Effect of Filament Materials (Tungsten, Lanthanum Hexaboride) in 250 keV/1 mA Electron Beam Machines on Empirical Capacity of RVNRL

Suhadah Rabi'atul Adabiah[1], Herry Poernomo[2], Djoko Slamet Pudjorahardjo[1], Suprapto[1], Darsono[1i]

Abstract. Some types of filaments sold commercially are made of tungsten with a lifetime of about 30-100 hours and a lanthanum hexaboride (LaB_6) filament with a lifetime of > 1000 hours. The lifetime of the filament significantly affects the effective operation time of one year on the Electron Beam Machine (EBM) for the vulcanization of natural rubber latex. This study aims to empirically determine the Radiation Vulcanized Natural Rubber Latex (RVNRL) capacity using one EBM unit with an electron gun made of tungsten filament or LaB_6 at maximum and safe operating conditions (e-beam energy, E = 250 keV; e-beam current, I = 1 mA; and the distance from the window to the NRL film, t_a = 3 cm). RVNRL capacity is determined using an empirical equation that contains several process condition variables and EBM technical specifications. The results of empirically determining the RVNRL capacity at maximum and safe operating conditions from EBM indicate that with the material selected for the filament is made of tungsten or LaB_6, the RVNRL capacity obtained is 20.22 tons/year or 36.92 tons/year respectively. It was concluded that the empirical calculation of RVNRL capacity in this study could be used to determine the amount of EBM at a certain RVRNL production capacity.

Keywords: Electron beam machine; Filament; Lanthanum hexaboride; RVNRL; Tungsten

1. Introduction

Natural rubber latex (NRL) is a milky white biopolymer latex derived from Hevea brasilliensis Muel.Arg. The NR molecule consists of cross-linked isoprene units that are linked together to form a cis-1,4 polyisoprene structure (Cifriadi *et al.*, 2017). World natural rubber (NR) production in 2019 based on statistical data was 13,804 million tonnes, which will increase by 2.7% annually (Muktaridha *et al.*, 2021). Vulcanized natural rubber latex with sulfur, the vulcanized latex product contains carcinogenic compounds such as N-nitroso morpholine, 4-nitroso morphine, and dimethylnitrosamine, which in parts per billion (ppb) alone can cause cancer (Widiyati & Poernomo, 2018).

The cross-linking process by using irradiation has many advantages and can be applied to improve materials performance (Febriasari, et al., 2021). The cross-linking of poly-isoprene in the RVNRL process is stronger than the vulcanized natural rubber latex (VNRL) process with sulfur. In RVNRL, there is a direct cross-linking between carbon atoms without going through a sulfur atom with a bond energy of around 58.6 kcal/mol. The C-C bond is larger than the carbon and sulfur bond energy of about 27.5 kcal/mol (Marsongko, 2013).

The filament materials that are widely used as electron sources in Electron Beam Machines (EBM), Scanning Electron Microscope (SEM) analysis equipment, and Electron Microscope Transmission (TEM) are tungsten and LaB_6. The raw material for making LaB_6 is lanthanum oxide (La_2O_3), which is a light rare earth oxide (LREO) (Trisnawati *et al.*, 2020). The lifetime of the tungsten filament is 30 - 100 hours, while the lifetime of the LaB_6 filament is > 1000 hours as shown by the specifications for the two types of filaments in **Table 1** (Poernomo & Saptaaji, 2012; EMS, 2023).

[i]Corresponding author's email:, Tel.: +00-00-000000; Fax: +00-00-000000
doi: 10.14716/ijtech.v0i0.0000

Table 1. Characteristics of LaB_6, CeB_6, and Tungsten filaments

Parameter	LaB_6	CeB_6	Tungsten
Brigtness (A cm^{-2} sr^{-1})	10^7	10^7	10^6
Short-term beam current stability (%RMS)	< 1	< 1	< 1
Typical service life (hr)	1000+	1500+	30-100
Operating vacuum (torr)	10^{-7}	10^{-7}	10^{-5}
Work function (eV)	~	~	4.5
Evaporation rate (g cm^{-2} sec^{-1})	$2.2x10^{-9}$	$1.6x10^{-9}$	

One of the existing low-energy tungsten filament-based EBMs in Indonesia was specifically designed for the RVNRL process with the following design specifications: electron beam energy E = 300 keV, electron beam current I = 20 mA, window size (window width s = 6 cm, window length L = 60 cm), Ti window foil thickness t_w = 20 µm, absorbed dose D = 50 kGy (Darsono, 2009).

EBM performance has been tested with initial design specifications of 300 keV/20 mA by measuring the maximum voltage and current that can be achieved under safe EBM operating conditions. The output electron beam energy and electron beam current that can be safely achieved are E = 250 keV and I = 1 mA, respectively (Sukaryono, 2021).

The EBM that has been tested under safe conditions with a maximum operating condition of 250 keV/1 mA is shown in **Figure 1** (Darsono, 2009; Suprapto & Djoko SP, 2007).

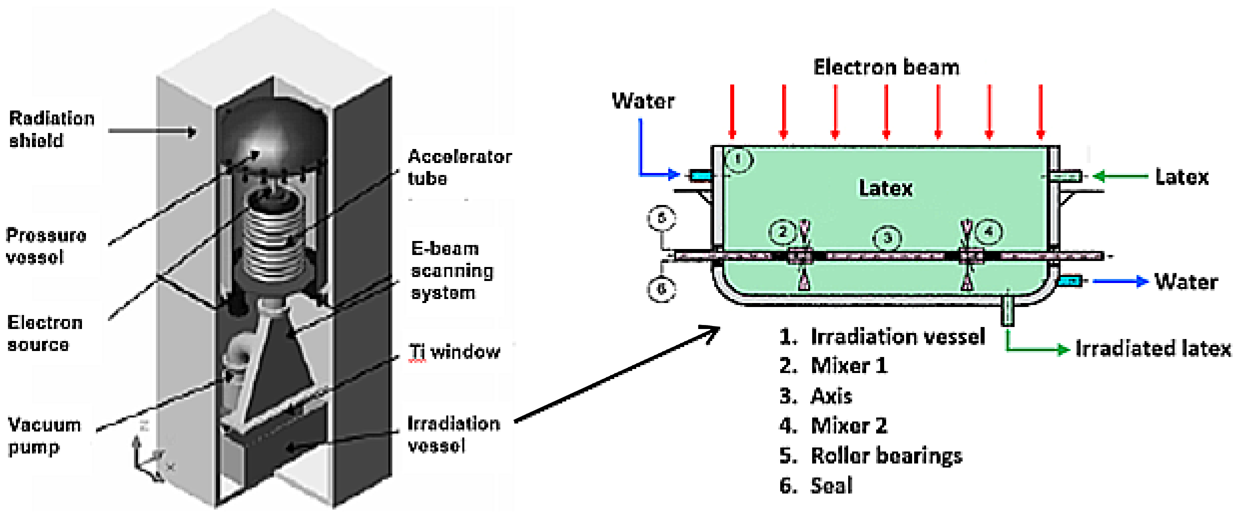

Figure 1. The EBM for RVNRL at maximum operational test conditions of 250 keV/1 mA.

The irradiation vessel system like **Figure 1,** has weaknesses, including:

- The top NRL thin layer irradiated with electron beams will receive a repeated bombardment of the electron beam, which causes the NRL to become hot, resulting in NRL degradation .
- When stirring, the foam may form in the NRL. The froth can reduce the quality of irradiated latex because most of the e-beam will be absorbed by the foam that appears, reducing the cross-linking process of isoprene in NRL to poly-isoprene.

- The rubber seals on the stirrer rotor interact with chemical reactants such as n-BA, KOH, and ammonia in NRL, it can accelerate damage to the rubber seals so that it can cause NRL leakage from the irradiation vessel.

One of the solutions to the problem of degradation of irradiated NRL due to the influence of the long irradiation time and temperature that arises in the RVNRL process as shown in **Figure 1** is by shooting the NRL film on a conveyor belt with an electron beam from EBM at a certain speed and a maximum distance of 3 cm as shown in **Figure 2**. (Kovalskiy, 2017).

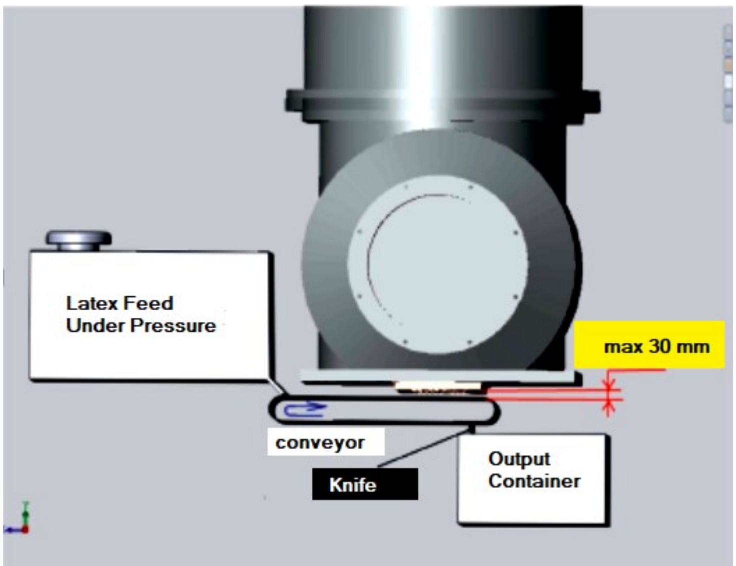

Figure 2. EBM 200 keV/26 A of prototype based on e-beam from plasma cathode for RVNRL process using belt conveyor.

The maximum window distance to the surface of the NRL film which is irradiated with electron beams produced from EBM with specifications of 200 keV/26 A as shown in **Figure 2** is t_a = 3 cm. The condition t_a = 3 cm is used as a database to determine the effect of t_a = 1, 2, 3, 4, and 5 cm on the RVNRL capacity when using EBM 250 keV/1 mA.

The RVNRL capacity is an important characteristic that can be used to determine the number and the specifications of EBM required in calculating the capital investment plan to establish a factory RVNRL using EBM. The RVNRL capacity determination can be done from several empirical equations that are affected by several variables from the EBM data characteristics, chemical and physical properties of latex, and the other operating conditions.

The difference in service life of the tungsten filament and LaB_6 in EBM will affect the amount of NRL irradiated by the electron beam per unit time which in this study is expressed by the RVNRL capacity.

The novelty of this study is how the effect of two types of filaments namely tungsten and LaB_6 as electron sources in the EBM irradiator with a maximum operating condition of 250 keV/1 mA has on the RVNRL capacity as an important parameter to determine the performance of the EBM irradiator.

The purpose of this study was to compare two types of filament materials, namely tungsten and LaB_6 as the electron source in the EBM irradiator based on the RVNRL capacity calculation results from the empirical equation with the maximum EBM operating conditions of 250 keV/1 mA.

The result of the RVNRL capacity determination with these EBM irradiator electron sources is tungsten or LaB_6 filament-based is expected to become the input data for the potential users to determine the number of EBM which could be used for the natural rubber latex vulcanization according to the RVNRL plant's production capacity design in Indonesia.

2. Methods

2.1. Determining electron beam penetration before passing window foil

Determination of the penetration of the electron beam is useful to determine the extent to which the electron beam can penetrate a material. Electron beam penetration is a dose control parameter in irradiating a material so that the material receives a homogeneous absorbed dose; that the irradiated material is of homogeneous quality. While the relative dose states the dose value which is based on a comparison of any dose to the maximum dose in an absorbed dose distribution. The reach of the electron beam produced by the filament as an electron source in the EBM (R, g/cm^2) is expressed by the following equation (Saptaaji, 2008):

$$R = 0{,}412 \times E^n \quad (1)$$

with, E = electron beam energy (MeV).
Under conditions: 0.01 <E < 2.5 MeV, then the n is determined by:

$$n = 1{,}265 - 0{,}094 \ln E \quad (2)$$

The energy absorbed in the material has an uneven distribution, meaning that the power absorbed per volume unit is a distance function. Empirically, the beam power absorbed by the unit volume p_A at a distance z is written as follows (Saptaaji, 2008):

$$\frac{p_A}{p_{Amax}} = 1 - \frac{9}{4}\left(\frac{z}{R} - \frac{1}{3}\right)^2 \quad (3)$$

with, p_{Amax} is the maximum value of absorption power per unit volume at electron penetration z of R/3 on the surface, z is penetration of the electron beam generated by the filament as a source of EBM electrons ranging from 0 g/cm^2 to (R, g/cm^2) at conditions of E that can be achieved.

2.2. Determining electron beam penetration after passing window foil

Heat accumulation occurred in the NRL film when it was applied with an electron beam causing water evaporation contained in the NRL. The water vapor that arose on the surface of the NRL film affected the penetration of the electron beam. The amount of the electron beam penetration after passing the window and the air gap (P_1) is determined by the following equation:

$$P_1 = P_0 - [(t_w \times \rho_w) + ((t_a \times \rho_a)] \quad (4)$$

with, P_0 = penetration of the electron beam before passing through the window (g/cm^2), t_w = window foil thickness (cm), ρ_w = window foil density (g/cm^3), t_a = air gap thickness containing water vapor in the top of the NRL film (cm), and ρ_a = the density of air (g/cm^3).

The electron beam that penetrates the NRL is backscattered, ionized, and excited; then as a technical factor the penetration of the electron beam is taken = 0.9×P_0 so that equation (4) can be written as follows (Poernomo & Saptaaji, 2012):

$$P_2 = 0.9 \times P_0 - [(t_w \times \rho_w) + (t_a \times \rho_a)] \quad (5)$$

2.3. *The maximum thickness of NRL film that can be penetrated by e-beam*

The amount of the electron beam penetration after passing through the window, the air gap, and the NRL film can be determined by the following equation (Poernomo & Saptaaji, 2012):

$$P_3 = 0.9 \times P_0 - [(t_w \times \rho_w) + ((t_a \times \rho_a) + ((t_l \times \rho_l)] \quad (6)$$

with, t_l = thick thin layer of latex (cm), ρ_l= latex density (g/cm^3)

The ideal penetration of the electron beam on the NRL film is when all the electron beams can penetrate and interact with the NRL; so that P_3 = 0.

$$0 = 0.9 \times P_0 - [(t_w \times \rho_w) + (t_a \times \rho_a) + (t_l \times \rho_l)] \quad (7)$$

From equation (7) it can be determined the thickness of the NRL film that can be penetrated by the electron beam (t_l) with the following equation (Widiyati & Poernomo, 2022):

$$t_l = [0.9 \times P_0 - [(t_w \times \rho_w) + (t_a \times \rho_a)]] / \rho_l \quad (8)$$

2.4. *Calculating the RVNRL capacity*

The correlation between velocity v (m/sec) materials irradiated with electron beam energy E (MeV), beam current I (mA), the efficiency factor η (%), penetration of the electron beam in the material P_t (g/cm^2), absorbed dose D (kGy or kJ/kg or kW.sec/kg), wide of scanning horns s (m) was explained in the following equation (IAEA, 2010):

$$v = (E \times I \times \eta) / (10 \times P_l \times D \times s) \quad (9)$$

The flow rate of the RNL film above the irradiated belt conveyor (Widiyati & Poernomo, 2018; Widiyati & Poernomo, 2022)

$$F = v \times A \quad (10)$$

With, F = flow rate in the NRL films on the belt conveyor (cm^3/sec), A = area of NRL film with the thickness as the electron beam penetration (cm^2). Consequently, the rate of latex film corresponding to the electron beam penetration is as follows:

$$F = v \times (t_l \times L) \quad (11)$$

with L = the window length (cm).
The capacity of RVNRL (C, g/sec) is as follows:

$$C = F \times \rho_l \quad (12)$$

3. Results and Discussion

3.1. RVNRL uses EBM with a continuous electron beam from a filament-based electron source of tungsten or LaB_6 materials

The RVNRL production process uses 330 operating days or 7920 hours of operation and the tungsten filament lifetime is 100 hours, then the replacement of tungsten filament must be done as much as 79 times/year. Using LaB_6 filaments with a service life of up to 1000 hours, the replacement of LaB_6 will be done about 8 times per year. Every time the start-up is re-conducted in EBM filament post-replacement, achieving the desired vacuum condition requires a vacuum pump operation time of around 2 hours. A window foil is another important component that needs replacement during the continuous operation of the EBM. It is predicted that every time replacements of filament, window foil, and re-conditioning in the vacuum system requires a total time of around 2 days, then:

- The number of effective days in one operational process year of RVNRL = 330 − (2 × 79) = 172 days (using tungsten filament).
- The number of effective days in one operational process year of RVNRL = 330 − (2 × 8) = 314 days (using LaB_6 filament).

3.2. The results of calculations of electron beam penetration (P_o) before window foil on the filament-based EBM

The dose distribution of the electron beam penetration in the NRL film is needed in general to determine the depth of the electron beam penetration. By using equations (1) and (2) at an energy of 0.250 MeV, the value of R is 0.059 g/cm². With the electron beam penetration (z) starting at 0 g/cm² to 0.05 g/cm², then can be obtained p_A/p_{Amax} from equation (3). Because beam penetration is a dose control parameter in irradiating a material so that the material receives a homogeneous absorbed dose so that the quality of the irradiated material is homogeneous, then $p_A/p_{Amax} = D/D_{max}$. Relative dose expresses the value of the dose based on the ratio of any dose to the maximum dose in an absorbed dose distribution written $D_{relative} = D/D_{max}$ Thus it can be taken the correlation z with $D_{relative}$ shown in Table 2.

Table 2. Correlation of z to $D_{relative}$.

z (g/cm²)	$D_{relative}$
0.000	0.750
0.010	0.938
0.020	1.000
0.030	0.935
0.040	0.742
0.050	0.423

From **Table 2**, the curve of relative dose distribution ($D_{relative}$) vs. electron beam penetration (z) can be drawn as shown in **Figure 3**, with $D/D_{max} = D_{relative}$.

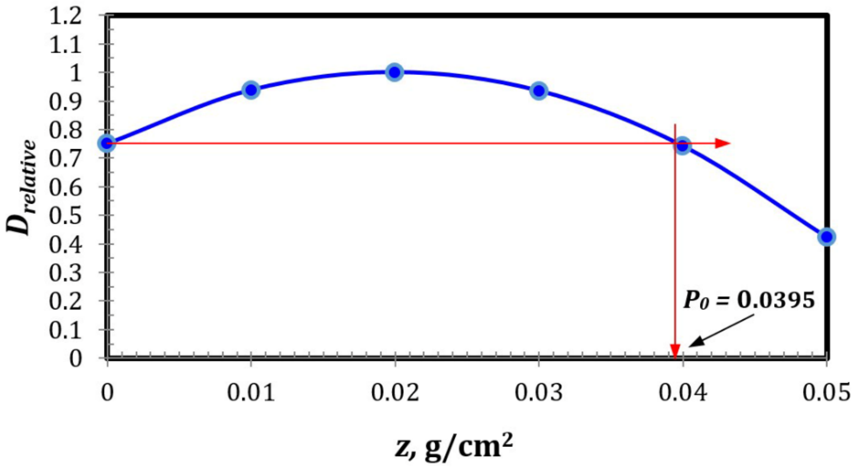

Figure 3. $D_{relative}$ vs. z at maximum operation condition EBM of 250 keV/1 mA.

The determination of P_o in this study was carried out at an electron beam energy of 250 keV as follows: At $D_{relative}$ = 0.75, a straight line is drawn to cut the curve. Then, a straight line is drawn from the point of intersection to intersect the abscissa of z on the points P_o of 0.0395 g/cm².

3.3. The results of calculations of RVNRL capacity using EBM with filament-based electron sources

Empirical calculation of RVNRL capacity on EBM under safe operating conditions 250 keV/1 mA for tungsten and LaB_6 are 172 effective days/year and 314 effective days/year, respectively. Based on some data such as E = 250 keV, I = 1 mA, s = 6 cm, L = 60 cm, D = 50 kGy, η = 60%, ρ_a = 0.00112 g/cm³, ρ_l = 0.913 g/cm³, t_w = 20 μm, ρ_w= 4.6 g/cm³; then from equations (4), (8), (9), (11), and (12) it can be obtained the effect of t_a and C as shown in **Figure 4** as follows:

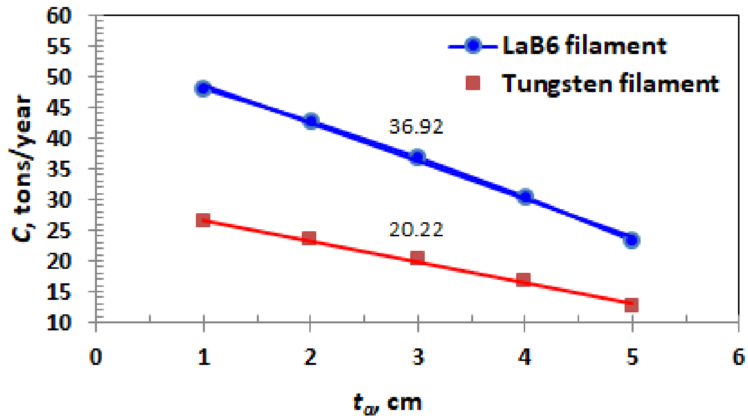

Figure 4. The effect of t_a and EBM filament materials on the C for EBM operates at E = 250 keV, I = 1 mA, and D = 50 kGy.

The choice of distance from the window to the NRL film (t_a) in the EBM operation is 250 keV/1 mA, which is safely adopted from the operating conditions of the plasma cathode-based EBM which has been successfully tested in Russia for the RVNRL process with t_a = 3 cm as shown in **Figure 2** (Kovalskiy, 2017). Based on some data such as E = 250 keV, s = 6 cm, L = 60 cm, D = 50 kGy, η = 60%, ρ_a = 0.00112 g/cm³, ρ_l = 0.913 g/cm³, t_a = 3 cm, t_w = 20 μm, ρ_w= 4.6 g/cm³; then from equations (4), (8), (9), (11), and (12) it can be obtained the effect of I and C as shown in **Figure 5** as follows:

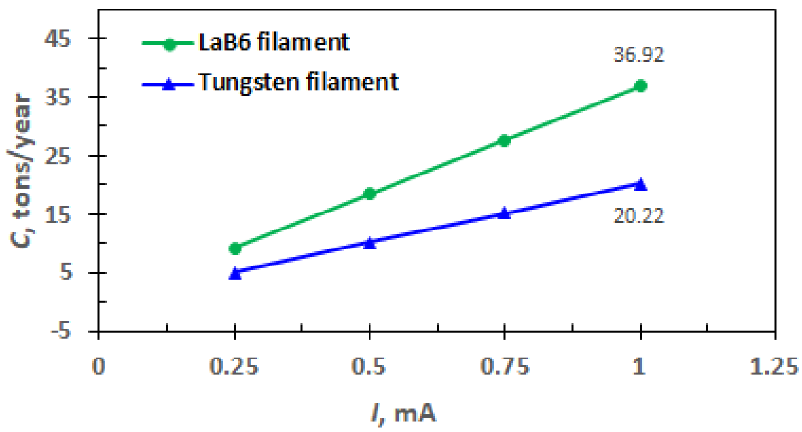

Figure 5. The effect of I and EBM filament materials on the C for EBM operates at E = 250 keV, t_a = 3 cm, and D = 50 kGy.

Figure 5 displays data on the effect of e-beam current on RVNRL capacity. This is necessary in anticipation of a decrease in performance during EBM operation as indicated by a decrease in the measured e-beam current, the RVNRL capacity will also decrease. **Figure 5** shows that the greater the electron beam current in EBM with a tungsten filament or LaB_6-based electron source, the greater the RVNRL capacity. This is because the linear speed of the NRL on the conveyor belt in equation (8) becomes larger with a larger electron beam current. Thus the calculation of the capacity of RVNRL (C) empirically using equations (10) and (11) shows that the calculation results for C are getting bigger. Based on the use of tungsten filament with maximum and safe EBM operating conditions at E = 250 keV, I = 1 mA, and t_a = 3 cm is used for the RVNRL process, then from empirical calculations, the capacity of RVNRL = 18.70 tons/year is obtained. In the use of tungsten filament material which is replaced with LaB_6, then from empirical calculations, it is obtained that the capacity of RVNRL = 34.15 tons/year.

The results of the absorbed dose calculation on the development of 250 keV and 300 keV filament-based EBM technology in Japan for each RVNRL process resulted in D = 168 kGy and 81 kGy, respectively (Poernomo & Saptaaji, 2012). EBM based on tungsten filament or LaB_6 can operate safely at a maximum condition of 250 keV/1 mA and can adjust the absorption dose to 50, 75, 100, 125, and 150 kGy. Based on some data such as E = 250 keV, I = 1 mA, s = 6 cm, L = 60 cm, η = 60%, ρ_a = 0.00112 g/cm^3, ρ_l = 0.913 g/cm^3, t_a = 3 cm, t_w = 20 µm, ρ_w = 4.6 g/cm^3; then from equations (4), (8), (9), (11), and (12) it can be obtained the effect of D and C as shown in **Figure 6** as follows:

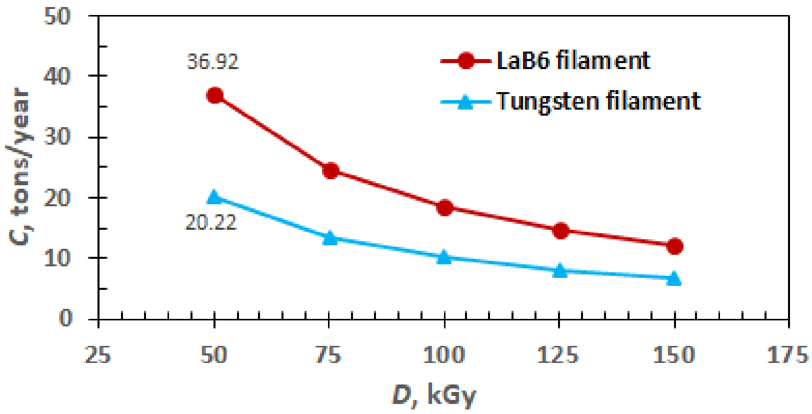

Figure 6. The effect of D and EBM filament materials on the C for EBM operates at E = 250 keV, I = 1 mA; and t_a = 3 cm.

Figure 6 shows that the lower the absorbed dose in the EBM for the RVNRL process, the greater the RVNRL capacity will be. The specific value used for t_l when obtaining data in Figure 4-6 under the conditions: E = 250 keV, I = 1 mA, t_a = 3 cm, and D = 50 kGy is with t_l = 0.0114 cm.

The results of calculations of empirical capacity RVNRL with tungsten or LaB_6 filament-based EBM, as shown in **Figure 4, Figure 5,** and **Figure 6** are the results of empirical calculation, then need to be supported by the quality of the results of experimental data of RVNRL such as crosslink density, tensile strength, elongation at break, modulus of elasticity (Ahmed & Sabbagh, 2015; Ahsan, *et al.*, 2015; Junian, *et al.*, 2015; Roslim, *et al.*, 2012; Soiket, *et al.*, 2015). EBM as a result of the design with the initial design of 300 keV/20 mA for RVNRL can be improved in performance so that operating conditions can be achieved E > 250 keV and I > 1 mA by replacing several important tool components according to manufacturer standards so that when EBM is operated in safe conditions.

4. Conclusions

RVNRL capacity for EBM under safe operating conditions: E = 250 keV and I = 1 mA with a tungsten filament which has a lifetime of 30-100 hours and can be replaced with a LaB_6 filament which has a long life of > 1000 hours. The filament chosen as the electron source is tungsten or LaB_6; then the RVNRL capacity in EBM with maximum and safe operational conditions is C = 20.22 tons/year or 36.92 tons/year, respectively. The method of determining RVNRL capacity on EBM 250 keV/1 mA could be used as data input in determining the amount of EBM required to calculate capital expenditure for constructing an RVNRL plant using electron beam machines in Indonesia.

Acknowledgements

The author would like to thank the head of the Research Center for Accelerator Technology and the head of the Research Center for Mining Technology at the National Research and Innovation Agency for providing this research opportunities.

References

Ahmed, N.M., and El-Sabbagh, S.H. 2015. The influence of doped-kaolin on the properties of styrene-butadiene rubber composites. International Journal of Advanced Research, 3(5), 1-19.

Ahsan, Q., Mohamad, N., Soh, T.C. 2015. Effects of accelerators on the cure characteristics and mechanical properties of natural rubber compounds. International Journal of Automotive and Mechanical Engineering, 12, 2954-2966.

Cifriadi1, A., Chalid, M., Santi Puspitasari, S. 2017. Characterization of hydrogenated natural rubber synthesized diimide transfer hydrogenation. International Journal of Technology, 3, 448-457.

Darsono., 2009. Industrial Scale MBE for Production of Irradiated Natural Rubber Latex: Manufacturing, Market Share, and Techno-economics of LKAI. Proceedings of Scientific Meeting and Presentation of Accelerator Technology and Its Applications, 91-101.

Electron Microscopy Sciences (EMS). 2023. Cathodes & Filaments for Electron Microscopes.

Febriasari, A., Suhartini, Meri., Yunus, A.L., Rahmawati, Sudirman, Hotimah, B., Hemana, RF., Kartohardjono, S., Fahira, A., Permatasari, IP. 2021. Gamma Irradiation of Cellulose Acetate-Polyethylene Glycol 400 Composite Membrane and Its Performance Test for Gas Separation. International Journal of Technology, 12, 1198-1206.

IAEA. 2010. Use of mathematical modelling in electron beam processing: A Guidebook. IAEA Radiation Technology Series No. 1.

Junian, S., Makmud, M.Z.H., Sahari, J. 2015. Natural rubber as electrical an insulator: A review. Journal of Advanced Review on Scientific Research, 6(1), 28-41.

Kovalskiy, S.S. 2017. Low-Energy Electron Beam for Medical and Plasma Chemistry Applications. Beam & Plasma Technologies LLC, Tomsk, Rusia.

Marsongko. 2013. Comparison of glove manufacture from radiation vulcanized natural latex and sulfur. J. Packaging Chemistry, 35(2), 131-136.

Muktaridha, O., Adlim, M., Suhendrayatna, Ismail, Abu Bakar, N.H.H. 2021. Photocatalytic degradation of skim-latex-vapor odor using iron-doped zinc oxide. International Journal of Technology, 12(4) 739-748.

Poernomo, H., and Saptaaji, R. 2012. Basic Design of Natural Rubber Latex Vulcanization System with Electron Beams on a Belt Conveyor. Proceedings of Scientific Meetings and Presentations-Basic Research on Nuclear Science and Technology, 102-107.

Roslim, R., Hashim, M.Y.A., Augurio, P.T. 2012. Natural latex foam. Journal of Engineering Science, 8, 15-27.

Saptaaji, R. 2008. Determination of the depth of penetration of the 800 keV electron beam in the exhaust gas of a power plant in an exhaust gas treatment system using an electron beam machine. Nuclear Forum Journal, 2(1), 51-62.

Shanghai Metal Market (SMM). 2023. Rare Earth Oxides Prices.

Soiket, M.I.H., Rana, M.R.A., Al Ratun, J. 2015. Experimental investigation on mechanical properties of indigenous rubber products. American International Journal of Research in Science, Technology, Engineering & Mathematics, 15, 139-142.

Sukaryono. 2021. Safety Analysis Report of a 300 keV/20 mA Electron Beam Machine. Research Center for Accelerator Technology, Research Organization for Nuclear Energy, National Research and Innovation Agency.

Suprapto, and Djoko SP. 2007. Design of irradiation vessel for vulcanization of natural rubber latex using electron beam irradiation. Proceedings of Technology Scientific Meeting and Presentation Accelerators and their Applications, 27-35.

Trisnawati, I., Prameswara, G., Mulyono, P., Prasetya, A., Murti Petrus, H.T.B, 2020. Sulfuric acid leaching of heavy rare earth elements (HREEs) from Indonesian zircon tailing. International Journal of Technology, 11(3), 804-816.

Widiyati, C., and Poernomo, H. 2018. Design of a prototype photoreactor UV-LEDs for radiation vulcanization of natural rubber latex. International Journal of Technology, 1, 130-141.

Widiyati, C., and Poernomo, H. 2022. Comparison of Technology of Radiation Vulcanized Natural Rubber Latex Using UV-mercury Lamp, UV-LED Lamp, and Plasma Cathode-Based EBM Irradiators. Jurnal Teknologi (Sciences & Engineering), 84(3), 111-123.