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Vol. 10(8), pp. 263-269, 30 April, 2015
DOI: 10.5897/IJPS2015.4276
Article Number: FCEC51A52342
ISSN 1992 - 1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Neutron and gamma-ray shielding properties of modified Ni- Ti- X Mo maraging steels

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Received 5 Febraury, 2015; Accepted 25 March, 2015

MCNP5 program was used to investigate the neutron and gamma shielding properties of Ni-Ti- X Mo maraging steels. The MCNP5 program experimental setup was designed using neutrons of 14.1 MeV from sealed neutron tube and ^{60}Co as a gamma ray source. Particular attention was given to the shielding properties of neutron and gamma for low nickel free cobalt, titanium containing modified maraging steel in correlation to the molybdenum as alloying element. Based on the shielding properties, Ni-Ti- X Mo maraging steels with different molybdenum content show the same shielding properties of neutron and gamma rays when compared to the standard maraging steel 18Ni (C250). In addition, the secondary gamma ray spectra due to neutron irradiation show no obvious difference between all steels under investigation. A comparison with available calculated and experimental results of the mass attenuation coefficient at gamma energies 1173 and 1332 keV for other steels has been done. From an economic point of view newly cobalt free low-nickel maraging steel is cheaper than standard C250 maraging steel as shielding materials.

Key words: Neutron shielding, gamma ray shielding, maraging steel, MCNP5 program.

INTRODUCTION

Today, nuclear radiation has a vital role in our recent live. It has applications in many fields like medicine, industry, agriculture, archaeology, geology, academics and many others. Radiation shielding materials are required to protect the population and equipments from harmful effect of radiation. For shielding design, neutrons and gamma rays are the main types of nuclear radiation, which have to be considered, since any shield that attenuates neutrons and gamma rays will be more effective in attenuating other radiations (Yılmaz et al., 2011). Therefore, in this study, the gamma linear and mass attenuation coefficients and the effective fast neutron removal cross-section with a mass removal cross section for compounds of maraging steels (Ni-Ti- X Mo) with different molybdenum content were calculated, in addition, the secondary gamma rays emitted due to neutron interactions with these compounds have been studied. Maraging steels belong to a new class of high strength steels with the combination of strength and toughness that are among the highest attainable in general engineering alloys (Shetty et al., 2008). Voluminous experimental data have been accumulated

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Table 1. The chemical composition of steels under investigation.

	Chemical composition, wt%												
Steel	C	Si	Mn	P	S	Cr	Co	Mo	Ni	Al	Ti	N	Fe
M15	0.019	0.071	0.021	0.013	0.008	0.007	-	0.007	12.0	0.06	0.0131	0.003	87.66
M19	0.015	0.185	0.099	0.02	0.010	0.007	-	4.63	12.0	0.10	0.130	0.008	82.79
M22	0.018	0.170	0.111	0.012	0.007	0.007	-	3.15	11.9	0.10	0.135	0.007	84.38
C250	0.030	0.100	0.100	0.010	0.030	-	8	3.20	18.0	0.10	0.200	0.001	70.22

on the effect of irradiation on the mechanical properties of many steels and alloys. Steels of this type with the highest strength are those containing cobalt. The use of steel with cobalt as a structural material in atomic applications is undesirable due to the high induced radioactivity under conditions of high-energy neutron bombardment. Expensive alloying additions such as Ni and Co increase the production cost for maraging steels as the cost has been the major roadblock for the widespread usage of these steels in domestic applications such as tooling, sport goods, etc. The high production cost in association with dual-use marketing issues has motivated research worldwide for cheaper alloy design. Cobalt-free maraging steels with high strength, ductility, and toughness have been developed in recent years (Hu et al., 2008; Nili-Ahmadabadi, 2008; Schnitzer et al., 2010; Leitner et al., 2011; Mahmoudi et al., 2011; Mahmudi et al., 2011; Sha et al., 2013). The best combination of properties of Maraging steel can be utilized in nuclear applications where high reliability is the principal concern. This work concerns, study the radiation resistance (neutrons and gamma rays) of low nickel titanium containing Maraging steel without cobalt and with different amounts of molybdenum in comparison with standard Maraging steel 18Ni (C250) through MCNP5 code. MCNP5 code is a general-purpose Monte Carlo radiation transport code for modeling the interaction of radiation with matter. It utilizes the nuclear cross section libraries and uses physics models for particle interactions and gives required quantity with certain error (MCNP X-5, 2003; Shultis and Faw, 2010). The neutron source used in the code is a point source which emits neutrons with energy 14.1 MeV. The two gamma energies used in the code are 1173 and 1332 keV emitted from ^{60}Co as a source of gamma rays.

EXPERIMENTAL

Material design

In this work, new developed free cobalt low nickel maraging steel with 12 mass percent nickel as base metal were designed. 12% Ni-Ti new developed maraging steel with different amounts of molybdenum were investigated. To study the radiation resistance (neutron and gamma) of new developed maraging steels, the authors also study comercial maraging steel 18Ni (C250) for the sake of comparison. Table 1 shows the chemical composition of steels under investigations.

MCNP5 experimental setup

To calculate the fast neutron removal cross section and the linear attenuation coefficient of gamma rays for maraging steels under study, two narrow beam transmission geometries were done. The first geometry, for neutron, Figure 1(a) shows a lead box of 3 x 3 x 3 m^3 dimensions as a neutron source housing with a cylinder collimator of 1 cm radius. The detector was put on the same line at a distance 61 cm from neutron source. The detector collimator has an aperture of 1 cm radius and 5 cm thickness. The investigated materials were put between the source and the detector at a distance 40 cm from the source. The materials under investigation were a cylinder of 3 cm radius and thicknesses with 2, 5, 10 and 15 cm. Tally type 4 was used to count the number of neutrons inter the detector per MeV. cm^2. s^{-1}. The number of histories used in the code in the neutron case is 30 x 10^6. The estimated statistical error in all neutron energy bens with these numbers of histories not exceed 10%. Also, The error in the energy bens of secondary gamma rays not exceed 0.05%. The second geometry, for gamma, Figure 1(b) shows the ^{60}Co house box with dimensions 15 x 30 x 30 cm^3 made of lead and coated by 0.5 cm thickness of steel. A cone lead collimator was put between the source and the investigated material with 15 cm length, end opening of 0.5 cm radius and also coated with 0.5 cm of steel. The investigated materials were put between the source and the detector at a distance 22.5 cm from the source and have the same dimensions as in neutron geometry. The gamma detector was put on the same line in front of a gamma source at a distance 44.5 cm from it. The detector shield face was 39.5 cm from the source with opening radius 0.5 cm. The same tally type 4 was used to estimate gamma photons registered in the detector per MeV. cm^2. s^{-1}. The number of histories used in the code is 20 x 10^6. The statistical error in the calculated data not exceed 0.05% for each gamma energy.

RESULTS AND DISCUSSION

Neutron shielding properties

Neutron attenuation through the investigated materials have been calculated by performing the transmission experiment in narrow beam geometry shown in Figure 1(a). Figure 2 shows the neutron flux transmitted to the detector in case of no material and the neutron flux transmitted through 2, 5, 10 and 15 cm thicknesses of the different shielding materials under investigation. The figure shows that, the fast neutrons were moderated and moves from its higher group to a group of less energy. The number of moderated neutrons was increased with

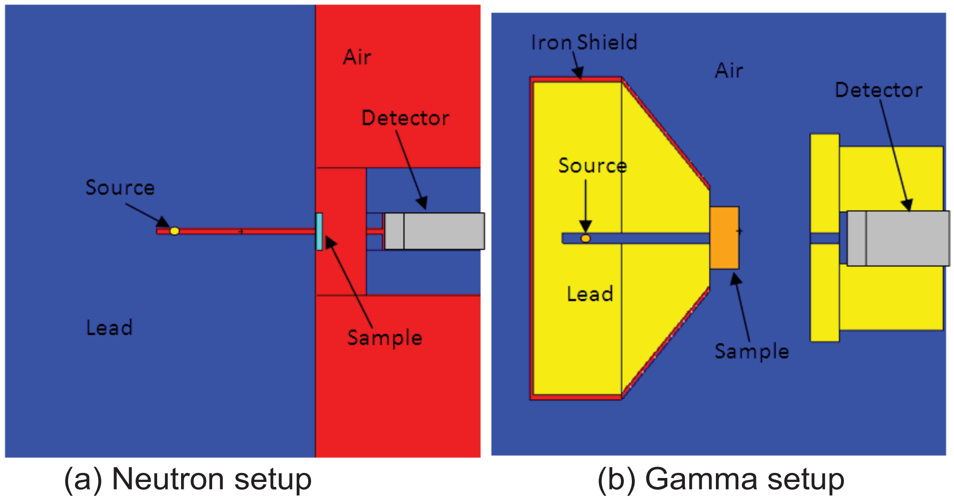

Figure 1. Experimental setup for measuring effective fast neutron removal cross-section (a) and gamma linear attenuation coefficient (b).

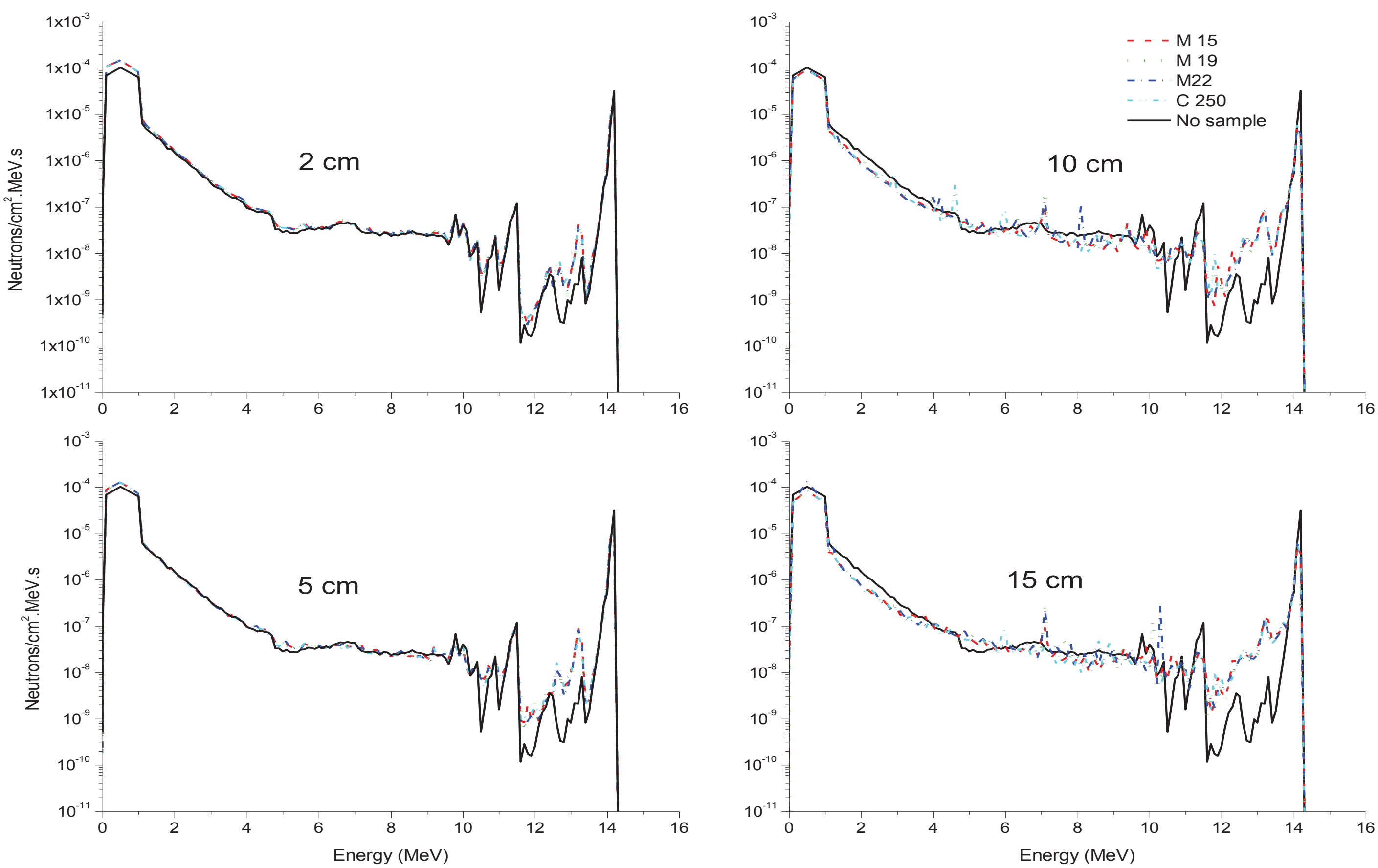

Figure 2. Transmitted neutron spectra versus neutron energy at different thickness of the investigated steels in comparison with neutron spectra without sample (black line).

shielding material thickness increased. The important is that, the neutron moderation ratio for the different steels and for the compared steel C250 is the same. This result was insured by calculating the effective fast neutron

Table 2. Effective fast removal cross section Σ_R (cm^{-1}) and mass removal cross section Σ_R/ρ (cm^2/g) for steels under study.

	Steel No.			
	M15	**M19**	**M22**	**C250**
Σ_R (cm^{-1})	0.4976E-01	0.5038E-01	0.5073E-01	0.5287E-01
Σ_R/ρ (cm^2/g)	0.6332E-02	0.6411E-02	0.6455E-02	0.6727E-02

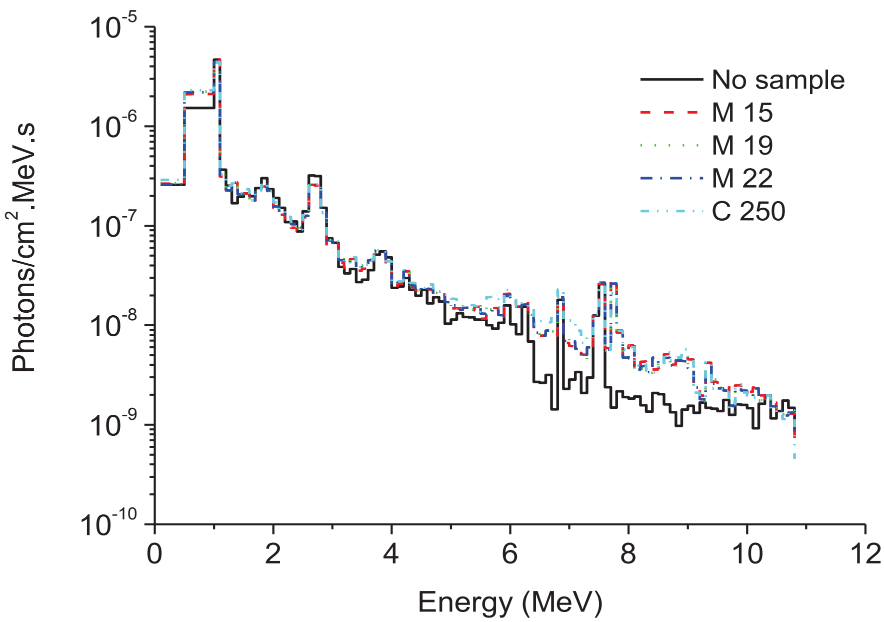

Figure 3. Secondary gamma ray spectra arising from neutron interactions with under investigation steels.

removal cross section Σ_R (cm^{-1}) which obtained by the equation $\Sigma_R = \frac{ln\frac{I_0}{I}}{x}$ where I and I_0 are the neutron intensity with and without the material between the neutron source and the detector respectively and x is the material thickness. Therefore, plotting each $ln\frac{I_0}{I}$ versus x, the slope of the straight line obtained is the value Σ_R of the material. The obtained effective fast neutron removal cross section Σ_R (cm^{-1}) and the mass removal cross section Σ_R/ρ (cm^2/g) for the investigated materials are tabulated in Table 2 with the values of standard steel for comparison. As shown in the table, the produced steels have approximately the same values of effective and mass removal cross-section and as the values of the standard material C250. This means that, our produced steels work as neutron shielding material and have the same neutron attenuation in comparison with the standard.

Secondary gamma rays

Interaction of neutrons with elements constitute the material produce secondary gamma-rays. Figure 3 shows the spectra of gamma-rays produced due to interactions of neutrons with 2 cm thickness of steels under investigation including the standard. There are no appear signals for gamma coming from the cobalt present in the standard sample C250 as expected. This can be explained by, the number of neutrons which moderated and arrived to thermal neutrons is a very modest number due to the small thicknesses used in the study. In addition, the self shielding of the material makes it absorb some of produced gamma rays specially low energy gamma like that produced from neutron interaction with cobalt (1173 and 1332 keV). Also, the figure shows an increase in secondary gamma for the standard steel in the energy range from 5.5 to 8 MeV more than others. Figure 4 shows the integral flux of secondary gamma versus the material thickness of all investigated materials. As shown in figure the integral flux decreases exponentially with material thickness increase.

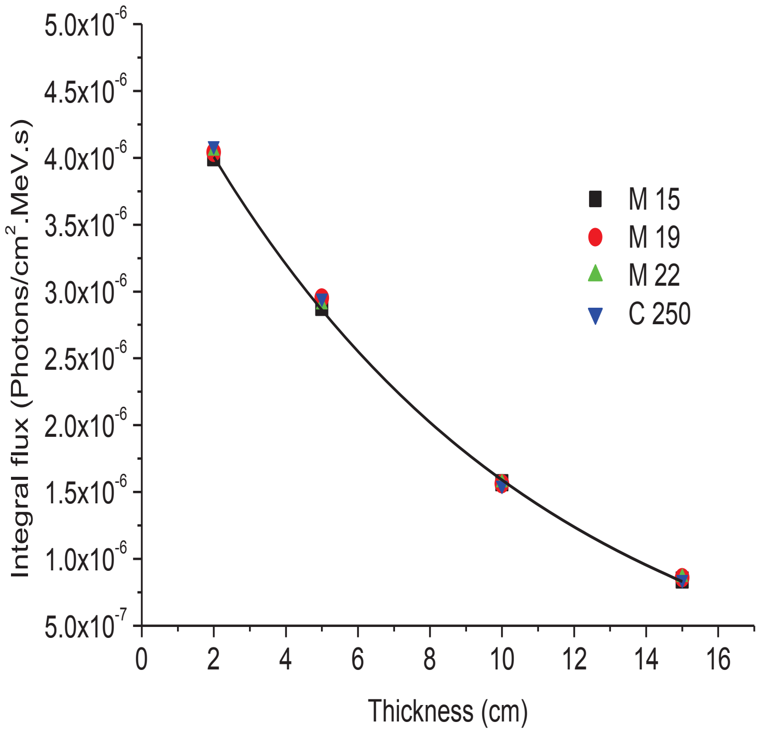

Figure 4. Integral flux of secondary gamma versus shielding material thickness of all studied materials.

This is because, the most number of neutrons interact through the first layers of shielding materials and produce secondary gamma rays which shielded from the residual layers of the material itself. An empirical equation for the emitted secondary gamma rays versus material thickness can be deduce in the form $\emptyset = ae^{-bx}$ where, $\emptyset$ is the integral flux of secondary photons and x is the material thickness and a, b are constants for the material type.

Gamma ray shielding properties

Narrow beam geometry shown in Figure 1(b) was used to study gamma ray attenuation through our materials and through the standard one. Figure 5 shows ^{60}Co gamma ray spectra transmitted through 2, 5, 10 and 15 cm thickness of the investigated materials with gamma spectra transmitted directly without material between the source and the detector. As shown in the figure, for all materials there is no obvious difference in the values of gamma attenuation. Also, when material thickness increase gamma intensity decrease. Intensity of the two gamma lines 1173 and 1332 KeV which collected under energy bins 1200 and 1350 KeV respectively were calculated versus the material thicknesses. As in the case of neutron, the gamma linear attenuation coefficient μ (cm^{-1}) of the two gamma lines for materials can be calculated from the equation $\mu = \frac{ln\frac{I_0}{I}}{x}$ where I, I_0 are the gamma line intensity with and without the material and x is the material thickness. Hence, plotting each $ln\frac{I_0}{I}$ versus x for each gamma line, the slopes of the two straight lines obtained are the values μ of the material for these two energy lines. The values of gamma linear attenuation coefficient μ (cm^{-1}) and mass attenuation coefficient μ (cm^2/g) of the materials for the two gamma lines are summarized in Table 3. The tabulated data show the obvious approximation between the investigated materials in attenuation of gamma rays. Also, there is no difference between standard steel and the investigated materials in gamma attenuation.

The results of the present simulation of the mass attenuation coefficient at energies 1173 and 1332 keV were compared with the experimental results of different steels (Akkurt, 2009; EL-Kameesy et al., 2011). In addition, the present results were compared with the theoretical and simulated results of WinXcom, Geant4 and MCNP (Singh et al., 2015) for steel 1. The chemical composition of compared steels is shown in Table 4. Table 5 shows the results of the present work and the possible experimental and calculated data reported in the mentioned different literatures. As shown in Table 5 the results of the present study agree with the theoretical

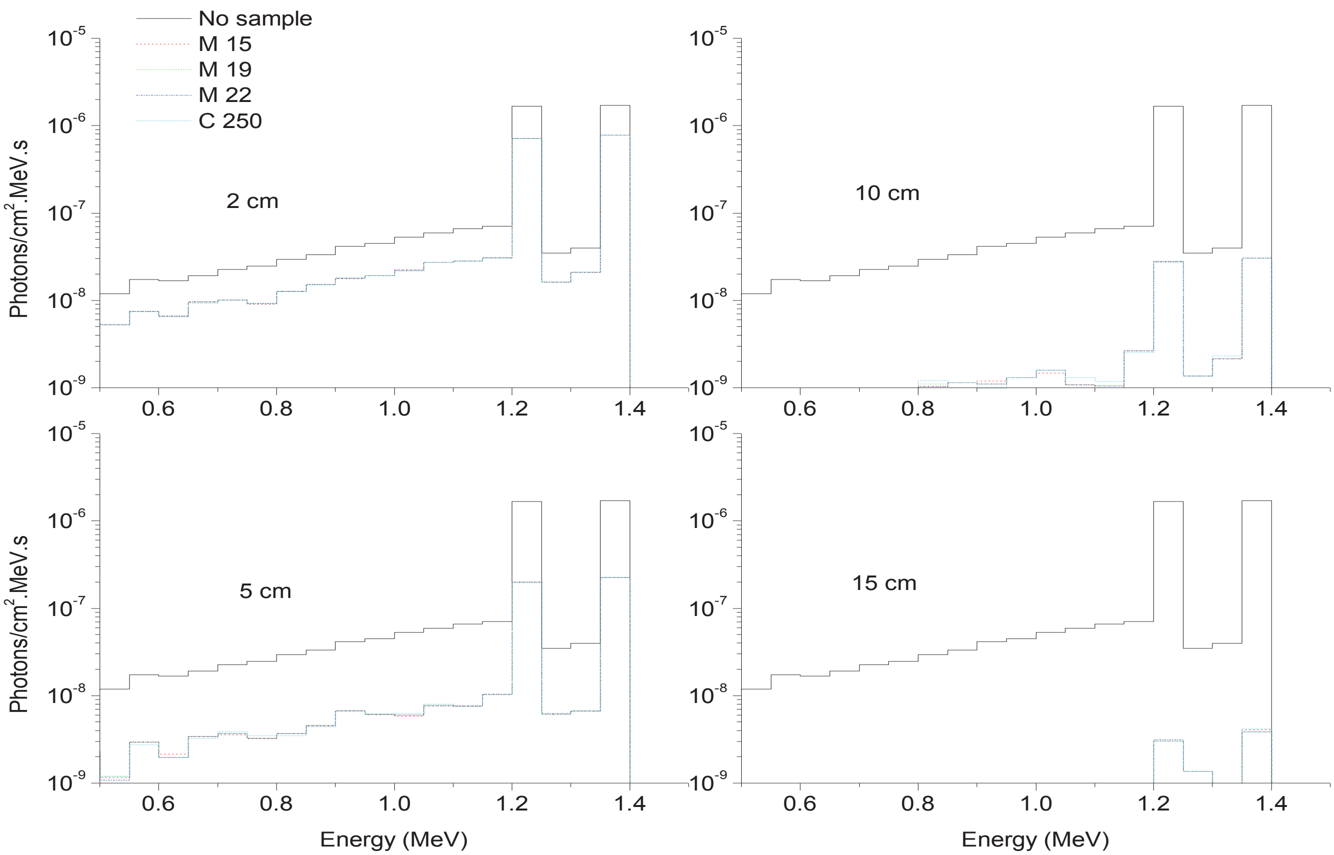

Figure 5. Gamma ray spectra transmitted to the detector in present of shielding materials with different thicknesses compared with no shielding materials.

Table 3. Gamma linear attenuation coefficient μ (cm^{-1}) and mass attenuation coefficient μ/ρ (cm^2/g) for steels under investigation.

Steel No.	Eγ=1173 KeV		Eγ=1332 KeV	
	μ (cm^{-1})	μ/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)
M15	4.1903E-01	5.3311E-02	4.0301E-01	5.1274E-02
M19	4.1992E-01	5.3424E-02	4.0460E-01	5.1475E-02
M22	4.1913E-01	5.3324E-02	4.0446E-01	5.1458E-02
C250	4.1958E-01	5.3382E-02	4.0301E-01	5.1273E-02

WinXcom and simulated Geant4, MCNP results for steel 1. The difference from the experimental results may be due to the setup of the experiments and the steel density, in addition to the difference in compounds of the steels.

Conclusion

The produced steels have the same ability to moderate neutrons and to attenuate gamma rays in comparison with C250 Maraging steel. The problem of secondary gamma rays produced due to neutron interactions with steel can be solved with higher material thickness, where there is an exponential relation between secondary gamma and the material thickness due to the material self shielding. The results of gamma ray mass attenuation coefficient at energies 1173 keV and 1332 KeV for steels under investigation were found comparable with experimental results, the theoretical WinXcom, the Geant4 and MCNP simulation values of others steels. From economical point of view, newly modified Maraging steel with previous shielding properties are promising material in shielding applications. Future work should be done to study neutron shielding properties and neutron reflection characteristics at higher thicknesses and at higher temperature for the produced steels to be used as a nuclear reactor vessel.

Table 4. The chemical composition of comparative steels (Akkurt, 2009; EL-Kameesy et al., 2011; Singh et al., 2015).

Steel	Chemical composition. wt%														
	C	Si	Mn	P	S	Cr	Co	Mo	Ni	Al	Ti	N	Cu	W	Fe
S1	0.1200	0.37	1.00	0.024	0.005	17.0	0.07	0.630	6.86	-	-	-	0.210	-	73.70
S2	0.9000	-	-	-	-	4.10	-	5.000	-	-	-	-	-	6.4	83.70
S3	0.1200	0.05	0.28	0.060	0.008	0.02	-	0.005	0.013	-	-	-	-	-	98.50
Steel 19	0.0102	-	-	-	-	3.71	-	3.190	12.03	-	0.0250	-	-	-	81.03
Steel 21	0.0880	-	-	-	-	4.36	-	3.180	12.16	-	0.0400	-	-	-	80.17
Steel 12	0.0169	-	-	-	-	5.04	-	2.870	12.12	-	0.0300	-	-	-	79.92
Steel 1	0.4200	0.25	0.89	0.021	0.110	1.05	-	0.200	0.06	0.049	0.0019	-	0.010	-	97.03

Table 5. The mass attenuation coefficient at energies 1173 keV and 1332 keV for the steels under investigation and the comparative steels (Akkurt, 2009; EL-Kameesy et al., 2011; Singh et al., 2015) for the sake of comparison.

Energy (keV)	Present study				Experimental (Akkurt, 2009)			Experimental (EL-Kameesy et al., 2011)			Theoretical and simulated (Singh et al., 2015)
	M15	M19	M22	C250	S1	S2	S3	Steel 19	Steel 21	Steel 12	Steel 1
1173	5.331E-02	5.342E-02	5.332E-02	5.338E-02	4.84E-02	4.449E-02	7.141E-02	6.700E-02	7.247E-02	7.081E-02	5.490E-02
1332	5.127E-02	5.147E-02	5.145E-02	5.127E-02	3.25E-02	3.336E-02	6.664E-02	6.245E-02	6.521E-02	6.360E-02	5.120E-02

Conflict of Interest

The authors have not declared any conflict of interest.

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