NEUTRON KERMA FACTORS, AND WATER EQUIVALENCE OF SOME TISSUE SUBSTITUTES

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Abstract

The kerma factors and kerma relative to air and water of 24 compounds used as tissue substitutes were calculated for neutron energy from $2.53x10^{-8}$ up to 29 MeV. The kerma ratio of the tissue substitutes relative to air and water were calculated by the ratio of kerma factors of the tissue substitute to air and water respectively. The water equivalence of the selected tissue substitutes was observed above neutron energies 100 eV. Kerma ratio relative to the air for Poly-vinylidene fluoride and Teflon are found to be nearest to unity in very low energy (up to 1 eV) and above 63 eV respectively. It was found that the natural rubber as a water equivalent tissue substitute compound. The results of the kerma factors in our investigation shows a very good agreement with those published in ICRU-44. We found that at higher neutron energies, the kerma factors and kerma ratios of the selected tissue substitute compounds are approximately same, but differences are large for energies below 100 eV.

Keywords: Neutron, KERMA, tissue substitute, water equivalence

1.- INTRODUCTION

Kinetic energy released per unit mass (kerma) is defined as the initial kinetic energy of all secondary charged particles liberated per unit mass at a point of interest by uncharged radiation [ICRU 1989; Attix 1986]. It is applicable to photons and neutrons having the same unit as the absorbed dose.

Neutron-induced reactions play an important role in the particle transport, radiation effects for transmutation, medical and material research. The neutron interaction is high LET which interact primarily via (n, p) or spallation reactions, depositing a large amount of energy and often transforming the atom in the DNA strand into a completely different atom.

A tumor cell whose DNA is damaged to this extent cannot repair itself and will ultimately die. However in low LET radiation (x- and γ-rays) the outer electrons of the atoms in the tumor cells is displaced, temporarily ionizing the atoms, but also allowing time for the electrons to get back in orbit and rebuild the tumor's DNA through chemical reactions. These reactions are completed through activated radicals produced during the atomic interactions. This rebuild process allows the growth of the tumor again. Therefore the neutron therapy is superior for cancer treatment than photon and proton due to its´ higher biological effectiveness, exponential cell survival and slow DNA damage. The sensitivity of salivary gland tumor, sarcomas, melanomas and prostate is to be observed higher than photon exposure.

The cancer cell damaged by high LET radiation has low probability to repair and continue to grow as compared with damaged by low LET radiation. This inability for the tumor to repair is one parameter accounting for the higher relative biological effectiveness of neutron therapy. The relevance of radiation therapy with photons, electrons, and neutrons has been discussed in reports published by the International Commission on Radiation Units and Measurements [ICRU 1989].

The required dose to kill the same number of cancerous cells by neutrons is about one third in comparison with photons [Chadwick *et al*., 1997]. Clinical reports indicate that a treatment with neutrons consists of less exposure as compared with photons or electrons. Practical neutron/photon treatment of a tumor involves the exposure of some healthy tissues with sub-lethal doses.

The radiation treatment of a patient requires extensive hard work and database for the energy deposition of the radiation in human organ and tissues. The energy deposition of radiation into the human organ is studied with the help of phantom and simulation methods. The phantom materials are being chosen having equivalent properties against radiation (X, γ and neutron) interactions. The neutron energy deposition and the energy of generated charged particle are important in fast neutron therapy [Kononov *et al*., 2006].

Kerma factors for neutrons in low-Z materials or compounds are important for the dosimetry of neutron radiotherapy beams [Wuu and Milavickas 1987]. In the determination of kerma factors for neutrons in different compounds used in radiotherapy, the elemental composition is important because it is mainly determined by the hydrogen content of tissues. The neutron-proton elastic scattering processes dominate the energy transfer process even at neutron energies of 60 to 70 MeV [Maughan *et al*., 1997]. The neutron interaction in various types of compound, mixture and elements have been investigated [Mousavi and Sardari 2013; Adnan 2010; Sheino *et al*., 2004; Xiaojun *et al*., 2011; Zhenzhou *et al*., 2008; Meulders *et al*., 2000; Schrewe *et al*., 2000].

Kerma values of gamma radiation are used in dosimetry for dose evaluation, similarly during the neutron interaction in the medium, the Kerma values are being defined for medical applications. The use of kerma factor in neutron dosimetry has being reviewed in the literature [ICRU 2000, Kondoa *et al*., 2008; Sun *et al*., 2008]. The kerma Neutron kerma factors of the human organs and few tissue substitutes are found the report [ICRU

1989]. Various studied on photon Kerma of the alcohols and thermoluminiscent dosimeters are reported recently [Singh and Badiger 2013a; Singh and Badiger 2013b].

The aim of this work was to calculate the neutron kerma factors (kerma per unit neutron fluence) of some tissue substitute compounds. These kerma factors were used to calculate the relative values to air and to water. The water equivalence was calculated for the reason that the water exhibits the most useful dosimetric properties for medical applications. The present study should be useful for neutron application in medical and simulation work with the tissue substitute compounds.

2.- MATERIALS AND METHODS

The Kerma is defined as the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of the charged ionizing particle liberated by uncharged ionizing particles in a material of mass dm. A series of kerma coefficients for elements (k(E)) were used to calculate the kerma.

The dissipation of neutron energy in the medium is a two-step process. In first step, neutron transfer energy to atomic nuclei, producing secondary charged particle. In the second step, the secondary charged particles traverse the medium, giving up the energy to the atoms and molecules of the medium by excitation and ionization. The kerma due to neutrons interacting with a medium is defined in equation 1.

$$K = \int_{E_{min}}^{E_{max}} \Phi_E(E)\, k_T(E)\, dE \qquad (1)$$

Where $\Phi_E(E)$ is the neutron spectrum, $k_T(E)$ are the neutron kerma factors for the compound or mixture. The $k_T(E)$ are calculated using the KERMA program using equation 2 [Vega-Carrillo *et al.*, 2007].

$$k_T(E) = \sum_i w_i \, k(E)_i \qquad (2)$$

here, w_i is the weight fraction of i^{th} element in the tissue and $k(E)_i$ is the neutron kerma factor of i^{th} element in the compound or mixture.

The kerma factors for the elements were taken from Caswell *et al*. [1982]. The tissue substitute compounds are given in the Table 1 for calculation of the neutron kerma factors for neutron dosimetry studies.

Table 1.- Elemental composition of tissue substitutes.

ID	**Tissue substitutes**	**ρ [g/cm³]**	**Weight fraction [%]**								
			H	C	N	O	F	S	Cl	Ca	Na
PCS	Poly-chloro-styrene	1.55	6.19	69.63	0.00	0.00	0.00	0.00	24.18	0	0
PPS	Poly-phenylene sulfide	1.64	3.73	66.63	0.00	0.00	0.00	29.65	0.00	0	0
PSU	Poly-sulfone (PSU)	1.25	5.01	73.28	0.00	14.46	0.00	7.25	0.00	0	0
PES	Poly-ether-sulfone	1.37	2.72	48.63	0.00	16.19	0.00	32.46	0.00	0	0
MC	Modeling Clay	1.273	0.00	19.76	0.86	75.83	0.00	3.55	0.00	0	0
NR	Natural Rubber	0.92	11.84	88.16	0.00	0.00	0.00	0.00	0.00	0	0
PP	Poly-propylene	0.946	14.37	85.63	0.00	0.00	0.00	0.00	0.00	0	0
PSc	Plastic-scintillator	1.06	8.53	91.47	0.00	0.00	0.00	0.00	0.00	0	0
PX	Perspex	1.18	8.05	59.98	0.00	31.96	0.00	0.00	0.00	0	0
BK	Bakelite	1.362	5.74	77.46	0.00	16.80	0.00	0.00	0.00	0	0
PAN	Poly-acrylo-nitrile	1.148	5.70	67.90	26.40	0.00	0.00	0.00	0.00	0	0
TF	Teflon	2.20	0.00	24.02	0.00	0.00	75.98	0.00	0.00	0	0
PVDF	Poly-vinylidene fluoride	1.78	3.15	37.51	0.00	0.00	59.34	0.00	0.00	0	0
OAW	Orange Articulation Wax	0.931	2.72	82.00	7.37	7.82	0.00	0.08	0.00	0	0
PETE	Polyethylene terephthalate	1.38	4.20	62.50	0.00	33.30	0.00	0.00	0.00	0	0
BW	Bee Wax	0.964	1.87	75.25	8.42	14.27	0.00	0.19	0.00	0	0
RAW	Red Articulation Wax	0.911	0.36	80.17	11.23	8.14	0.00	0.09	0.00	0	0
PF1	Paraffin 1	0.959	0.61	81.73	0.74	16.81	0.00	0.10	0.00	0	0
PF2	Paraffin 2	0.918	0.68	79.61	9.63	9.94	0.00	0.14	0.00	0	0
BL	Bolus	1.112	0.50	82.22	0.78	16.41	0.00	0.09	0.00	0	0
PT	Pitch	1.148	0.19	42.18	0.42	56.76	0.00	0.46	0.00	0	0
PMMA	Methylmetacrylate	1.178	0.24	94.96	4.71	0.00	0.00	0.10	0.00	0	0
----	Solid Water	1.020	8.1	67.2	2.4	19.9	0	0	0.1	2.3	0
----	Frigerio Gel	1.120	10	12	4	73.3	0	0.2	0.1	0	0.4

Neutron Kerma, relative to air and to water were calculated using equations 3 and 4 respectively, given below.

$$\frac{K_{\text{Tissue substitute}}}{K_{\text{Air}}} = \frac{K_T(E)_{\text{Tissue substitute}}}{K_T(E)_{\text{Air}}} \qquad (3)$$

$$\frac{K_{\text{Tissue substitute}}}{K_{\text{Water}}} = \frac{K_T(E)_{\text{Tissue substitute}}}{K_T(E)_{\text{Water}}} \qquad (4)$$

3.- RESULTS AND DISCUSSION

The neutron kerma factors of PCS, PPS, PSU and PES tissue substitutes are shown in figure 1 for neutrons from $2.53\text{x}10^{-8}$ up to 30 MeV.

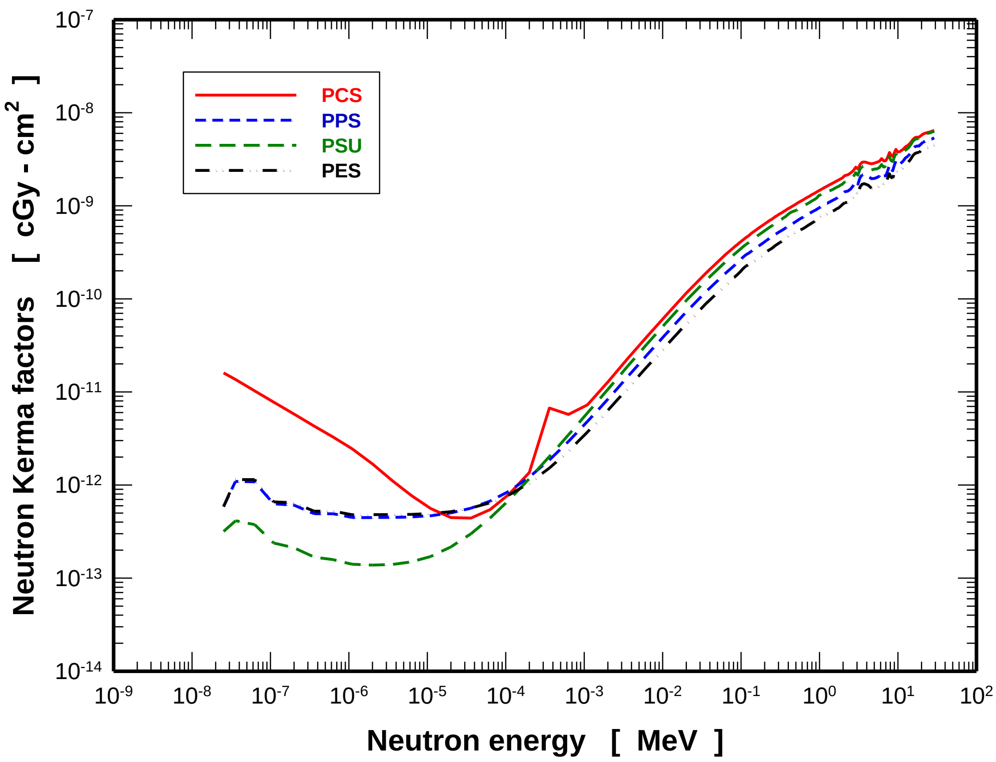

Figure 1.- Neutron kerma factors of PCS, PPS, PSU and PES.

The neutron kerma factors of MC, NR, PP and PSc tissue substitutes are shown in figure 2.

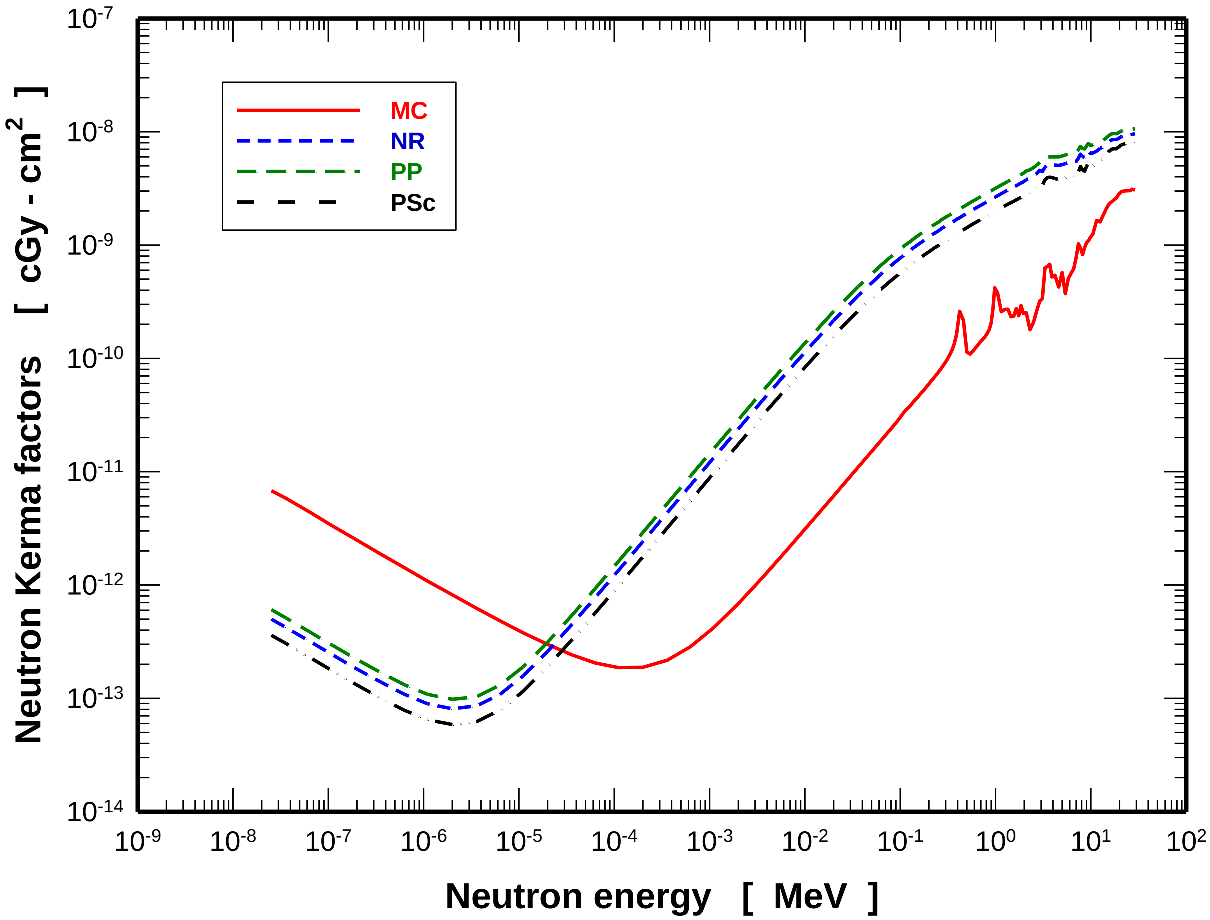

Figure 2.- Neutron kerma factors of MC, NR, PP and PSc.

The neutron kerma factors of PX, BK, PAN and TF tissue substitutes are shown in figure 4.

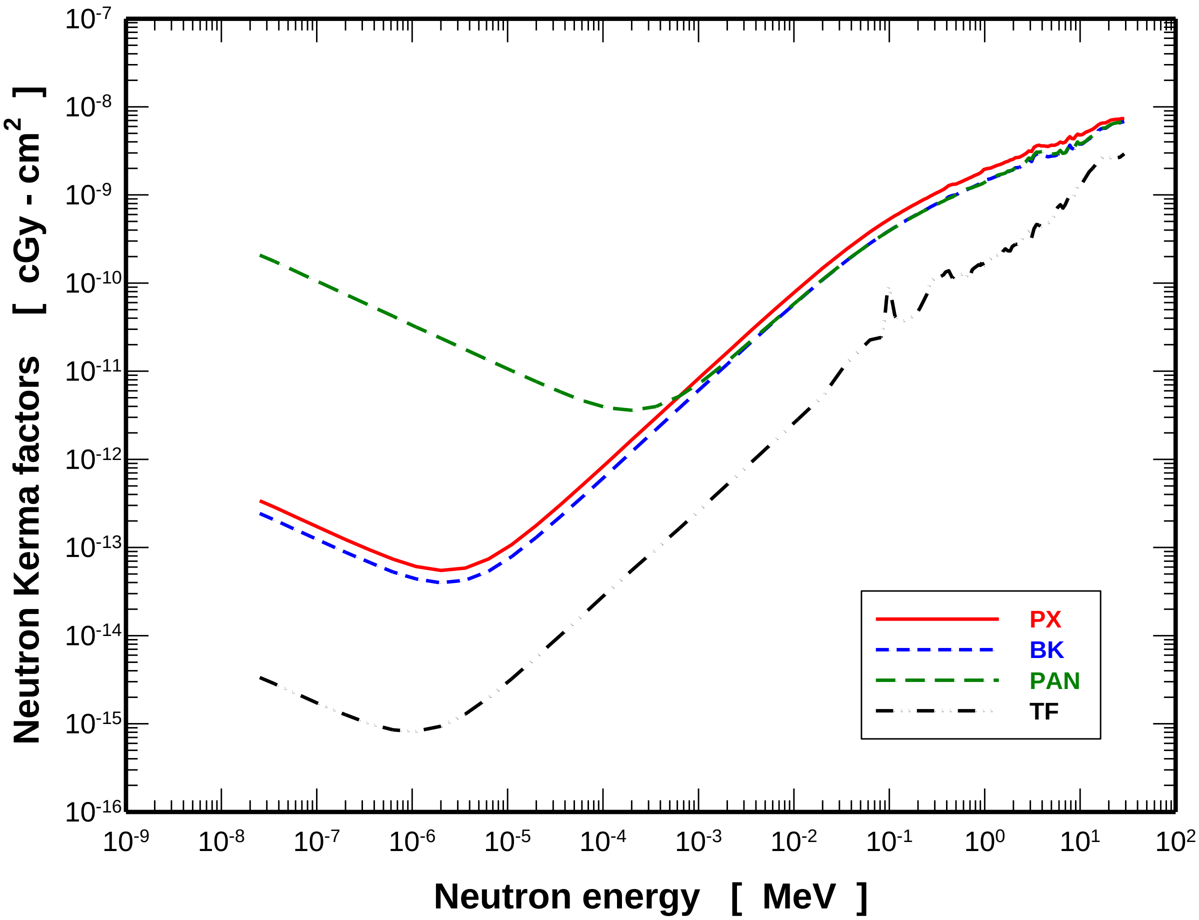

Figure 4.- Neutron kerma factors of PX, BK, PAN and TF.

The neutron kerma factors of PVDF, OAW, PETE and BW tissue substitutes are shown in figure 5.

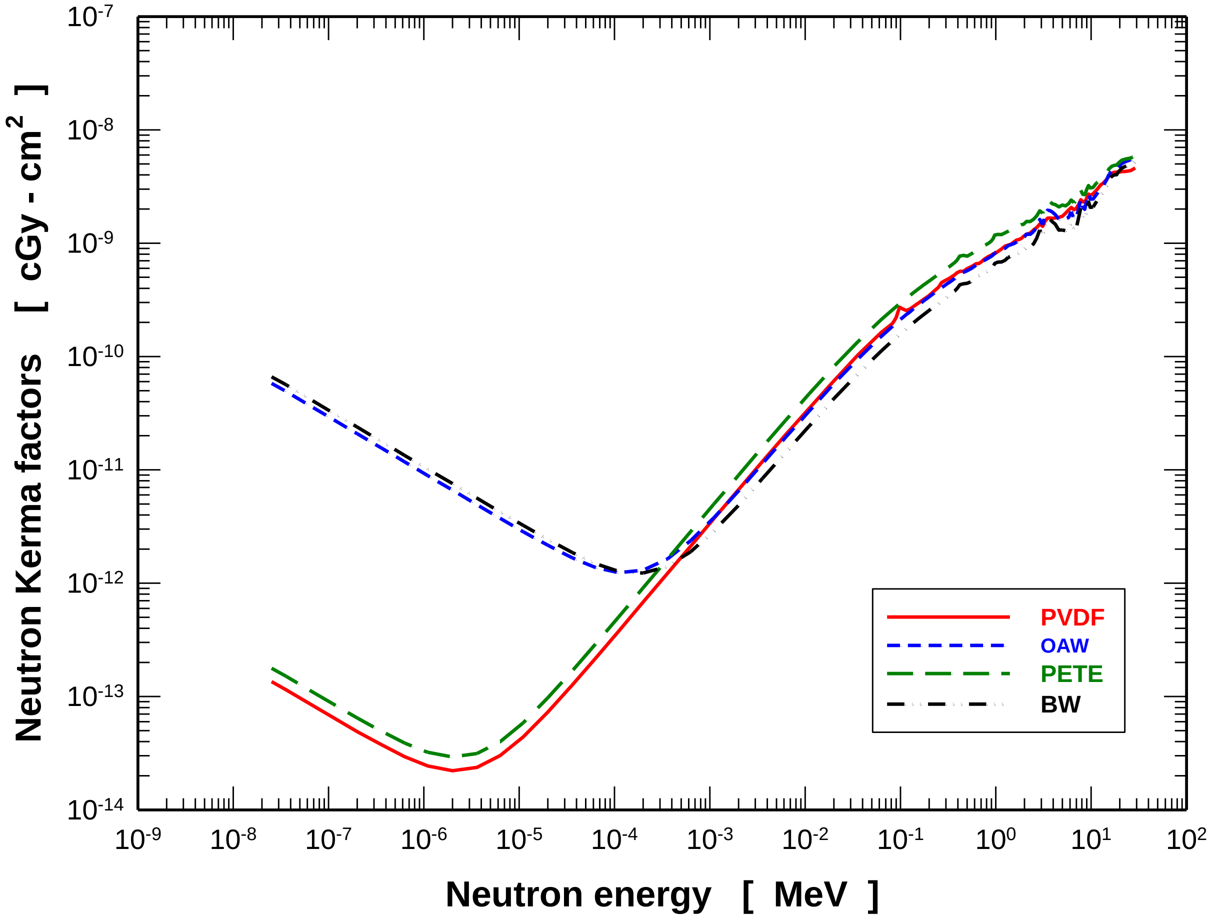

Figure 5.- Neutron kerma factors of PVDF, OAW, PETE and BW.

The neutron kerma factors of RAW, PF1, PF2 and BL tissue substitutes are shown in figure 6.

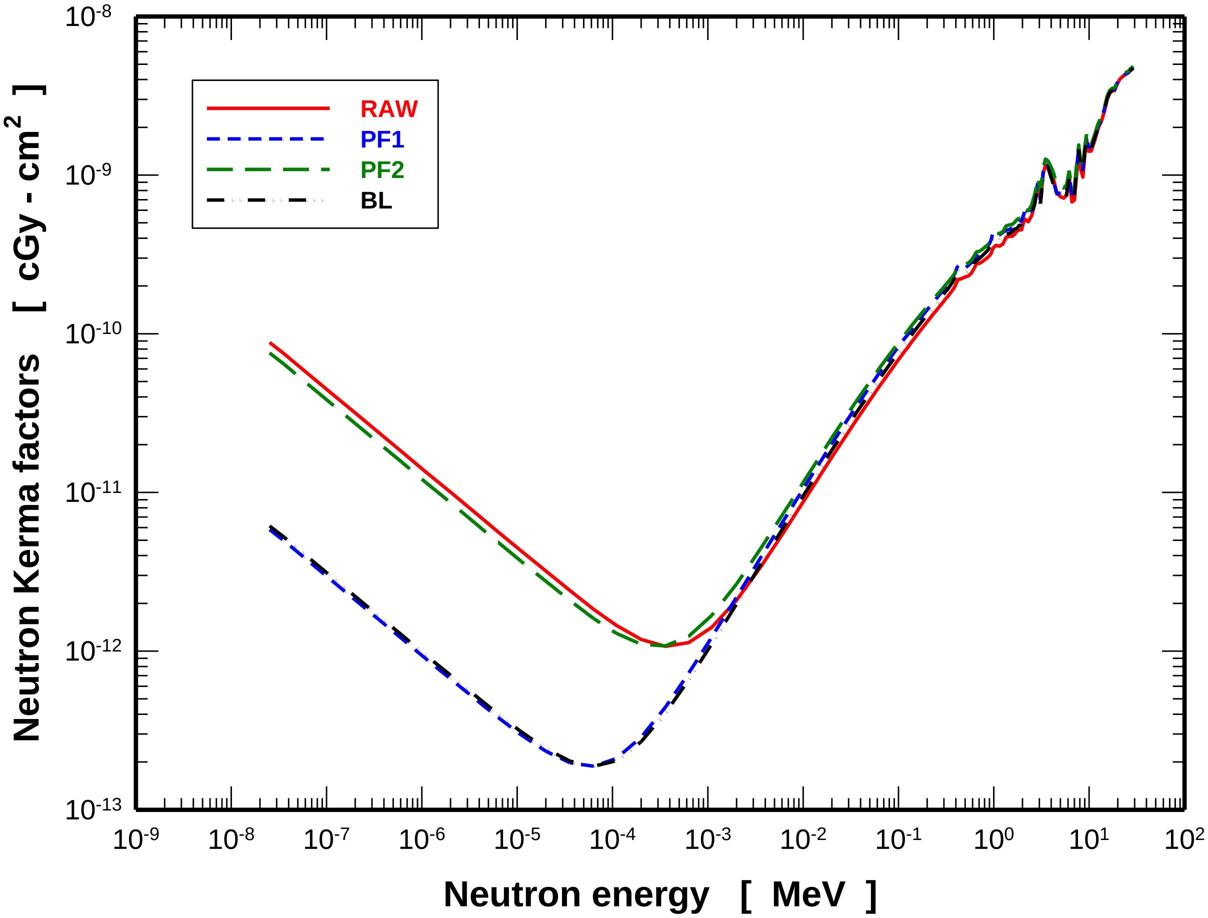

Figure 6.- Neutron kerma factors of RAW, PF1, PF2 and BL.

The neutron kerma factors of PT, PMMA, Solid water and Frigerio gel tissue substitutes are shown in figure 7.

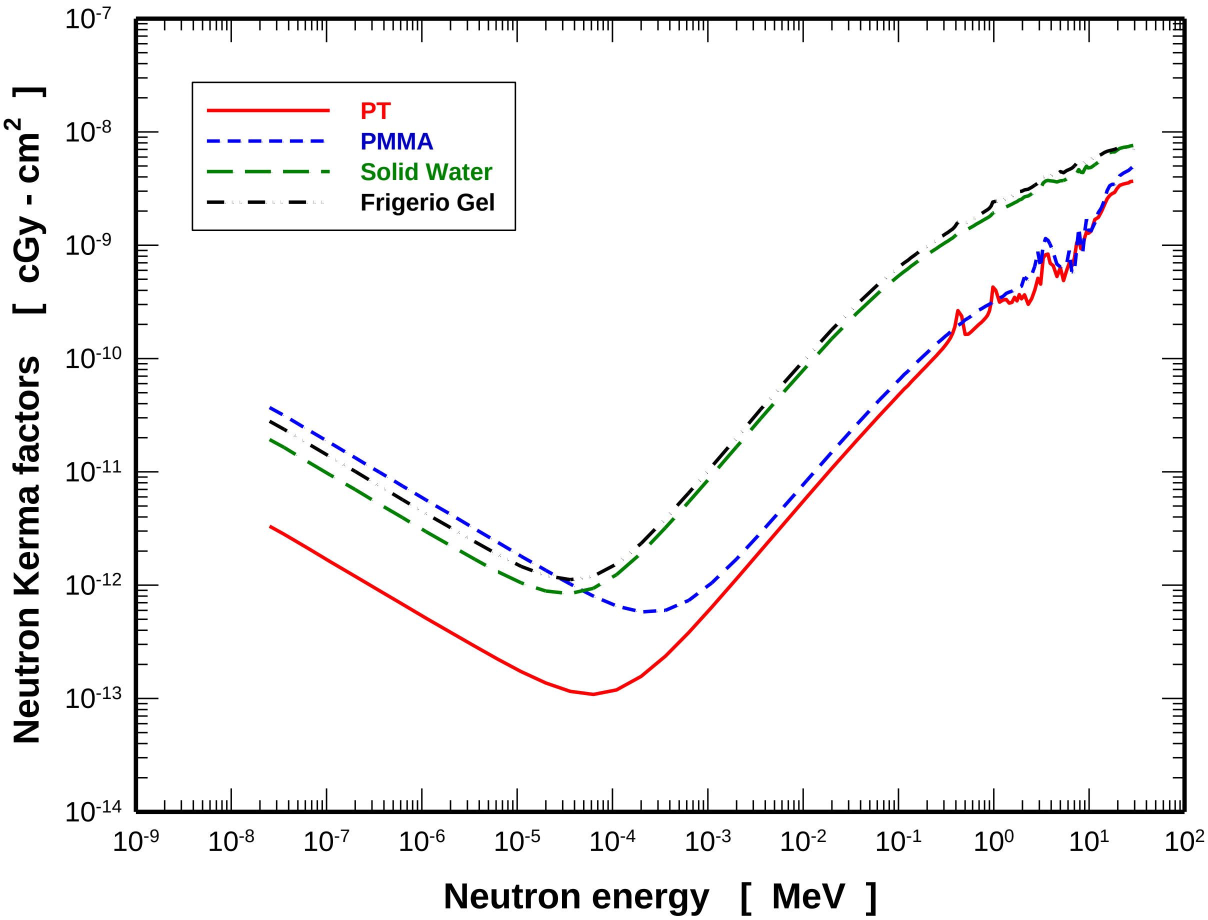

Figure 7.- Neutron kerma factors of PT, PMMA, Solid water and Frigerio gel.

The kerma factors of the selected tissue substitute compunds can be divided in two energy regions, low energy (<100 eV) and high energy (>100 eV). The high energy neutron (>100 eV) are called as fast neutrons.

The minima values of the kerma factors were observed at 1.1 eV for PCS, PPS, PES and TF; 2 eV for PSU, NR, PP, PSc, PX, BK and PETE; 36 eV for solid water Frigerio gel and PVDF; 63 eV for PF1, BL and PT; 110 eV for MC and OAW; 200 eV for PAN, BW and PMMA; 360 eV for RAW and PF2.

For fast neutron, kerma factors increase with energy and having peaks at energy ranging from 0.5 to 10 MeV due to high-Z elements. The tissue substitute compounds having low or nil Hydrogen contents (e.g. MC, TF, PT and PMMA) were found to be having smaller kerma factors compared with the other tissue substitute compounds in fast neutron spectrum.

The neutron kerma factors of the tissue substitutes relative to air are shown in figure 8 and the water equivalence of the tissue substitutes for neutron interaction is shown in figure 9.

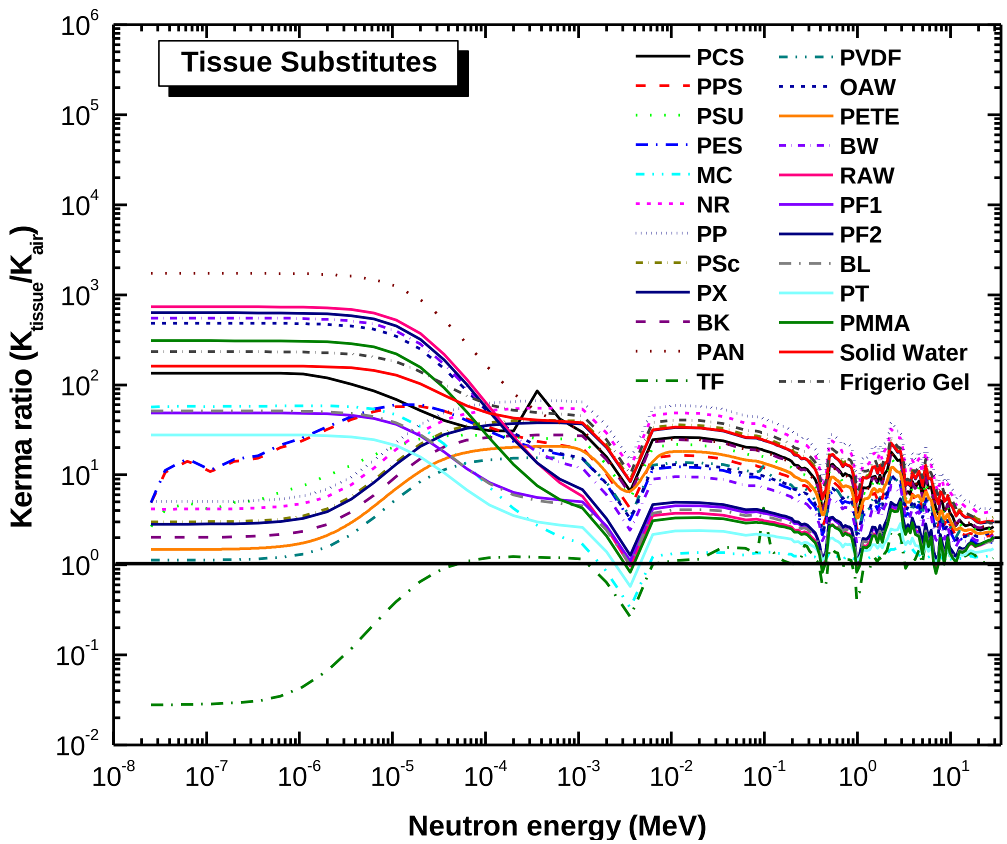

Figure 8.- Neutron kerma factors of the tissue substitutes relative to air.

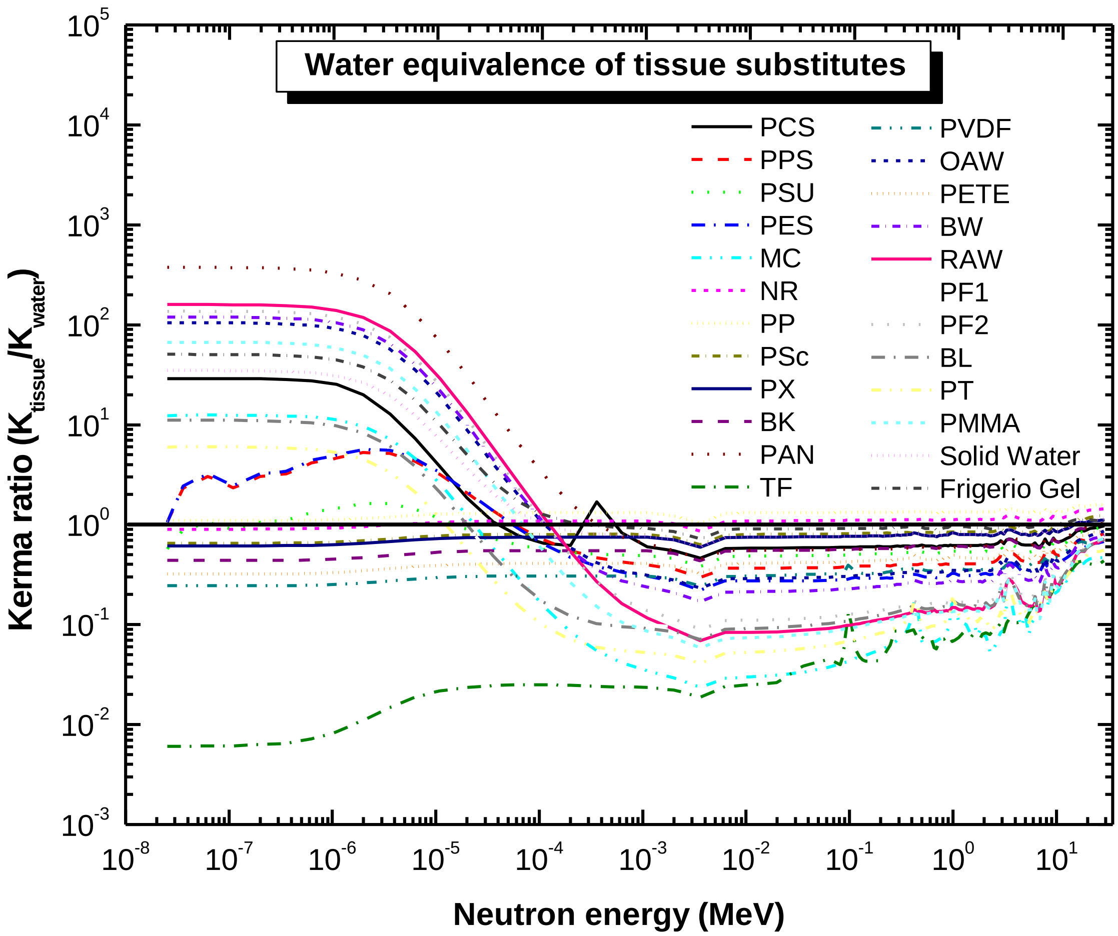

Figure 9.- Neutron kerma factors of the tissue substitutes relative to water.

The neutron kerma ratio of the selected tissue compounds to air ranges 0.027 to 1732, found nearest to unity for PVDF for neutron energy up to 1 eV whereas TF was nearest to unity above 63 eV. The water equivalence of the tissue substitute compounds was investigated by kerma ratio of tissue substitute to water as shown in Fig.3. It was found that the NR was water equivalent compound among the selected tissue substitutes. The neutron kerma factors of the solid water, Frigerio gel and PMMA were compared with the literature ICRU [1989] and a very good agreement was observed. If a neutron spectrum is available neutron kerma can be calculated using the neutron kerma factor of different tissue substitute compounds.

4.- CONCLUSIONS

The neutron kerma factors and kerma ratio for air and water for 24 tissue substitute compounds were investigated in the present paper. It was found that the kerma factors of the tissue substitutes were of same order in high neutron energies however these differences were large for neutrons with energies less below 100 eV.

The Kerma ratio relative to the air for Poly-vinylidene fluoride and Teflon are found to be nearest to unity in very low energy (up to 1 eV) and above 63 eV respectively. It was found that the natural rubber as a water equivalent compound among the selected tissue substitutes.

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