 1950–55 being 6·4 per cent compared with 4·0 per cent increase annually. Phelps believed that this situation could be expected to continue, with even greater differences in the years to come, as annual consumption in the United States is now about 19 lb. per caput in contrast to 1 lb. per caput for all other countries combined. He concluded that rubber consumption will continue to increase rapidly for some time to come—barring a lack of supply, which is unlikely, or a world-wide depression—and that the rate of increase will be greater elsewhere than in the United States.

Decade-doubling of Consumption

Since 1900, the annual consumption of rubber (Table XIX) has roughly doubled during each decade. Table XX shows the percentage increases in world consumption of rubber at ten-year intervals, starting with 1900. Had there been an exact doubling of consumption during each decade since 1900, the consumption in 1950 would have been 1,680,000 long tons. The actual consumption in that year of 2,302,500 long tons (Table XIX) substantially exceeds the calculated decade-doubling consumption. The 1959 consumption of 3,677,500 tons already exceeds the calculated decade-doubling rate (2,360,000 tons) for 1960 but is only about 60 per cent increase over the actual consumption in 1950.

Any projection of decade-doubling of consumption past 1960 would quickly lead to unbelievably large figures, outside the realm of possibility. There is no indication, however, that any saturation point is being reached in the consumption of rubber, and a substantial increase in the rate of consumption is forecast by responsible authorities. Estimates prepared by the United States Materials Policy Commission (1952), the so-called Paley Commission, set consumption at around five million long tons in 1975. Phelps (1957) pointed out that the annual rate of increase in rubber consumption since the issuance of this report had exceeded the rate necessary to fulfil that estimate.

In comparisons of annual consumption, the effects of wars and economic fluctuations have major influence on the rate of consumption of rubber. It is interesting to note, however, that the two world wars and the economic depression of the early nineteen-thirties in the United States had only temporary influence on the course of the world's decade-doubling trend in rubber consumption. The immediate effects are

TABLE XIX

ANNUAL WORLD CONSUMPTION OF RUBBER FOR THE PERIOD 1900–1957, SHOWING THE PERCENTAGES OF NATURAL AND SYNTHETIC RUBBERS USED*

Year	Total Consumption *long tons*	Natural *per cent*	Synthetic *per cent*
1900	52,500	100·0	—
1901	52,500	100·0	—
1902	50,000	100·0	—
1903	57,500	100·0	—
1904	65,000	100·0	—
1905	70,000	100·0	—
1906	75,000	100·0	—
1907	77,500	100·0	—
1908	76,000	100·0	—
1909	87,500	100·0	—
1910	100,000	100·0	—
1911	100,000	100·0	—
1912	120,000	100·0	—
1913	130,000	100·0	—
1914	120,000	100·0	—
1915	160,000	100·0	—
1916	185,000	100·0	—
1917	222,500	100·0	—
1918	235,000	100·0	—
1919	312,500	100·0	—
1920	297,500	100·0	—
1921	277,500	100·0	—
1922	405,000	100·0	—
1923	445,000	100·0	—
1924	465,000	100·0	—
1925	552,500	100·0	—
1926	542,500	100·0	—
1927	595,000	100·0	—
1928	685,000	100·0	—
1929	805,000	100·0	—
1930	710,000	100·0	—
1931	682,500	100·0	—
1932	690,000	100·0	—
1933	822,500	100·0	—
1934	920,000	100·0	—
1935	940,000	100·0	—
1936	1,045,000	100·0	—
1937	1,092,500	99·8	0·2
1938	960,000	99·5	0·5
1939	1,130,000	98·6	1·4
1940	1,152,500	96·3	3·7
1941	1,312,500	94·5	5·5
1942	877,500	87·2	12·8
1943	907,500	67·7	32·3
1944	1,125,000	34·4	65·6
1945	1,127,500	23·3	76·7
1946	1,467,500	37·8	62·2
1947	1,735,000	63·8	36·2

* Data from Phelps (1957) and *International Rubber Study Group* (1960).

TABLE XIX—*contd.*

Year	Total Consumption *long tons*	Natural *per cent*	Synthetic *per cent*
1948	1,902,500	74·8	25·2
1949	1,887,500	76·2	23·8
1950	2,302,500	74·8	25·2
1951	2,327,500	65·1	34·9
1952	2,355,000	61·5	38·5
1953	2,527,500	65·5	34·5
1954	2,515,000	70·6	29·4
1955	2,942,500	63·9	36·1
1956	3,035,000	63·7	37·3
1957	3,147,500	60·0	40·0
1958	3,227,500	61·3	38·7
1959	3,677,500	57·4	42·6

TABLE XX

WORLD ANNUAL CONSUMPTION OF RUBBER AT TEN-YEAR INTERVALS, AND INCREASE IN ANNUAL RATE OF CONSUMPTION FOR EACH DECADE*

Year	Consumption *long tons*	Increase in Decade *long tons*	*per cent*
1900	52,500		
1910	100,000	47,500	90·5
1920	297,500	197,500	197·5
1930	710,000	412,500	138·7
1940	1,152,500	442,500	62·3
1950	2,302,500	1,150,000	99·8

* Data from Phelps (1957) and *International Rubber Study Group* (1958).

indicated by the variations in annual consumption in Table XIX; but, when the consumption is shown only at ten-year intervals in Table XX, there is no indication other than that of steadily increasing usage. Large-scale introduction of synthetic rubber has not affected the general trend in over-all usage of rubber.

The Paley Commission predicted an increase in consumption of rubber to around 5 million tons a year by 1975. The Mission of Enquiry into the Rubber Industry of Malaya (1954) stated: 'We think that it would be unsafe to base policy on the assumption that the increase in the demand for rubber, both natural and synthetic, will be as great as the Paley Commission suggested, though we have no doubt that it will be very great.'

Phelps (1957), on the basis of a careful, objective analysis of the rate of increase in consumption of rubber before and after the Paley report, stated: 'A statistical projection based upon the cumulative rate of increase in world consumption in the period 1950-1955 (5·1 per cent "annually") would suggest a doubling of demand in the next 14 years.'

Phelps showed that by 1975, at this rate of increase, the amount of new rubber consumed would be approximately three-and-a-half times the amount used in 1950 (rather than two-and-a-third times the 1950 consumption as estimated in the Paley report). Phelps concluded that world consumption of rubber could easily double between 1950 and 1965.

Natural Rubber *v.* Synthetic Rubber

Since the phenomenal development of the synthetic rubber industry during World War II, it has been accepted that there is a group competition between the synthetic rubbers and natural rubber. It is increasingly apparent that each of the synthetic rubbers is in competition, not only with natural rubber, but with all of the other synthetic rubbers, for the available elastomer market, and that the competition between the synthetic rubbers may become much more intense than that between natural and the synthetics as a whole. The rubbers, natural and synthetic alike, are in competition with plastics, ceramics, metals, wood, glass, and composition materials, for border-line uses for which high extensibility is not essential.

General-purpose Rubbers

Natural rubber (NR) is the most versatile of all of the rubbers. In much of its usage, and particularly in tyres, NR is in direct competition with the so-called general-purpose rubbers—chiefly the styrene-butadiene co-polymers (SBR). In this usage, superiority is not clear and unquestioned, for each type of rubber has elements of superiority. NR has lower hysteresis and crack growth, superior performance at high temperatures, and a wider adaptability to changes in temperature. SBR has superior resistance to abrasion and is less affected by oils, oxidation, and ozonation. On the other hand, butyl rubber, though not considered a general-purpose rubber, has greater resistance to oxidation than either NR or SBR, and has the added important characteristic of being clearly superior in its ability to retain air. It has a higher hysteresis than either NR or SBR.

Use in Small Tyres. Smaller tyres, such as those used on most passenger motor-cars, are made with high proportions of SBR in the United States, and this usage may be expected to spread to other countries where the established use of NR has hitherto retarded the shift to synthetic rubber. This shift may be expected to take place both because of the superiority of the SBR treads and because of the impact of competition with tyres using low-cost SBR.

Use in Large Tyres. Tyres with a large cross-section, such as those used on aircraft, buses, trucks, and the larger passenger cars, must have resistance to the effects of flexing. The lower hysteresis of NR gives it an advantage in this usage. It is possible that in the future other types of rubbers, including the synthetic polyisoprene rubbers, may compete with natural rubber in this application. At the present time, however, no synthetic rubber can compete satisfactorily in the manufacture of large tyres, or of those designed to operate at low pressures that result in excessive flexing and heat build-up.

General-purpose v. *Special-purpose Rubbers*

Competition of the future may well be between the general-purpose rubbers, such as NR and SBR, and the speciality rubbers. Improved versatility of the general-purpose rubbers, and improved compounding techniques, may greatly reduce the field for rubbers suited only to limited application. Oil resistance, resistance to oxidation, and adaptability to changes in weather, can be increased or decreased by compounding and vulcanization techniques, and the field for specialized rubbers is already being narrowed. On the other hand, some of the speciality rubbers, such as neoprene, butyl, and the polyurethanes, are being compounded to have a degree of versatility that may place them in the general-purpose category.

It may well be that in the future (1970 or 1980) there will be a half-dozen general-purpose rubbers supplemented by a half-dozen speciality rubbers that, together, will cover the entire range of useful qualities for which elastic materials are needed. That will not come about, however, without the creation of new elastomers and a great increase in the number under commercial test and use. The speciality rubbers will find use in limited quantity to perform specific duties. The general-purpose rubbers will compete primarily on the basis of cost, consisting of relative production cost, compounding cost, and replacement cost.

Expanding European Usage of Synthetic Rubbers

A rapid shift is taking place from the long-established natural rubber to synthetics even in countries such as Great Britain that have enjoyed the profits of plantation rubber. *The Oil, Paint and Drug Reporter* (1958) states that A. J. Pickett, editor of *Rubber and Plastic Age*, reported that natural rubber is being replaced in many applications by a synthetic or a plastic, or by a combination of the two, and that this change is even more rapid in Europe than in the United States. Pickett mentioned particularly the flame-resistant conveyor belting used in mines. In Britain, after the terrible Cresswell colliery disaster in 1950, when eighty men lost their lives, the Government laid down a regulation that all new conveyor belts for the mines had to be made of flame-resistant PVC.*

In 1957, about 85 per cent of the belting in use in Britain in the mines was made of PVC, about 8,000 tons of PVC being used per year to replace somewhere around 7,000 tons of natural rubber. Pickett pointed out that in France and Germany, neoprene rubber is used in flame-resistant

* PVC is a plastic, polyvinyl chloride.

conveyor belting, and the natural rubber in hosing is being replaced by oil-resistant synthetic rubbers and by PVC. In cable insulation, one of the most important outlets for natural rubber in Europe in the past, synthetic rubber, PVC, and polyethylene, have almost entirely supplanted the natural product because of advantages in resistance to moisture, ageing, oils, and fire, as well as superior electrical properties. In recent years, considerable inroads have been made into the European foam-rubber market by flame-resistant neoprene and PVC, and by the polyurethane foams, which can also be rendered flame-resistant. Natural latex that is used in the manufacture of bonded fibre fabrics or non-woven textiles, may eventually be replaced by flame-resistant synthetic bonding agents—particularly where there is a fire hazard.

It has been noted that the physical and chemical characteristics of natural rubber can be altered materially by 'grafting' other chemical units onto the rubber molecule. It has also been possible to alter the character of the final product by blending natural rubber with various synthetic rubbers and plastics in compounding. The natural rubber–synthetic rubber–plastics relationship is complicated by the very considerable field of overlap covered by these rapidly-developing blending processes.

An important group here are the high-styrene-butadiene co-polymers used chiefly as a replacement for leather in shoe soleing. Rubber and polyethylene are used in blends. Butyl rubber is added in the ratio of about 5 per cent to cable coverings such as those used for transatlantic telephone cables. The European plastics industries have shown great interest in rigid rubber-modified resins as developed in the United States. High-polystyrene moulding powders are replacing conventional, clear polystyrene in many applications. Styrene-butadiene-acrylonitrile co-polymer blends have been adopted in Europe and are being manufactured in Germany.

Cost as the Prime Factor in Future Competition

There is already a recognition in plantation circles that future competition between natural and synthetic rubbers will be primarily on cost. The *Natural Rubber News* (1958) quotes H. T. Karsten, a director of the United Baltic Corporation and chairman and director of several other Malayan companies, who stated: 'So long as the price of natural rubber is above that of synthetic there is an inducement to the manufacturers to use synthetics.'

In spite of many arguments and extensive calculations, no one is able to place a valid over-all figure on the cost of raising natural rubber. A director of the Anglo-American Corporation was quoted in the early part of 1958 as believing that efficient large estates have operating costs as low as \$M 0·38 to \$M 0·40 * per lb. of RSS 1 (first-quality ribbed

* \$M = 0·33 \$U.S.

smoked sheet). He stated that at prices of \$M 0·60, or over, these estates made a satisfactory profit. Smaller and less efficient estates have costs of \$M 0·50 to \$M 0·60 per lb. and are the first to complain when prices drop. There is a feeling that a price of around \$M 0·75 gives a reasonable profit to producers of natural rubber and gives a satisfactory competitive position in relation to existing types of synthetic rubber. On the other hand, one of the major producers of natural rubber in another area is reported to be placing rubber in New York at an over-all cost of 9 U.S. cents a pound, which amounts to less than half the production cost estimated for the less efficient estates in Malaya.

Risdon & Fonseka (1957), in anticipation of a future estimated New York competitive price of \$U.S. 0·20 per lb., assume that Ceylon must be prepared for a future selling price of 85 cents * (Ceylon) per lb. Large estates must attain annual yields of 693 to 810 lb. of rubber per acre while smallholders, with low overheads, need annual yields of 529 lb. of rubber per acre, to meet this price. Assuming that 25 per cent of the 322,985 acres of estate rubber and 336,262 acres of smallholdings (*Rubber Statistical Bulletin*, May 1958) were out of tapping because of obsolescence or immaturity, reported yields of 79,660 and 18,504 long tons of rubber, respectively, represented 737 and 164 lb. of rubber per acre. The smallholder rate of 164 lb. of rubber per acre would be unprofitable even at 135 cents (Ceylon) according to Table 2 of Risdon & Fonseka.

Replanting with high-yielding clones may contribute more than any other single factor to reduction in the cost of producing natural rubber. A tapper can handle as many high-yielding trees as he can low-yielding trees. It is possible for an individual tapper to produce double the rubber now being obtained, with no increase in labour other than that involved in taking the additional weight of latex to the estate factory—and the provision of overhead trolley wires in Liberia has already pointed the way to solving this problem. The planting, care, and other features of plantation management are not increased. The plantation factory costs are related directly to the amount of latex handled, and would be increased in direct proportion to the increase in production. Increases in efficiency and higher-yielding plantations will undoubtedly be accompanied by increases in wages. The increased productivity of the individual workers when handling high-yielding trees could more than compensate for the increased labour costs.

The cost of producing general-purpose synthetic rubbers may also be decreased. Here, also, increasing wages may tend to offset technological improvement; but labour costs are not as important in factory operation as they are in plantation operation. Tapping a rubber tree is a hand operation: there is no milking machine for trees!

* \$Ceylon (Rupee) = 0·21 \$U.S.

Expansion of Production Facilities to Meet Increased Consumption

The ability to expand sources of supply to meet increasing demand is a controlling factor in any major increase in consumption. Before the development of synthetic rubbers, expansion in the consumption of rubber was first dependent on intensified exploitation of wild sources of rubber—a relatively expensive operation—and then, later, on the relatively slow expansion of plantation production. Great elasticity in the demand for rubber, and relatively little elasticity in the sources of rubber, led to high prices when demand was high, and to a considerable time-lag in the reflection of high prices in increased production. Sustained demand led to an enormous expansion of the rubber plantations during the first three decades of this century.

Now that acceptable grades of synthetic rubber can be produced by standardized processes, increases in production can be made as rapidly as the capital expenditures can be justified, authorized, and translated into factories and facilities—a much shorter period than is required to transform a seed into a mature, rubber-producing tree. A single year of commercial and industrial development may equal half a decade of agricultural activities in the development of rubber-producing facilities. This, more than any other factor, will determine the proportion of natural and synthetic rubbers used in the manufacture of commercial products in 1980, for example.

Expansion of Plantations

A multifold increase in synthetic rubber production in line with a continuing increase in the rate of rubber consumption, does not appear nearly so difficult of attainment as a doubling in natural rubber production. The *Rubber Statistical Bulletin* of the International Study Group for February 1958, estimates the total acreage of plantation rubber throughout the world as 11,210,000 acres. World production of natural rubber in 1957 is estimated at 1,892,500 long tons, or an average of only 378 lb. of rubber per acre for the entire planted area. There is now a large acreage of clonal rubber with comparatively high yield, but the predominant acreage of rubber trees consists of unselected seedlings with mean yields below that quoted as the over-all average. There are, of course, considerable acreages that have been replanted and that have not come into full bearing. If rubber plantations are to continue on a sound, healthy programme of expansion, all future estimates of production will need to make allowance for high proportions of immature trees. The existing acreage may be expected to yield more rubber as the young trees come into full bearing. On the other hand, increasing yield of the maturing areas may be somewhat counterbalanced by decreased production of obsolescent plantings and areas taken out of production for replanting. Risdon &

Fonseka (1957) assume that at any one time some 25 per cent of the planted acreage will be out of tap because of immaturity, or will be yielding at an uneconomic rate.

Expansion of Production Facilities for Synthetic Rubber

The expansion of facilities for the manufacture of synthetic rubber is going forward much more rapidly than the expansion of plantations. Announcements have been made of the construction, or plans for the construction, of new factories for the production of synthetic rubber in France, Great Britain, Holland, Italy, Northern Ireland, Russia, Scotland, and West Germany. Each of the new factories will have an annual capacity of from 5,000 tons to 60,000 tons of rubber. They include chiefly SBR types of rubber, but also butyl, buna, perbunan, neoprene, and other speciality types.

In Russia, it has been stated that synthetic rubber is now being produced in factories in seventeen different places, and that by 1960 the total capacity for producing synthetic rubber will reach a level of 800,000 to 850,000 long tons per annum. It is clear that the capacity of the world to produce synthetic rubber is being expanded rapidly, and this rate of expansion may be expected to continue as long as there is prospect that consumption increases will continue at a rate comparable with those now being experienced.

New facilities now being developed are predominantly for the production of general-purpose rubbers, for which there is a good assurance of continued demand for a sufficient period to amortize the cost of the facilities. Individual types of general-purpose rubber are subject to severe competition not only from natural rubber, but also from new synthetic rubbers that are under experimental test or that will be found in the future. The demand for the speciality rubbers is much more difficult to predict, and the future competition among them may be even more intense.

Research Facilities

Science in Industrial Development

Usage of rubber has doubled and redoubled during the first half of the twentieth century because of the economic and industrial progress of the world. Rubber has fitted into this economic expansion because of the speculative urge that has circulated throughout the world—to develop and increase the sources of natural rubber, to supply machinery and equipment for the manufacture of synthetic rubber, and to utilize the natural and synthetic rubbers in the fabrication of articles adjusted to the advancing technology.

While the profit motive has been largely responsible for this phenomenal expansion, it alone, even though accompanied by the utmost in energy, could not have succeeded without the use of vast resources of scientific skill and concentrated research effort. The rubber industry, from plantation through to finished goods, is a monument to the union of commercial, industrial, technical, and scientific efforts. The future of the industry may well be determined by how well these skills are combined and utilized in the coming years. There is no saturation point in sight in the usage of rubber. Each new invention and advance in technology has increased rather than decreased the need for rubber. Limitation in the expansion of its usage can come only through the failure of technical and research effort to develop properties to meet each new demand, or of the rubber industry to increase sources of supply to meet the increased demand.

Science in Plantation Development

Merely planting greater acreages of rubber trees, or constructing more factories for the production of synthetic rubber, is not the answer to fulfilling increased demand in the future. Greater yields are possible from existing plantings through the improvement of tree response—by nutrients, bark stimulants, and improved tapping sequences. The majority of the trees on existing plantations are unselected 'seedlings' with poor growth characteristics and inferior yield. Improved seedling and clonal selections are available for use in planting new areas, or for replanting existing areas. This planting material is not universally adaptable and, for best results, must be selected and proven for particular conditions. Variations in soil, rainfall, temperature, and disease, control the selection of new clones or seed stocks. It is probable that the best of the present clones will be superseded by new clones with greatly superior yield, better bark characteristics, and higher levels of resistance to the known diseases.

There is, at present, a greater limitation in human populations capable of caring for rubber trees than there is in land capable of nurturing rubber plantations. While tropical areas suited to the cultivation of rubber are not unlimited, the human resources are relatively much more limited. Major increases in rubber production on plantations must come, to a great degree, by increasing the output of the human elements through increased yields—so that each individual can produce hundreds of pounds of rubber instead of tens.

The character of the plantation product must be improved to keep pace with carefully prepared chemical rubbers. Extraneous impurities must be rigidly excluded and the character of the rubber hydrocarbon itself improved, or altered, in any suitable manner to meet new demands or improved characteristics of competing products.

The Scientific Knowledge of Rubber

Merely doubling the production of present grades and types of synthetic rubber will not maintain a maximum rate of expansion in the future use of chemical rubbers. There are already too many synthetic rubbers, and many more will be created and tested before radical weeding out will be forced on the industry—to eliminate those with such limited usefulness that they can no longer be produced economically, even for highly specialized usage, if a rubber with greater adaptability can be substituted.

The future of rubber production, both natural and synthetic, depends to a great degree on the scientific effort put into fundamental research on what rubber is, and on the chemical and physical factors that constitute elasticity. There must be production research of an increasingly high quality and scope, geared both to advancing fundamental research and to industrial technology. Knowledge is needed, among other things, on the biosynthesis of natural rubber, on its structure, on the relationship of structure to physical properties, and on how the structure can be improved either before or after tapping. The relationship between natural and synthetic polymers and their chemical structures needs to be determined. The changes brought about by vulcanization are only imperfectly known, as are the basic factors in compounding. The precise comparison of natural and synthetic rubbers will only become possible as knowledge is gained—not only of the structural changes in the rubber molecule during vulcanization and ageing, but also of the basic relationship of the rubber and non-rubber constituents of the mix.

Plantation Research

Natural Rubber News (1958*a*) reports a radio press statement by S. N. King, retiring Chairman of the Rubber Producers Council of Malaya, on 27 February 1958. King, in conjunction with a valuable summary of the present status of the plantation rubber industry, states:

> There is, I believe, a need for some clear thinking on research. Comparisons are made between the amounts spent on research, on synthetic and on natural rubbers. It should be remembered that the aim of synthetic research is to produce something like natural rubber from any of an infinite number of ingredients; we already have what they are trying to make and so our field of research is much narrower.

This attitude is not unique and represents a great weakness of many leaders of the rubber plantation industry who fail to understand the advances that have been made in rubber synthesis. The conclusion is not justified as, in general, research on synthetic rubber is directed not towards reproducing or simulating natural rubber, but towards producing materials superior to natural rubber. While the versatility of natural rubber has not yet been matched, synthetic rubbers now have superior qualities in the way of oil-resistance, resistance to oxidation, and non-flammability, that may result in a permanent preference for synthetics in the future—if more fundamental research is not put into improving the quality of natural rubber in those important characteristics. Market grades of natural rubber are greatly inferior in purity and cleanliness to competing grades of synthetic rubber.

Few tropical crops have better or more adequate research guidance than the rubber plantation industry. A source of great strength, but at the same time a major source of weakness in the research set-up, is the fact that support and control are largely in the hands of 'practical' planters who provide space for many of the experiments and take enthusiastic interest in applying the results of current research. Their support and assistance in the testing work stretch the available funds and make possible the quick application of research findings. Their interest is instrumental in assuring adequate financial support to keep the research work going, and their active collaboration keeps the research workers in touch with the problems of the planters.

A difficulty of the active, interested support of practical planters is that immediate aims are emphasized to the exclusion of fundamental studies that are not directly related to current problems. This is chronic in agricultural research in many lands and is certainly not confined to the rubber industry. On the other hand, the future of the rubber plantation industry may depend, in large measure, on the degree to which producers of natural rubber are able to meet the threat of synthetic competition by the production of new, superior types of natural rubber. Future costs of production may depend on having and utilizing fundamental knowledge of the physiology of the tree, including the chemical and physical processes involved within the latex system in the transformation of precursors into rubber, in the formation of the precursors of rubber, and in the translocation of those precursors to the seat of rubber synthesis.

These answers are not to be obtained merely by studying the nutrition of the plant, or even through the detailed study of tapping methods. Fundamental studies are needed on the living processes within the plant, on how and why rubber is formed, and on the physiological nature of the response to tapping and stimulation, and of resistance to disease. Such studies may not lead to immediate increases in yield or decreases in cost. They may require years of costly research without significant gain in plantation techniques. But they are important in the long-range increase in rubber production. Neglect of them may represent the Achilles' heel of natural rubber. Comparable fundamental research in high-polymer chemistry is under way in many countries and assures the future of synthetic rubber.

In the producing areas of the East, research institutions of a high order of competence are maintained in Ceylon, Malaya, Indonesia, and Viet-Nam. Each of the institutions maintains publication facilities, both for technical articles and for farmers' informational leaflets. They are active in expansion work and are strong in local farm leadership. They are active in developing and testing new clones, in improving tapping methods, in the study of cover and catch-crops, in plantation management, in plantation sanitation, including the control of pests, weeds, and diseases, and in methods of improving the quality of plantation rubber. These institutions have attracted and utilized the services of outstanding men—B. J. Eaton, O. de Vries, W. Bobilioff, P. J. S. Cramer, N. L. Swart, A. A. L. Rutgers, T. Petch, and A. Steinmann—just to name a few at random, and even at the cost of leaving out many whose contributions have been equally great. The institutions are manned today by outstanding scientists, who are adding to the knowledge and improving the practices of rubber production.

Ceylon. The Rubber Research Institute of Ceylon (RRIC) is located at Dartonfield Estate, Agalawatta, and is supported primarily by an export tax on rubber. *Oidium* leaf disease has been a controlling factor in the work of the Institute, and the effective control of that disease represents an outstanding contribution of the Institute. During World War II, Ceylon was a major continuing source of free-world natural rubber and the Institute took the lead in developing tapping systems designed to obtain a maximum yield of latex. The Institute is also active in research on manuring, on the use of cover-crops, and on the preparation of rubber, and it has an active smallholder advisory service.

The research findings of the Institute are published in annual reports, quarterly circulars, and occasional bulletins. In addition to these, advisory circulars are issued to keep local planters informed regarding recommended practices in the cultivation, tapping, and preparation of rubber. The Rubber Research Institute of Ceylon has interchanged high-yielding clones with the Rubber Research Institute of Malaya and other research groups in the East, and has organized a new breeding programme to combine not only the best qualities of the Eastern clones, but also to utilize the breeding material that has been developed in the Western Hemisphere. This material includes not only the clones imported by the Rubber Research Institute of Malaya, but also new clones and breeding materials that were not in the original exchange.

Indonesia. Rubber research is strongly entrenched in Indonesia, where the General Organization of Planters in East Sumatra (AVROS) and the Foundation Indonesian Rubber Research Institute (INIRO) both conduct agricultural and processing research that looks towards the improvement of rubber-production techniques and the production of high-quality rubber in Indonesia. This Institute has been co-operating actively on problems connected with the production of classified rubber, has taken part in interchanges of high-yielding clones, and is conducting fundamental studies on the constituents of latex.

Through the Central Association of Experimental Stations (CPV) in Djakarta-Kota, the *Archives of Rubber Cultivation* is published as a record of the research on rubber in Indonesia. This publication succeeded and continued the work of the *Archief voor de Rubbercultuur in Nederlandsch-Indie*—a series which was started in 1917 and represents the most valuable existing contribution to rubber cultivation. Through its pages, one may obtain acquaintance with the research that has been the scientific basis for the plantation industry as it exists today—not only in Indonesia but wherever plantation rubber is produced.

Malaya. The Rubber Research Institute of Malaya (RRIM) is located at Kuala Lumpur and is supported mainly by an export tax on rubber. An outstanding contribution from recent work of this Institute has been the development of the RRIM 500 and 600 series of new clones. These clones have resulted from breeding operations and detailed growth and tapping tests at the station and on plantations of co-operating planters. This Institute has also taken the lead in an interchange of Eastern high-yielding clones for disease-resistant clones developed in the Western Hemisphere. This interchange of clones with the West has also led to an interchange of superior clones with other research institutions of the East, and to the development of comprehensive breeding programmes that may be expected to result in the development of hardier, healthier, and higher-yielding clones or hybrid types that can be grown as 'seedlings'. The Rubber Research Institute of Malaya has developed Superior Processing Rubber and has taken a lead in the production of Classified Rubber. It is outstanding in its research on cultivation techniques, disease control, tapping methods, yield increase by means of growth stimulation by fertilization or by stimulating bark activity chemically, and also in its close co-operation with growers to translate research findings into planting techniques.

In addition to technical articles that appear in the *Journal of the Rubber Research Institute of Malaya*, the Institute issues advisory information in the *Planters' Bulletin*. According to *Natural Rubber News* (1958*b*), RRIM has recently established a smallholders' college in Negri Sembilan, where a one-month extension course is offered to show smallholders the best methods of planting rubber and of selecting planting material. The one-month course costs the smallholder $M 50·00 (about $U.S. 16·70) and has proved so popular that other centres are planned elsewhere.

Viet-Nam. The Institut des Recherches sur le Caoutchouc en Viet-Nam is located at Saigon and is active in all phases of plantation-rubber production research. An outstanding contribution of this Institute was in leading the development of classified rubber. The original classifications suggested by this Institute were accepted and used by the other institutes and organizations involved in the production and sale of classified rubber.

This Institute has been active in studying the physiology of rubber formation and has contributed to the knowledge of latex-flow stimulation —both by means of hormones and bark treatments, and by adjustment of tapping schedules to provide periodic intensified tapping.

Its findings are published in annual reports, technical bulletins, and miscellaneous bulletins. It issues planters' advisory leaflets and is active in extension activities both with estates and amony smallholders.

The Institute is conducting an active breeding programme, and has interchanged clones with RRIM—getting not only the best of the RRIM clones but also of those from the West that are being used primarily to obtain disease resistance. Tests are under way on plant improvement through vegetative selection and also sexual propagation and selection. Methods of making yield tests at an early age are being studied, to facilitate the identification of potential high yielders for immediate use in the breeding programme—without the necessity of having to wait some five to ten years for adequate evaluation by tapping.

Synthetic Rubber Research

The creation and development of new synthetic rubbers have been largely in the hands of industrial corporations. During World War II, all facilities for research on synthetic rubber in the United States were pooled under the direction of the Government. After the end of the war, the synthetic rubber factories were sold to industry, and competitive research soon took over to replace that formerly conducted by the Government.

Research in the field of synthetic rubber is divisible roughly into three fields, namely, the search for new polymers, the development of production facilities, and the study and testing of compounding, vulcanization, and fabrication techniques. Government laboratories in England, France, and the United States, contribute to the comparative testing of the new rubbers —particularly in the development of rubber specifications such as those for the Armed Services in the United States, which are handled by the Bureau of Ships or the Army Ordnance Laboratory. The National Bureau of Standards of the United States Department of Commerce is a leading institution for the scientific testing of rubbers and rubber compounds of all types, as part of its basic responsibility for developing specifications for the use of the United States Government.

High-polymer Research

The basic study of natural and synthetic rubber with respect to chemical structure and structural changes lies in the comparatively new field of high-polymer chemistry. All developments of new synthetic rubbers involve the use of some of the principles of high-polymer chemistry, and this science is used extensively in the research laboratories of the large rubber and industrial companies interested in rubber synthesis. Fundamental research in this field, however, is done chiefly in universities in the United States and Europe. In Russia, such studies are conducted primarily at the Institute for Macromolecular Compounds in Leningrad and at the Institute for Element-Organic Compounds in Moscow. The

United States Government encourages fundamental studies on high polymers by grants through the National Science Foundation.

These studies on the fundamental character of elastic polymers involve both natural and synthetic rubber, and seek to determine the basic nature of elasticity and how polymeric materials can be constructed to impart the desirable characteristics. Some of the studies involve the mechanics of vulcanization and the role of the non-rubber constituents of the compound, as well as the structural changes that take place in the rubber.

Interchange of Information

The capacity of an industry to grow can also be measured by the number and quality of its facilities for the interchange of information. The rubber industry is represented by outstanding trade and scientific journals.

Trade journals include *Rubber Age*, New York, monthly; *Rubber and Plastics Age*, London, monthly; *Rubber Journal*, London, weekly; and *Rubber World*, New York, monthly. The *Revue Générale du Caoutchouc*, Paris (monthly), is the official organ of the associated rubber research institutes of France and Viet-Nam. Scientific journals devoted solely to rubber include *Rubber Chemistry and Technology*, Lancaster, Pa., issued quarterly by the Division of Rubber Chemistry of the American Chemical Society; *Rubber Formulary*, Bakersfield, California, monthly; and *Transactions of the Institution of the Rubber Industry* and *Proceedings of the Institution of the Rubber Industry*, London, bound together, and published every two months. The Institution of the Rubber Industry also issues an annual *Report on the Progress of Rubber Technology*, and the Division of Rubber Chemistry of the American Chemical Society is preparing a comprehensive bibliography on rubber that is now complete through 1951.

Several of the rubber and chemical companies issue periodicals of considerable merit covering their own products. The Malayan rubber producers maintain a Natural Rubber Bureau in Washington that issues *Natural Rubber News* monthly.

In addition to the official statistics included in the governmental summaries issued by various countries, the producing and consuming countries of the world have organized an International Rubber Study Group which issues the comprehensive *Rubber Statistical Bulletin*, London, monthly. *World's Rubber Position*, London (monthly), has been a leading source of rubber statistics for many years.

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* The addition of the publishing authority or authorities to a Latin name in this Index indicates that the plant concerned is a rubber-bearing one.—Ed.

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AUTHOR INDEX

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Edited by

Professor Nicholas Polunin,

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