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***Yazar(lar) (Author(s))**: Zeynep AYGUN[1], Murat AYGUN[2]*

ORCID: 0000-0002-2979-0283

ORCID: 0000-0002-4276-3511

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Evaluation of radiation shielding potentials of Ni-based alloys, Inconel-617 and Incoloy-800HT, candidates for high temperature applications especially for nuclear reactors, by EpiXS and Phy-X/PSD codes

Highlights

- *Photon atteunation parameters of Inconel-617 and Incoloy-800HT have been calculated.*
- *Phy-X/PSD and EpiXS codes have been used.*
- *Alloys 617 and 800HT can be used as shielding materials for nuclear applications.*

Graphical Abstract

The radiation-matter interaction parameters were obtained in a wide energy range by using Phy-X/PSD and EpiXS softwares in order to determine the radiation shielding potentials of the alloys.

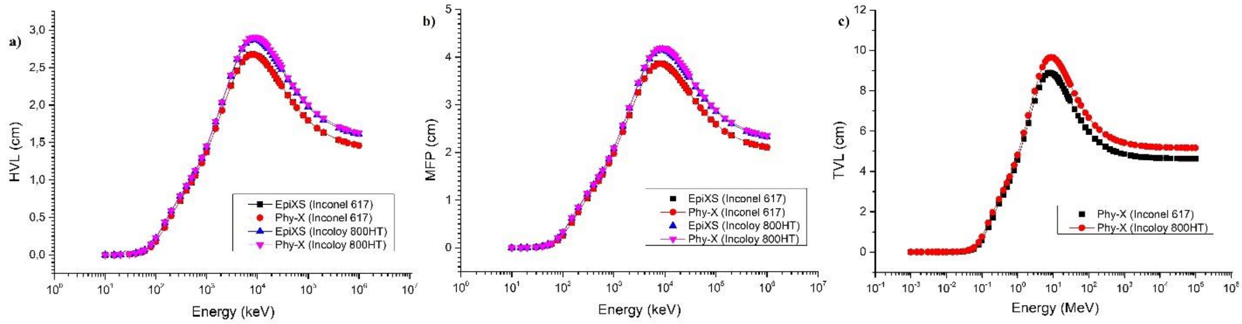

Figure The variations of HVL (a) MFP (b) and TVL (c) versus photon energies.

Aim

In the present study, it is aimed to calculate photon-matter interaction parameters of Ni-based alloys, Inconel-617 and Incoloy-800HT, which are the main candidates for high-temperature applications such as spacecraft, gas turbines, nuclear reactors and rocket motors.

Design & Methodology

The radiation shielding parameters were obtained in a wide energy range by using Phy-X/PSD and EpiXS softwares.

Originality

There is no research in the literature about this topic.

Findings

It was observed that Inconel-617 has higher shielding ability than Incoloy-800HT. The shielding potentials of the alloys were compared with those of other shielding materials reported before, and it was concluded that Inconel-617 and Incoloy-800HT have more shielding ability than those

Conclusion

As a result, it is mentioned that Inconel-617 and Incoloy-800HT can be evaluated as shielding materials for high temperature applications especially for nuclear applications. Also, alloy 800 HT is slightly more suitable for neutron shielding than alloy 617.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Evaluation of radiation shielding potentials of Ni-based alloys, Inconel-617 and Incoloy-800HT, candidates for high temperature applications especially for nuclear reactors, by EpiXS and Phy-X/PSD codes

Araştırma Makalesi/Research Article

Zeynep AYGUN[1*], Murat AYGUN[2]

[*1]Bitlis Eren University, Vocational School of Technical Sciences, 13100, Bitlis, Turkey

[2]Bitlis Eren University, Faculty of Science and Arts, Department of Physics, 13100, Bitlis, Turkey

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ABSTRACT

In this paper, our purpose is to calculate photon-matter interaction parameters of Ni-based alloys, Inconel-617 and Incoloy-800HT, which are the main candidates for high-temperature applications such as spacecraft, gas turbines, nuclear reactors and rocket motors. The radiation attenuation parameters and buildup factors were obtained in a wide energy range by using Phy-X/PSD and EpiXS softwares to determine the radiation protection capabilities of the alloys. Fast neutron removal cross sections of the alloys were also calculated. It was observed that Inconel-617 has higher shielding ability than Incoloy-800HT. The shielding potentials of the alloys were compared with those of other shielding materials (ordinary concrete, hematite-serpenite, ilmenite-limonite, steel-scrap, basalt-magnetite, steel-magnetite and ilmenite concretes) reported before, and it was concluded that Inconel-617 and Incoloy-800HT have more shielding ability than those.

Keywords: Radiation attenuation parameters, radiation shielding, Inconel-617, Incoloy-800HT

Özellikle nükleer reaktörler için yüksek sıcaklık uygulamalarına aday Ni bazlı alaşımların, Inconel-617 ve Incoloy-800HT, radyasyon zırhlama potansiyellerinin EpiXS ve Phy-X/PSD kodları ile değerlendirilmesi

ÖZ

Bu çalışmada, uzay aracı, gaz türbinleri, nükleer reaktörler ve roket motorları gibi yüksek sıcaklık uygulamaları için ana aday olan Ni bazlı alaşımlar Inconel-617 ve Incoloy-800HT'nin foton-madde etkileşim parametrelerinin hesaplanması amaçlanmıştır. Alaşımların radyasyondan korunma potansiyellerini belirlemek için radyasyon zayıflama ve yığılma faktörleri gibi parametreler geniş bir enerji aralığında Phy-X/PSD ve EpiXS yazılımları kullanılarak elde edilmiştir. Alaşımların hızlı nötron uzaklaştırma tesir kesitleri de belirlenmiştir. Inconel-617'nin Incoloy-800HT'den daha yüksek zırhlama kabiliyetine sahip olduğu gözlemlenmiştir. Alaşımların zırhlama potansiyelleri daha önce bildirilen diğer malzemelerin (sıradan beton, hematit-serpenit, ilmenit-limonit, çelik-hurda, bazalt-manyetit, çelik-manyetit ve ilmenit betonları) zırhlama potansiyelleriyle karşılaştırılmış, Inconel-617 ve Incoloy-800HT'nin bu malzemelerden daha fazla zırhlama kabiliyetine sahip olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Radyasyon zayıflama parametreleri, radyasyon zırhlama, Inconel-617, Incoloy-800HT.

1. INTRODUCTION

Ni-based alloys are the main candidates for high-temperature applications, especially in next-generation nuclear and advanced coal-fired power plants [1]. Generation IV nuclear reactor concept is important for electricity and hydrogen production, and consists of a high-temperature gas-cooled reactor and a very-high-temperature reactor (about 1000 °C) [2]. Materials with high temperature operating properties are needed in nuclear reactors, rocket motors, spacecraft and gas turbines etc. Inconel-617 is one of the primary candidates capable of meeting the structural material requirements of very high temperature applications. Properties of oxidation resistance and high strength at temperatures of 980°C and above, enables Inconel- 617 a

**Sorumlu yazar (Corresponding Author)*
e-posta : zaygun@beu.edu.tr

potential material for use in both land-based gas turbines and aircraft. It is a nickel-molybdenum-chromium-aluminum-cobalt alloy. Carbon imparts to material high temperature strength, molybdenum and cobalt provide solid-solution strengthening. Chromium is a key element for oxidation resistance by forming a sticky and protective layer on the surface of alloy that does not allow further oxidation [3]. Incoloy-800HT is a variation of Incoloy-800 and 800H. Alloy 800HT is an iron-nickel-chromium solid-solution strengthened alloy, one of the featured materials for fourth generation nuclear power plant, with the properties of good resistance to corrosion, oxidation, and appreciable strength at high temperatures [4]. Alloy 800HT can be used as for control rod sheath materials for very-high-temperature reactor and in industrial heating equipment, hydrocarbon processing industry etc. [3,5].

Many studies about alloys for different purposes were reported before [6-14]. Among the alloys, Ni-based alloys, Inconel-617 and Incoloy-800HT, were also studied by many researchers previously [1,4,15-20]. The researches were generally focused on the oxidation behaviors in different environments, mechanical, metallurgical and tensile properties of the alloys 617 and 800HT. The alloys used in reactor environment and nuclear applications should be also evaluated for their radiation shielding capabilities in addition to the other features mentioned above. To the best of our knowledge, radiation protection features of Inconel-617 and Incoloy-800HT have not been investigated, yet. The aim of this study is to obtain the photon attenuation parameters such as mass attenuation coefficients (MAC), linear attenuation coefficients (LAC), effective atomic numbers (Z_{eff}), half-value layers (HVL), mean free paths (MFP), tenth-value layers (TVL), and buildup factors of Inconel-617 and Incoloy-800HT. For the purpose of learning about the radiation protection abilities of the alloys, recently developed two codes Phy-X/PSD [21] and EpiXS [22] were used. The obtained results were compared with the shielding potentials of other materials.

2. MATERIAL and METHOD

In the study, we used the chemical compositions of Inconel-617 and Incoloy-800HT taken from the literature by [2]. The densities of the used alloys 617 and 800HT are 8.36 and 7.94 g/cm^3, respectively.

The MAC corresponds to the interaction possibility between the mass per unit area of a material and photons can be obtained by the Beer–Lambert as given in Eq. 1:

$$I = I_0 e^{-\mu t} \quad (1)$$

$$\mu_m = \frac{\mu}{\rho} = ln(I_0/I)/\rho t = ln(I_0/I)/t_m \quad (2)$$

where μ(cm^{-1}) and μ_m(cm^2/g) are linear and mass attenuation coefficients, respectively.

We can obtain MAC for any compound as follows [23];

$$\mu/\rho = \sum_i w_i (\mu/\rho)_i \quad (3)$$

where w_i and $(\mu/\rho)_i$ are the weight fraction and the MAC of the *i*th constituent element, respectively.

ACS (σ_a) for any sample is given by Eq. 4;

$$ACS = \sigma_a = \frac{N}{N_A}(\mu/\rho) \quad (4)$$

ACS (σ_a) is also identified as the sum of partial cross sections in Eq. 5,

$$\sigma_a = \sigma_{PE} + \sigma_{coh} + \sigma_{incoh} + \sigma_{PP-N} + \sigma_{PP-E} \quad (5)$$

ECS (σ_e) is given by Equation (6);

$$ECS = \sigma_e = \frac{\sigma_a}{Z_{eff}} \quad (6)$$

By using the Equations (4) and (6), Z_{eff} of the material can be written as follows;

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (7)$$

The other parameters, HVL, TVL and MFP, important to analyze the shielding feature are determined by using μ as follows;

$$HVL = \frac{In(2)}{\mu} \quad (8)$$

$$MFP = \frac{1}{\mu} \quad (9)$$

$$TVL = \frac{In10}{\mu} \quad (10)$$

Information about the parameters mentioned above was given with more detail in previous studies [21,24]. Exposure buildup factors (EBF) and energy absorption buildup factors (EABF) can be obtained by the given equations below [21,25-27]. G-P fitting parameters for the material are determined by using fitting parameters [28] in Eq. 11. Buildup factors can be obtained using Eq. 13 or 14 by determining *K*(*E*,*x*) in Eq. 15.

$$Z_{eq} = \frac{Z_1(logR_2 - logR) + Z_2(logR - logR_1)}{logR_2 - logR_1} \quad (11)$$

$$F = \frac{F_1(logZ_2 - logZ_{eq}) + F_2(logZ_{eq} - logZ_1)}{logZ_2 - logZ_1} \quad (12)$$

$$B(E,x) = 1 + \frac{(b-1)(K^x-1)}{(K-1)} \quad \text{for} \quad K \neq 1 \quad (13)$$

$$B(E,x) = 1 + (b-1)x \quad \text{for} \quad K = 1 \quad (14)$$

$$K(E,x) = cx^a + d\frac{\tanh\left(\frac{x}{X_k} - 2\right) - \tanh(-2)}{1 - \tanh(-2)}, x \leq 40\text{mfp} \quad (15)$$

3. RESULTS AND DISCUSSION

The chemical compositions of Inconel-617 and Incoloy-800HT obtained from literature is given in Table 1 [2]. Changes of the calculated MAC values versus photon energies (1keV-1GeV) are shown in Fig. 1(a). At low energies (1-100keV) where the photoelectric process is effective, MAC values decreased sharply with increasing energy. At mid-energies (100keV–5MeV), MAC values slightly changed and the Compton scattering dominantly effects these changes. In the region higher than 5MeV, by Pair production process, MAC values increased with increasing energy [29,30]. The small increase seen at 0.02 MeV can be due to the K-absorption edges of Mo, which was also reported by Sayyed et al. [31] for some alloys.

LAC is a parameter which depends on both MAC and density of the sample. Dependence of the calculated LAC values versus photon energies (1keV-1GeV) is displayed in Fig. 1(b). It was obtained that the MAC and LAC values of both alloys were very near to each other for the given energies and the determined values by two codes are in good agreement. Generally, MAC and LAC values of 617 alloy are slightly bigger than those of 800HT, it can be said that 617 alloy has more absorption feature than 800HT alloy. According to the obtained higher MAC values of the Inconel-617 and Incoloy-800HT, it can be said that the alloys have more shielding abilities than the widely used shielding materials (ordinary concrete, hematite-serpenite, ilmenite-limonite, basalt-magnetite, steel-scrap, ilmenite and steel-magnetite concretes) reported by Bashter [32]. Also, MAC values obtained for the studied alloys are very close to those obtained for Inconel-718 and Inconel-625 reported before [31]. The determined MAC values of the studied alloys and other reported materials are given in Tables 2-3.

The HVL, TVL and MFP are the other parameters used for determining shielding abilities. HVL, MFP and TVL values changing versus photon energies determined by EpiXS and Phy-X/PSD are given in Fig. 2. It is seen that the calculated parameters by using two codes are in good agreement. At mid-energies, where Compton scattering is dominant, most photons are more likely to be scattered. Therefore, their absorption probabilities are lower and hence thicker materials are required and photons have longer MFP. It is preferred to have low HVL, MFP and TVL values in the high energy regions for better shielding property. According to the obtained results, alloy 617 has lower HVL, MFP and TVL values than alloy 800HT. Therefore, it can be concluded that alloy 617 has higher shielding ability than alloy 800HT.

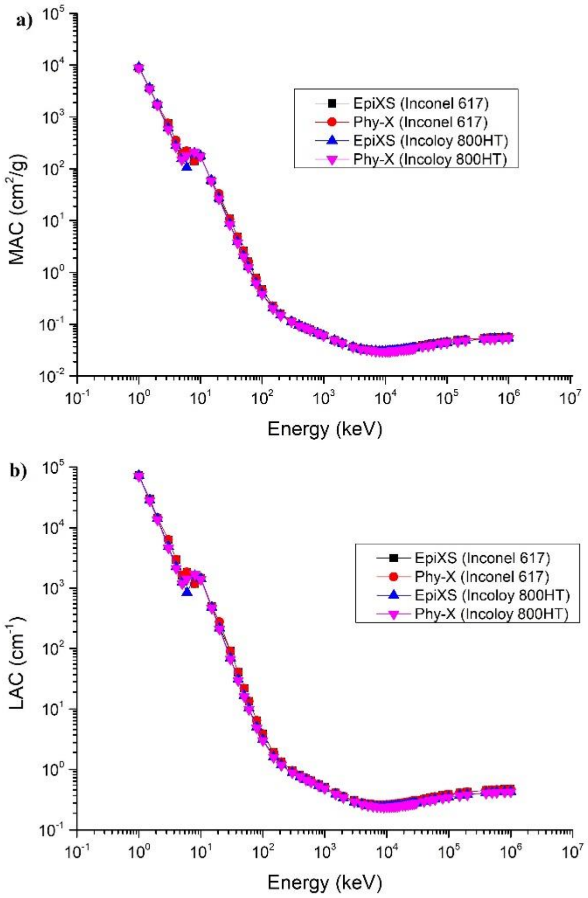

Figure 1. The variations of MAC (a) and LAC (b) versus photon energies.

Z_{eff} variations versus photon energies obtained by two codes are given in Fig. 3. At low energies due to the photoelectric effect, maximum Z_{eff} values were obtained. The first maximum Z_{eff} at around 0.0018 MeV can be obtained by the K-absorption edge of Si [33]. The second maximum Z_{eff} at around 0.02 MeV can be due to K-absorption edges of Mo [31]. By increasing energy, these values decreased sharply. Then the values increased and remained stable at high energies. Due to the higher Zeff values of alloy 617 than those of alloy 800HT, it can be said that Inconel 617 shows higher shielding potential. Additionally, the obtained Z_{eff} values of the Inconel-617 and Incoloy-800HT, are also higher than the Z_{eff} values of RS 253 glass, ordinary concrete, hematite-serpenite and basalt-magnetite calculated by Alım [30] and hence, the alloys show

Table 1. Chemical compositions of 617 and 800HT alloys.

Alloy	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Co	Mo	P	B
Inc617	0.08	0.23	1.46	0.001	0.2	0.02	53.27	22.02	1.10	0.32	11.91	9.38	0.005	0.002
Inc800HT	0.061	1.27	46.24	0.001	0.42	0.2	30.65	19.7	0.56	0.54	0.1	-	0.024	-

Table 2. MAC values of the alloys and other shielding materials.

Energy (MeV)	EpiXS Inc617	Phy-X/PSD-Inc617	EpiXS Inc800 HT	Phy-X/PSD Inc800 HT	Ord-concrete [32]	Steel-Scrap [32]	Ilmenite-limonite [32]	Steel-magnetite [32]	Ilmenite [32]	Hematite-serpentite [32]	Basalt-magnetite [32]
1.00E-02	175.2	175.4	179.7	173.7	22.56	113.8	89.68	135.2	88.15	65.33	62.60
1.50E-02	59.14	59.03	60.60	58.24	7.079	37.92	29.64	45.11	29.12	21.54	20.47
2.00E-02	26.75	32.97	27.40	26.26	3.105	17.02	13.28	20.28	13.04	9.661	9.156
3.00E-02	10.83	10.79	8.763	8.380	1.048	5.445	4.250	6.473	4.174	3.124	2.971
4.00E-02	4.861	4.843	3.899	3.723	0.541	2.446	1.907	2.892	1.891	1.443	1.295
5.00E-02	2.626	2.617	2.101	2.009	0.358	1.345	1.074	1.576	1.055	0.826	0.789
6.00E-02	1.608	1.601	1.291	1.235	0.241	0.849	0.690	0.983	0.678	0.547	0.526
8.00E-02	0.774	0.772	0.634	0.609	0.204	0.445	0.378	0.502	0.372	0.319	0.309
1.00E-01	0.467	0.466	0.392	0.379	0.172	0.296	0.261	0.325	0.267	0.232	0.227
1.50E-01	0.226	0.226	0.203	0.199	0.142	0.176	0.165	0.183	0.158	0.159	0.157
2.00E-01	0.159	0.160	0.149	0.147	0.127	0.139	0.134	0.141	0.133	0.133	0.132
3.00E-01	0.114	0.115	0.111	0.111	0.108	0.109	0.108	0.109	0.107	0.109	0.109
4.00E-01	0.096	0.096	0.095	0.094	0.096	0.095	0.095	0.094	0.094	0.096	0.096
5.00E-01	0.086	0.086	0.085	0.085	0.088	0.085	0.085	0.085	0.085	0.087	0.087
6.00E-01	0.078	0.078	0.077	0.077	0.079	0.079	0.079	0.078	0.078	0.080	0.080
8.00E-01	0.068	0.068	0.067	0.067	0.071	0.068	0.069	0.068	0.068	0.070	0.072
1.00E+00	0.060	0.060	0.060	0.060	0.064	0.063	0.061	0.061	0.061	0.063	0.063
1.50E+00	0.049	0.049	0.049	0.049	0.052	0.051	0.050	0.049	0.050	0.051	0.050
2.00E+00	0.043	0.043	0.043	0.043	0.045	0.045	0.043	0.042	0.043	0.044	0.044
3.00E+00	0.037	0.037	0.036	0.036	0.036	0.037	0.036	0.036	0.035	0.036	0.036
4.00E+00	0.034	0.034	0.033	0.033	0.031	0.033	0.032	0.032	0.031	0.032	0.031
5.00E+00	0.032	0.032	0.032	0.032	0.028	0.031	0.029	0.030	0.029	0.029	0.029
6.00E+00	0.031	0.031	0.031	0.031	0.026	0.030	0.028	0.029	0.028	0.027	0.027
8.00E+00	0.031	0.031	0.030	0.030	0.024	0.028	0.026	0.028	0.026	0.025	0.025
1.00E+01	0.031	0.031	0.030	0.030	0.022	0.027	0.025	0.028	0.025	0.024	0.024

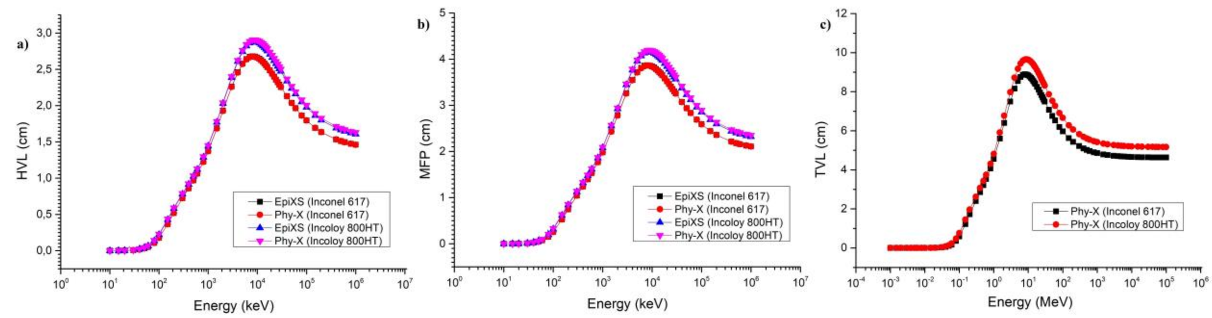

Figure 2. The variations of HVL (a) MFP (b) and TVL (c) versus photon energies.

more shielding property than these previously reported shielding materials.

EABF and EBF of the alloys were determined for 7 penetration depths by EpiXS. The change of EBF and EABF versus incident photon energies is shown in Fig. 4. EBF and EABF reach the maximum at mid-energies. Since low energy photons are absorbed, buildup factor values are small at low photon energies as a result of the photoelectric effect. The dominant process at mid energies is Compton scattering. In Compton region, an increase in photon accumulation is observed due to the large number of scattered photons and hence EABF and EBF are in great values at medium energies. The dominating process at high energies is Pair production and a strong photon absorption is observed in this region. Therefore, at higher energies the buildup factors decrease [34,35]. The obtained values of EABF and EBF show that the photons cluster a little more for 800HT alloy than 617 alloy. As a result, it can be said that the maximum Compton scattering effect is observed for Incoloy-800HT.

Table 3. MAC values of the studied alloys and other reported alloys.

Energy (MeV)	EpiXS Inc617	Phy-X/PSD-Inc617	EpiXS Inc800HT	Phy-X/PSD Inc800HT	In625 [31]	In718 [31]	WI-52 [31]
1.50E-02	59.14	59.03	60.60	58.24	65.70	59.00	66.24
3.00E-02	10.83	10.79	8.763	8.380	9.549	10.41	9.830
5.00E-02	2.626	2.617	2.101	2.009	2.287	2.51	2.412
8.00E-01	0.068	0.068	0.067	0.067	0.068	0.067	0.068
1.00E+00	0.060	0.060	0.060	0.060	0.061	0.060	0.060
3.00E+00	0.037	0.037	0.036	0.036	0.037	0.037	0.036
5.00E+00	0.032	0.032	0.032	0.032	0.032	0.032	0.032
8.00E+00	0.031	0.031	0.030	0.030	0.031	0.031	0.031
1.00E+01	0.031	0.031	0.030	0.030	0.031	0.031	0.031

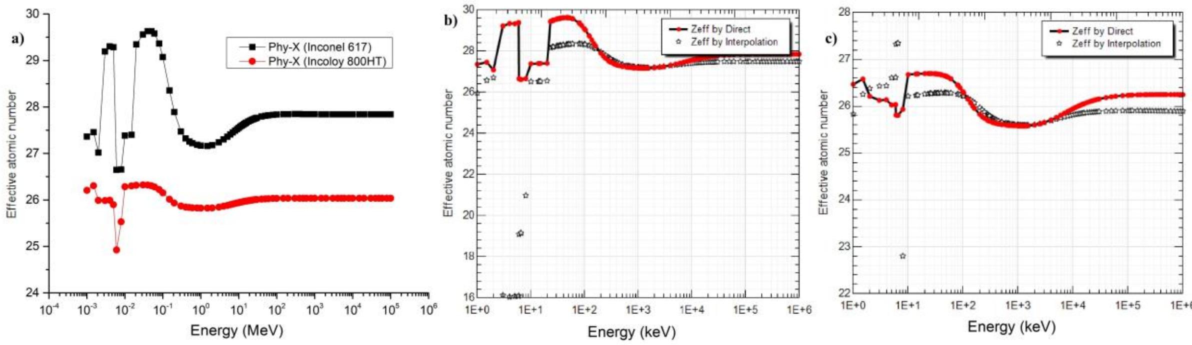

Figure 3. The changes of Z_{eff} (b) Alloy 617 (EpiXS) (c) Alloy 800HT (EpiXS) versus photon energies.

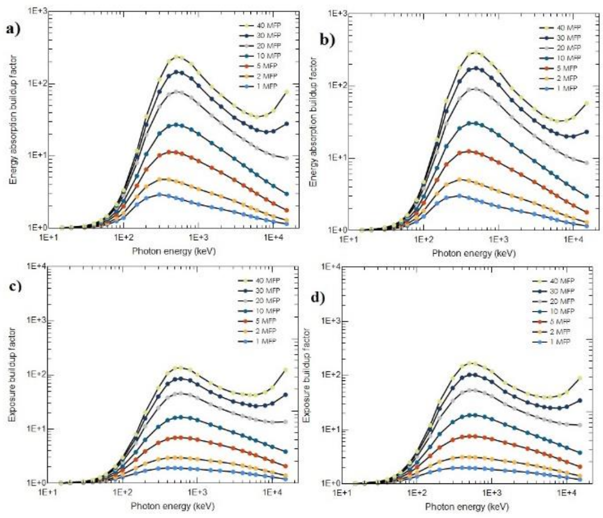

Figure 4. The changes of EABF for Alloy 617 (a) Alloy 800HT (b) and EBF for Alloy 617 (c) Alloy 800HT (d) versus photon energies by EpiXS.

Equivalent atomic number (Z_{eq}) is an effective parameter on determination of energy absorption calculation and absorbed dose. While Z_{eff} is obtained by the addition of all partial photon interactions, Z_{eq} is determined solely by Compton scattering [36]. The calculated Z_{eq} of the samples are given in Table 4. Z_{eq} has its maximum value at 1 MeV for both alloys. It is observed that Z_{eq} values of Inconel-617 are higher than those of Incoloy-800HT.

Table 4. Z_{eq} values of 617 and 800HT alloys between the energies of 0.015-15MeV.

Energy (keV)	Z_{eq} (Inc617)	Z_{eq} (Inc800HT)
15	26.46104	26.47957
20	26.45470	26.50107
30	28.59625	26.52105
40	28.70020	26.50251
50	28.75756	26.53665
60	28.80680	26.54707
80	28.86903	26.55556
100	28.91059	26.55063
150	29.00115	26.56072
200	29.05314	26.56221
300	29.11305	26.56657
400	29.14712	26.56913
500	29.16834	26.57028
600	29.18479	26.57050
800	29.19192	26.57456
1000	29.19869	26.57403
1500	28.83937	26.49461
2000	28.40207	26.40110
3000	28.11853	26.34982
4000	28.04009	26.33604
5000	28.00175	26.32920
6000	27.97497	26.32054
8000	27.94756	26.31632
10000	27.93625	26.31598
15000	27.92845	26.32064

Lastly, fast neutron attenuation abilities of the alloys were determined by Phy-X/PSD. Fast neutron removal cross section (FNRCS) is obtained as 0.163 cm^{-1} for 800HT alloy, while that is obtained as 0.161 cm^{-1} for 617 alloy. The lower FNRCS is observed for Inconel-617 due to the higher Z_{eff} values. It can be said that alloy 800 HT is slightly more appropriate than alloy 617 for neutron shielding.

4. CONCLUSIONS

In the study, radiation-matter interaction parameters of Inconel-617 and Incoloy-800HT alloys were determined by Phy-X/PSD and EpiXS codes in the range of 1keV-1GeV in order to determine the radiation protection capabilities. Among the parameters, buildup factors were determined only by using EpiXS, and TVL was obtained only by Phy-X/PSD. Other calculated parameters were obtained by both codes. According to the obtained results, although, the parameters of the studied alloys have near values to each other, Inconel-617 has higher shielding ability than Incoloy-800HT. It can be also mentioned that both of the alloys show higher shielding capability than the commonly used shielding materials such as ordinary concrete, hematite-serpenite, ilmenite-limonite, steel-scrap, basalt-magnetite, steel-magnetite and ilmenite concretes reported before. As a result, it is mentioned that Inconel-617 and Incoloy-800HT can be evaluated as shielding materials for high temperature applications especially for nuclear applications. Also, alloy 800 HT is slightly more suitable for neutron shielding than alloy 617.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Zeynep AYGUN: Performed the study, analysed the results and wrote the manuscript.

Murat AYGUN: Analysed the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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