Electron Beam Vulcanization of Elastomers*

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1 Introduction

Vulcanization of elastomers through electron beam (EB) processing is accomplished at high throughput rates without the application of heat. It is also achieved instantaneously when preformed elastomeric products are exposed to high energy electrons.

Continuous on-line EB vulcanization processes are designed to treat rubber products at production throughput rates. The electron processing system can be located in a production facility so that rubber sheet automatically enters the EB vulcanization chamber after forming and is instantaneously vulcanized as it passes under the beam and is then wound into fully cured rolls.

This automated process provides several distinct advantages over conventional high temperature vulcanization processes. Handling of weak uncured sheet is eliminated since the rubber sheet is completely vulcanized after forming. The uncured sheet is never rolled upon itself and talcing is not necessary. A reproducible homogeneous cure is achieved with electron energy; the inconsistencies in curing due to time/temperature variances which occur when large rolls are vulcanized by conventional methods are eliminated. Materials with strict tolerances on thickness specifications can be produced with electron treatment since thin spots associated with high temperature curing of rolled sheet rubber are not formed. Labor costs are reduced since several intermediate processing steps involving transport of the large rolls from the production area to the vulcanization area are eliminated. The total time needed to produce and cure a roll is reduced to slightly more than the time required to produce the roll. One operator can oversee the entire EB process.

An understanding of these advantages is best obtained by outlining the crosslinking mechanisms and compounding materials for electron vulcanization, the hardware and physics principles of electron acceleration, the industrial applications areas and economics of electron vulcanization. The following sections deal with these topics.

2 Mechanism of electron vulcanization

Crosslinking reactions initiated by electrons in elastomers proceed via free radicals or by means of transient ionic species. The ionic contribution to crosslinking is considered to be less significant than the free radical contribution. *A. Charlesby* attributes this to several factors [1]:

> "Crosslinking can occur readily in dilute aqueous solutions where there is little likelihood that two polymer ion molecules will be in the correct position for linking during the short life of the ion.
>
> Polymer radicals can be observed in irradiated solid polymer in concentrations comparable with the eventual crosslinking density.
>
> The presence of radical scavengers can greatly reduce the density of crosslinking."

Thus, the most thoroughly studied and widely accepted mechanism for electron crosslinking is through the formation and combination of free radicals. Polymer free radicals are generated when electrons transfer their energy to yield an excitation-ionization step which is followed by the formation of a polymer radical and a hydrogen atom.

Polymer radicals on adjacent chains can combine to form carbon-carbon bonds or a free radical can attack a double bond in an adjacent polymer chain. This results in the generation of a crosslink and the regeneration of a free radical. The reaction involving two polymeric free radicals occurs in saturated polymers as well as in many of the elastomers containing unsaturation [2].

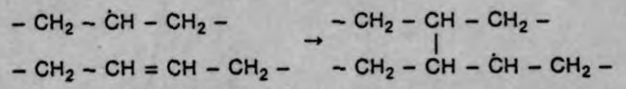
Reaction 1

$\dot{R}1 + \dot{R}2 \rightarrow R1\,R2$

Where R represents polymer chain segments.

Unsaturated elastomers may undergo crosslinking by a reaction which corresponds to the propagation step in polymerization processes as shown in Reaction 2.

Reaction 2



$$\begin{matrix} -CH_2-\dot{C}H-CH_2- \\ -CH_2-CH=CH-CH_2- \end{matrix} \rightarrow \begin{matrix} -CH_2-CH-CH_2- \\ \quad\quad\;\; | \\ -CH_2-CH-\dot{C}H-CH_2- \end{matrix}$$

The type of carbon-carbon crosslinks which are formed are the same as would be expected with a peroxide cure, since the same generation and combination of free radicals occurs in both processes. However, the crosslinks are not the same as the carbon-sulfur linkages which are formed during sulfur vulcanization.

Comparative studies have found that electron cured rubbers exhibit better thermal stability owing to the absence of sulfur crosslinks and catalyst residues [2]. Abrasion resistance, compression set and oil swell properties are also improved. In general, properties resulting from electron curing are remarkably similar to those of peroxide cured elastomers, and this is attributed to the predicted molecular link structure. On the other hand, the high physical strength properties observed in sulfur-vulcanized rubbers arise from the ability of crosslinks to break and reform with another chain branch under strain, a process which is neither anticipated to occur, nor has been observed for carbon-carbon crosslinks. Studies done in the late 50's and early 60's indicate that improvements in thermal stability were not accompanied by an increase in physical strength of dynamic properties. Recent publications and data provided in this paper report physical strength values in electron cured rubbers comparable to those obtained by sulfur vulcanization, casting doubt on the earlier postulation of the slipping process of polysulfide crosslinks.

Crosslinking and degradation more often than not occur simultaneously during electron vulcanization of polymers. The ultimate effect on a polymer is determined by the predominance of one of these two reactions. Most polymers have now been classified by this criteria as those which undergo crosslinking and those which undergo degradation. Interestingly, the crosslinking reaction predominates in all but a few elastomers. The elastomers which fall into the crosslinkable group are shown in *Table 1*. Not included are butyl rubber and the totally halogen substituted fluoroelastomers which undergo degradation when exposed to electron beam treatment.

Table 1. **Elastomers which can be EB crosslinked**

Butadiene rubber
Chlorinated polyethylene
Chloroprene rubber
Chlorosulfonated polyethylene
Ethylene-propylene copolymer
Ethylene-propylene-diene terpolymer
Fluoroelastomers
Halobutyl rubber
Natural rubber
Polyethylene
Silicone rubber
Styrene-butadiene rubber
Thermoplastic elastomers

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The incorporation of additives which enhance electron crosslinking (*Table 2*) can reduce the time required to achieve a full cure; this improves processing efficiency by increasing throughput rates and lowering processing costs. The promotion of crosslinking with additives optimizes electron crosslinking in elastomers and blends. Properties of electron crosslinked elastomers compare to those of elastomers which have been crosslinked by conventional vulcanization processes. Enhanced crosslinking may be accomplished through the use of two major types of additives which produce different results in the molecular structure of the vulcanized rubber.

Table 2. Additives which enhance EB crosslinkability of elastomers

Allylacrylate
Chlorobenzene
Ethylene glycol dimethacrylate
N', N'-hexamethylene-bis-methacrylamide
Multifunctional monomeric esters
Neopentyl chloride
Nitrous oxide
Tetravinylsilane
Triallyl cyanurate
Triallyl isocyanurate
Trimethylol propane trimethacrylate

The first type of additive consists of catalyst-type promoters which do not enter directly into the crosslinking reaction but act to enhance the production of reactive species, such as free radicals which then lead to the formation of crosslinks. Indirect crosslink promoters which have been studied include among others: halides, nitrous oxide, and sulfur monochloride. The presence of indirect crosslink promoters effectively increases the G value, defined as the number of chemical events occurring for every 100 electron volts of energy absorbed by the material being treated. G values typically range from 1 – 3 in elastomers but they can be greatly increased when an appropriate additive is present.

The second type of additive consists of crosslink promoters which enter directly into the crosslinking reaction and become the molecular link between two polymer chains. Direct crosslink promoters include maleimides, thiols, acrylic and allylic compounds. Acrylates have been found to be more reactive than allylics. The amount of additive which is required to minimize the curing time is usually not more than 5 – 10 % by weight of the rubber.

A recent review article by *Bohm* and *Tveekrem* discusses the mechanisms and effectiveness of crosslink promoters [3].

3 Principles of electron treatment

Accelerated electrons are a form of energy, as is heat. But accelerated electrons are electrical energy, representing kilowatts of power rather than Btu's[1] or calories associated with thermal energy.

The hardware associated with accelerated electrons for industrial applications consists of four major equipment pieces:

1. A high voltage power supply which generates DC power to create the acceleration potential for the electrons;
2. An electron accelerator where the electrons are emitted and accelerated to their potential energy;
3. A scanning system which uniformly distributes the accelerated beam of electrons over an area dictated by the product dimensions;
4. An automated process controller which ties in all production variables for synchronous operation of the line.

An electron vulcanization application requires evaluation of the three major variables available with electron beam processing. These are: power, dose and utilization efficiency. Simplified definitions of each provide an understanding of the processing capabilities of electron vulcanization [4].

For electrical energy, power is the product of voltage and current. Electron processing systems (EPS) have a rated voltage (normally in kV) and a rated current (normally in mA); the resulting power is given in kW. It is the power available from an EPS which will dictate its maximum production capacity. Next, the depth to which accelerated electrons can penetrate material is a function of their accelerated voltage potential. Industrial electron processing systems for most vulcanization applications are available with voltages ranging from 300 – 4000 kV. Penetration capability is inversely proportional to specific gravity. Electrons accelerated within the range of 300 – 4000 kV have the capability of penetrating from 0,38 – 12,7 mm in materials of specific gravity equal to 1,0, but thicknesses from 0,30 – 1,07 mm when the specific gravity of the material is equal to 1,2. These penetration values allow for consistent cure on top and bottom surfaces of a sheet product when passed through the electron treatment station once. *Figure 1* shows this relationship between voltage rating and useful depth of penetration. The other half of the power equation – current – is normally referred to as beam current. This is the number of electrons being made available by the EPS for vulcanization. Since the voltage of the EPS defines the sheet thickness to be processed, the beam current defines the number of electrons per unit time, and is directly proportional to production throughput. The higher the beam current of the EPS, the higher the potential production rate of the system.

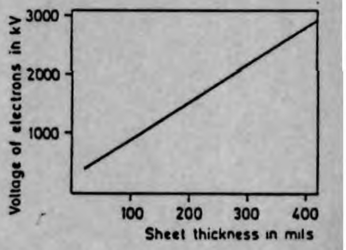

Figure 1. 60 % exit point of electrons in unit density material (100 mils = 2,54 mm)

The second variable of electron processing is dose. Dose is the amount of energy absorbed per unit mass of material (such as erg/g or Ws/g). In the simplest sense, with known electron voltage and beam current, dose becomes a function of the dwell time of the product under the EB. Thus, the process speed for vulcanization of a product is inversely proportional to the dose required for vulcanization of the given material. Maximum process speeds for an EPS are achieved at the lowest dose requirements. This explains why much emphasis has been placed on identifying additives which enhance electron vulcanization and enable a reduction in the dose required to achieve full cure. The common term for dose in electron processing is the megarad (Mrad), defined as the absorption of 100 erg/g (or 10 μJ/g or 10 μWs/g, respectively) of material. Vulcanization doses typically fall into the range of 5 – 25 Mrad. To indicate the dwell time magnitudes fo electron processing, a single EPS station can fully vulcanize 1 m^2 of sheet in 2 s at 5 Mrad or 10 s at 25 Mrad (1 ft^2 in 0,2 s at 5 Mrad or 1 s at 25 Mrad).

An accelerated electron gives up its energy as it strikes matter but at varying rates as its energy is absorbed in matter. This effect of those varying rates can be predicted by plotting the dose absorbed (percent relative ionization) at different depths in the material versus product thickness. These curves (commonly referred to as "depth-dose curves") indicate that cure within the sheet will be greater than on the top or bottom surfaces. *Figure 2* shows depth-dose curves for electrons at different potential voltages. Any value of dose for a given application can be substituted for percent relative ionization. For example, an application which requires that a minimum of 5 Mrad be received throughout a 3,05 mm sheet will receive 5 Mrad (60 %) on the top side, 8,3 Mrad (100 %) at a depth of 0,18 mm and 5 Mrad (60 %) on the bottom side.

The third variable of electron processing is utilization efficiency. Since the kilowatts of power available from an EPS dictate its maximum potential production capacity, the efficiency with which this power is intercepted and absorbed will dictate the realized production rate. For example, an EB is conservatively scanned across the

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[1] Btu or BTU = British Thermal Unit; 1 BTU = 1,056 kJ.

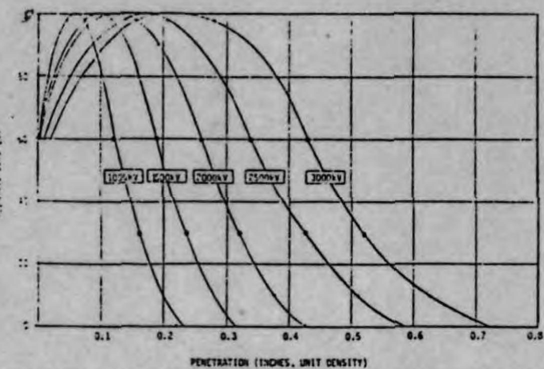

Figure 2. Depth-dose curves, 1000 – 3000 kV (0,1 inch = 2,54 mm)

product width using about a 10 % overscan on the sides of the product to ensure full coverage including tracking tolerances of the product handling system. Scan sizes are available from a few inches up to 10 ft (3,05 m) to enhance utilization efficiency for specific product widths. When the required dose is delivered to the bottom of the sheet, the remaining electron energy (the tail of the depth-dose curve) is lost. Thus, the total utilization efficiency for sheet products typically ranges from 65 – 90 % of the power capacity at 100 % efficiency depending on the process parameters and geometry of an individual application. For reference, the power capacity at 100 % efficiency is 360 Mrad kg/kWh (795 Mrad-lbs/hr-kW).

4 Applications

Many different types of elastomers, blends and thermoplastics have been compounded and crosslinked with EB treatment such as those used in tire components, electrical insulations and rubber sheeting.

By programming electron precure into selective tire components and tire fabrication processes, *Goodyear* is able to lower the cost of manufacturing steps and produce a product with superior performance [5]. Goodyear first installed radiation sources to evaluate and explore crosslinking applications in 1957. Today, Goodyear continues to lead the rubber industry with installed EB equipment treating hundreds of millions of pounds of products per year. In the tire industry, EB treatment is used to partially crosslink or precure tire components prior to tire assembly and final vulcanization in a mold. Precuring improves the green strength of the components and permits tire manufacturers to significantly reduce the conflicts which inherently exist between tire performance and tire manufacture.

EB precure produces tire components with greatly improved form stability which allows the retention of their shape during assembly, molding and vulcanization. This is especially important in the manufacture of radial tires where dimensional tolerances are very rigid and critical.

With electron precure, a greater proportion of synthetic rubber can be used in place of NR without a loss in strength. Also, fewer off-spec tires are produced since the increased green strength of the precured components during molding and vulcanization prevents cord slippage, thus minimizing rejects and loss of raw materials. Since the components have more form stability, thinner gauges can be used and raw materials savings are achieved. Automated machinery can be used to wrap plys around the drum when tires are being constructed.

During the past several years, the *Firestone Tire and Rubber Company* has conducted an extensive research program designed to identify possible applications of electron crosslinking in the manufacture of rubber products, generally, and tires, specifically [6]. Tire components including innerliners, chafer strips, white sidewalls, veneer strips and body and tread ply skims or skim coats have been evaluated. Results from this research provide useful information on electron crosslinking of these various tire components and the elastomers which are used in them, as summarized in the following:

1. Innerliner stock formulated from a blend of butyl rubber, SBR, NR and tire reclaim shows improved physical properties in green strength and recovery. Therefore, better retention of innerliner gauge can be maintained during construction and vulcanization when precured innerliners are used thus eliminating the practice of using an overly thick innerliner.

2. The green strength of chafer strips formulated from a blend of NR and SBR can be improved by electron precure to the extent that cord reinforcement of the strip is not required.

3. Precured white sidewalls formulated from a blend of NR, SBR and EPDM have increased green strength and recovery. The precured sidewalls offer more resistance to the migration of staining materials such as oil, antioxidants and other discoloring materials from the surrounding black portions of the tire. The tendency toward discoloration of the sidewall is reduced.

Tables 3 and 4 contain data from the Firestone work and indicate the change in green strength and recovery which is achieved by increasing the precure dose [6].

Table 3. Green strength (peak in kg) as a function of dose [6]

Dose in Mrad	0	5	10	15	20
1. Innerliner	1,4	6,9	9,1	10,4	15,3
2. Chafer Strip	10,3	15,9	19,1	23,6	26,4
3. White Sidewall	3,7	8,0	9,1	9,6	–

Table 4. Percent recovery as a function of dose

Dose in Mrad	0	5	10	15
1. Innerliner	3,6	14,3	19,3	36,3
2. Chafer Strip	4,1	17,7	21,8	24,5
3. White Sidewall	4,5	16,1	51,5	49,9

Butyl rubber is typically cited as the prime example of an elastomer which has not been successfully crosslinked with electrons. *Mohammed* et al. have evaluated EB crosslinking of halobutyl compounds for application as innerliners for radial tires in order to impart high green strength to the component and maintain other desirable physical properties which are exhibited by 100 % halobutyl compounds [7, 8]. They found green strength improvement was achieved at low doses in compounds based on 100 % brominated butyl rubber. However, fatigue resistance, adhesion and stress-strain properties were essentially unaffected by electron induced green strength improvement. Blends of chlorinated butyl and NR and also brominated butyl and regular butyl showed enhanced green strength after electron treatment but losses were observed in fatigue resistance, tensile strength and modulus. Later work indicates that differences in behaviour of electron treated bromobutyl and chlorobutyl rubber may be attributed to differences in the degree of halogenation.

Patented work done in electron precure of tire components also identifies several other processing advantages. One such process development relates to the elimination of an airbag or bladder in the curing process. This has been accomplished when the inner surface of a green tire, provided with an airsealing liner, is cured or partially cured with electrons. A steam and water resistant surface is also claimed to be produced [9].

Electron treatment within the tire industry has been developed to the extent that this precure technique can readily be transmitted to other rubber assembly operations if greater form stability can contribute to the efficiency of a production assembly and/or final cure process.

Another application area which is highly developed is the production of quality crosslinked electrical insulations using EB processing. EB crosslinking is widely accepted in the wire and cable industry because it offers producers several advantages over conventional crosslinking methods. These advantages include reproducibility of physical and electrical properties, faster processing rates, minimum insulation wall to meet voltage specifications, reduction in start-up scrap, and up to an 80 % reduction in energy costs. Insulated wire sizes from AWG # 40 (American Wire Gauge) to cables in the MCM (thousands circular mils) range are being treated (0,005 mm^2 to several hundred mm^2).

CPE, CSPE, polyethylene, EPDM, fluoropolymers and modified elastomers are routinely crosslinked with electrons in commercial insulation processes. Silicone rubber crosslinks readily when exposed to an EB. A recent U.S. patent provides a process which imparts green strength to uncured silicone rubber through a transient cure step so that this characteristically weak rubber can be handled for vulcanization under an EB [10]. Prescribed compounding involves the use of an hydroxyl terminated polysiloxane with an end-stopped silicone rubber polymer and fumed silica filler. EB crosslinked silicone rubber exhibits superior heat aging characteristics and excellent resistance to solvents and fuels [11].

In addition to insulated conductors, heat-shrinkable insulations of many elastomers and thermoplastics are manufactured with electron treatment. This is accomplished by EB crosslinking a preformed product, elastically distorting or expanding the preformed product at an elevated temperature and quenching the product in the expanded state. The product is then applied as desired and is subsequently heated. Heating causes the product to return to its pre-expanded crosslinked dimension. Products thus manufactured include tubing, tape and end caps. Heat shrinkable components provide skin tight mechanical and electrical protective coverings for a variety of electronic, electrical, electro-mechanical and mechanical uses. Applications for heat-shrinkable tubings, tapes and end caps include harnessing, encapsulation, splicing, component covering and protection and terminal insulation. Heat-shrinkable tubing manufactured using EB processing has improved intrinsic properties including wide operating temperature range; abrasion, fuel and oil resistance; and resistance to acids and alkalis. Heat-shrinkable products are also produced from polyolefins, polyvinylidene fluoride (Kynar®), modified neoprene and fluoroelastomers (Viton®). As an example, heat-shrinkable tubing made from poly blends using Viton®, provides physical properties which have not been obtained with other vulcanization processes. These include serviceability ratings in the range of − 55 °C to 200 °C. Viton® heat shrinkable tubing offers high temperature synthetic fuel and hydraulic oil resistance.

Miller and Sperling have successfully crosslinked Viton® GLT to produce a transparent and tough material. Optimum results were achieved when a 1 : 1 blend of trimethylol propane trimethacrylate (TMPT) and triallyl isocyanurate was used to enhance crosslinking. This additive mixture consisting of 3 % of each additive provided for crosslinking at a low dose (3 Mrad) and maintained transparency in the elastomer after crosslinking. The crosslinked products had tensile strengths in the range of 1000 – 1400 psi (7 – 9,8 MPa) with elongations in the range of 100 – 300 % [12, 13].

Thermoplastic elastomers based on blends of ethylene propylene rubber and polyolefins and neoprene rubber and polyethylene (CR/PE) can be crosslinked with electrons [14, 15]. *Spenadel* found that blends of ethylene propylene rubber and polyethylene (EP/PE) of electrical insulation quality crosslink readily when exposed to electrons even without the addition of crosslinking accelerators. Blends of ethylene propylene rubber and polypropylene (EP/PP) require the addition of trimethylol propane trimethacrylate (TMPT) to promote crosslinking. This is not surprising since polypropylene undergoes chain scission when exposed to electrons. Crosslinking EP/PP with electrons improves physical properties including mar resistance, flexural set and deformation at elevated temperatures. These improvements are desirable in many automotive applications.

EB crosslinking of CR/PE blends improves tensile stength, tension set, toughness, solvent resistance and high temperature properties [15]. Crosslinking promoters including TMPT and triallyl phosphate can be used to reduce the dose required to achieve full cure.

Radiation curable EPDM compounds have been developed for roofing membrane applications, wire insulation, tubing, hose and cable jacketing. An emerging application area for electron vulcanization is in the high growth single ply roofing membrane industry. EPDM roofing membrane is typically calendered in 1,14 – 1,52 mm thick sheets requiring full vulcanization. Many of the manufacturing advantages gained with on-line electron rubber vulcanization can be realized with the roofing membrane application. These advantages include elimination of talcing, elimination of intermediate roll handling, high continuous production throughput rates, thickness specification tolerance and reproducible and homogeneous cure. Also, the physical properties of electron vulcanized roofing membranes are equivalent or superior to those obtained with conventional high temperature vulcanization. Electron vulcanization of roofing membrane has been chosen as the example in the following sections on EPDM compounding and electron vulcanization economics in order to provide additional details of this application.

Expertise has evolved in compounding EPDM to enhance its EB crosslinkability [16]. TMPT is a very effective crosslink promoter. Ethylene glycol dimethacrylate (EDMA) can also be used effectively. Monomer levels up to 15 phr have been used to significantly reduce the dose required to achieve full cure. In general, the multifunctional acrylates are more efficient than allylic or pendant vinyl crosslinking agents in reducing the dose to cure. EPDM polymer with a relatively high level (about 3 %) of unsaturation is recommended. 5-ethylidene-2-norbornene (ENB) unsaturation is preferred over 1,4-hexadiene unsaturation. Higher molecular weight EPDM also crosslinks more readily.

The presence of antioxidant in EB cured EPDM compounds helps to maintain physical properties after aging. This is shown in *Table 5* where an EPDM roofing membrane compound was radiation crosslinked at 10 and 15 Mrad with and without antioxidant. Physical properties were measured initially and after aging at 115 °C for 166 h. Although all physical properties surpassed the proposed ASTM specifications for EPDM roofing membrane, samples prepared with antioxidant showed a greater retention of tensile strength and elongation after aging. No change in hardness was observed after aging. Low temperature flexibility and ozone resistance of EPDM are unaffected by radiation curing.

Table 5. Comparing antioxidant addition in EB vulcanized EPDM roofing membrane

	Without antioxidant		With antioxidant	
	Original	Aged[a]	Original	Aged[a]
At 10 Mrad				
Hardness Shore A	66	66	66	66
Modulus at 300 % in MPa	5,6	6,1	5,3	5.8
Tensile Strength in MPa	12,8	12,2	12,2	11,8
Elongation, at break in %	675	575	650	600
Tear, die C in N/mm	30,6	-	32,0	-
At 15 Mrad				
Hardness Shore A	66	66	65	65
Modulus at 300 % in MPa	6,7	6,2	6,7	6.6
Tensile Strength in MPa	13,3	11,9	13.6	13.3
Elongation at break in %	600	525	550	525
Tear, die C in N/mm	33,3	-	35.0	-

[a] Aged 166 h at 115 °C

Proposed ASTM Specifications:

	Original	Aged 166 h/115 °C
Tensile Strength, min. in MPa	9,0	8.3
Elongation, at break, min. in %	300	225
Tear Resistance, die C in N/mm	26,0	22,0

Compounds formulated from NR and vulcanized with electrons have properties which are comparable to chemically vulcanized NR when proper additives are used. Dichlorobenzene and trimethylol propane trimethacrylate are such crosslink promoters. Crosslink promoters also produce NR materials with higher tensile strengths. This is because a lower cure dose is required and NR undergoes *detectable chain scission and isomerization at high doses.* Radiation cured rubbers exhibit greater retention of maximum tensile strength at elevated temperatures than chemically vulcanized rubbers [17]. NR latex may also be crosslinked with electrons. Irradiated rubber latex yields solid polyisoprene which has the properties of vulcanized rubber. Suitable additives reduce the cure dose to 1,5 – 2,0 Mrad.

Calendered NR sheet compounded for radiation crosslinking was irradiated at different doses using an 800 kV EB processing system. Test results from this work are summarized in *Table 6.* The EB cured sheet which was exposed to 15 Mrad had initial physical performance properties which were comparable to the sulfur cured sheet. Properties of the radiation cured sheet after aging for 3 h at 148,9 °C (300 °F) under specified stress were also equivalent to those obtained with a sulfur cure.

Table 6. Properties of EB and sulfur cured NR sheet (0,76 mm thickness)

	EB cured at 16 Mrad	sulfur cured
Elongation at break in %	545	650
Tensile strength in MPa	27,3	33,8
Modulus at 300 % in MPa	1,7	1,7
Modulus at 500 % in MPa	12,4	10,3

5 Economic evaluation

Typical processing and investment costs for an EPS designed to provide continuous on-line vulcanization of rubber sheet can best be illustrated by the use of an example. Single ply roofing membrane having a thickness of 1,52 mm and specific gravity of 1,2 can be vulcanized most efficiently using a 1500 kV EPS. A 1500 kV EPS with a maximum current rating of 75 mA has the capacity to vulcanize 32,5 m²/min of sheet based on a dose requirement of 10 Mrad.

Typical investment for a 1500 kV – 75 mA EPS includes the purchase and installation of the processing system including the power supply, accelerator/scanner and programmable controller. It also includes the custom design and construction of a shielded facility to house the EPS and underbeam handling equipment to transport materials under the beam. Total investment based on 1983 dollars is estimated at $ 1200000. Operating costs include power, cooling water, parts, maintenance and labor. The hourly *operating costs for the 1500 kV – 75 mA EPS are estimated as follows:*

Total Power ($ 0,065/kWh)	$ 12,15
Cooling Water	0,70
Parts	2,25
Maintenance	1,00
Labor (one man at $ 7,50/h plus 30 % fringe)	9,75
Hourly Operating Cost	$ 25,85

Amortization of the total investment over ten years at 12 % cost of capital and on-line operation of 6000 h (3 shifts) per year yields an amortization cost of $ 34,43/h.

The total hourly cost then becomes $ 25,85 + $ 34,43 = $ 60,28.

Since the machine can process 32,5 m²/min (350 ft²/min) or 1950,9 m²/h (21000 ft²/h) the unit processing cost can be calculated. The total cost for EB vulcanization is 3,09 cts/m² or less than 0,3 cts/ft².

6 Acknowledgement

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