Determination and Fabrication of New Shield Super Alloys Materials for Nuclear Reactor Safety by Experiments and Cern-Fluka Monte Carlo Simulation Code, Geant4 and WinXCom

Bünyamin Aygün[1], Turgay Korkut[2] and Abdulhalik Karabulut[3]

[1]Atatürk University Faculty of Science, Department of Physics, Erzurum, Turkey,
[2]Sinop University, Faculty of Engineering, Department of Nuclear Engineering, Sinop, Turkey.
[3]Atatürk University Faculty of Science, Department of Physics, Erzurum, Turkey,

E-mail: akara@atauni.edu.tr

Abstract. Despite the possibility of depletion of fossil fuels increasing energy needs the use of radiation tends to increase. Recently the security-focused debate about planned nuclear power plants still continues. The objective of this thesis is to prevent the radiation spread from nuclear reactors into the environment. In order to do this, we produced higher performanced of new shielding materials which are high radiation holders in reactors operation. Some additives used in new shielding materials; some of iron (Fe), rhenium (Re), nickel (Ni), chromium (Cr), boron (B), copper (Cu), tungsten (W), tantalum (Ta), boron carbide (B4C). The results of this experiments indicated that these materials are good shields against gamma and neutrons. The powder metallurgy technique was used to produce new shielding materials. CERN - FLUKA Geant4 Monte Carlo simulation code and WinXCom were used for determination of the percentages of high temperature resistant and high-level fast neutron and gamma shielding materials participated components. Super alloys was produced and then the experimental fast neutron dose equivalent measurements and gamma radiation absorpsion of the new shielding materials were carried out. The produced products to be used safely reactors not only in nuclear medicine, in the treatment room, for the storage of nuclear waste, nuclear research laboratories, against cosmic radiation in space vehicles and has the qualities.

1. Introduction

Radiation is a natural part of our lives. When we breath the radioactive gases in the atmosphere (such as the actinonin 86 and radioactive isotopes of radon and thoron), as a result of this radioactive materials naturally occure in our bodies, our muscles, our bones, our cells. For example, potassium has a half-life of 1.42 million years in our body (^{40}K). The radiation, we are exposed to, contains cosmic radiation, comes from outside of the world, and also the natural radiation exist in our world naturally. Beside this, we are also subjected to the radiation (X-ray) used in medicine for diagnosis and treatment, nuclear tests, nuclear power centrals, nuclear accidents and radioactive waste. One of the most important problems of mankind is to meet the growing need for energy. Fossil fuels are used to meet the energy needs to a great extent. However, both are in line and came to a halt near the damage they cause to the environment.

Other energy sources are solar, wind and water as known renewable energy. However, the use of these resources is limited and insufficient. In this case, considering the huge damage caused as a result of an accident that occurs to provide energy, nuclear power plants are coming to the fore. Therefore the safety of nuclear power plant is essential. Ordinary materials cannot be used to prevent radiation leaks in nuclear power plants. The materials to be used specifically must have both a good ability to withstand radiation and high retention in addition to the feature temperatures. For these reasons to meet the growing needs in this field studies about new generation high temperature resistant shielding

materials have gained speed. Work has been done on this subject in the literature. Alloy materials, such as CS-516, SS-403, SS-410, SS-316, SS-316, SS-304L, Incoloy-600, Monel-400 and Cupero-Nickel had determined the neutron and gamma shielding properties. Cupero-Nickel was found to be best shielding for gamma rays. For neutron, SS-316 was found to be the best shielding materials in energy 2–12 MeV [1]. Ferro-tungsten investigated the neutron shielding properties. Fast neutron shielding property of the ferro-tungsten steels has soft compare. They ultimately determine ferro-tungsten is doing better than steel shielding against fast neutrons [2]. 0.8% C, 0.05% Pb, 17% Cr, 11% Ni, 20% Mo + 1.92% W, 4.5 to 0.5% B, 0.05% Gd by using thermal corrosion resistant material they managed to get a patent by neutron shielding alloys [3].   To stop the fast neutron fission in the reactor tungsten (W) and rhenium with the compound (Re), tantalum (Ta), titanium (Ti) with such elements, alloys has done [4].   Medical applications and the of radio isotopes transportation during in nuclear reactors, gamma, neutron radiation in order to avoid leakage tungsten ratio of 90-98% (W), nickel (Ni), iron (Fe) such as metals combining have made heavy armor alloy. This heavy armor of material lead to commonly used gamma radiation of, to be said better than uranium [5]. They increased the percentage of armor materials in austenitic and ferritic stainless steel pipe and developed ductile and received patents against neutron radiation with good heat conduction [6]. They examined the scattering of neutrons at high pressure and to neutron shielding used in the tungsten carbide ceramic tubes [7]. Suitable for use in nuclear applications for control purposes, good neutron absorbent the contents of nickel, chromium, molybdenum, gadolinium alloy have developed armor material with about 5% by weight of boron [8]. Storage of nuclear waste for transport with high boron and Fe (49.7%), CR (17.7%), Mn (1.9%), Mo (7.4%), W (1.6%), B (15.2%), Cu (3.8%) and Si (2.4%) with the elements and stainless steel alloys, Ni-Cr-Mo high dose of neutron radiation in the desired diameter using alloys have made tubes to good shielding [9]. The base metal is iron, being more resistant to corrosion and neutrons, gamma radiation tungsten to its high absorption capacity, Al-boron carbide, borate, stainless steel, Ni, Cr, Mo, have developed a composite armor material containing Gd alloy [10].

The principal goals of this study are to acquire neutron cross section and neutron capture via Geant4 Monte Carlo code for samples.

2. Material and methods
The used materials to develop super alloys, of iron (Fe), rhenium (Re), nickel (Ni), chromium (Cr), boron (B), copper (Cu), tungsten (W), tantalum (Ta), boron carbide (B4C). Mixture ratios have identified with Geant4 Monte Carlo Simulation Code high fast neutron cross sections. Benefiting from international alloys standard powder metallurgy method we used for the production samples of super alloys. All of these samples have 2.5 g. weights and 2cm. diameter. These powder materials mixtured for 4 hours. After was pressed by SPECAC model hydraulic pellet press machine at 600MPa. Finally, disc samples were annealed at 1100^0C during four hours. In this study 5types of super alloys were produced.

Radiation test was carried out by exposing to neutron source ^{241}Am-Be (number of events processed 1000000) and Ba^{133} 10mCi. Five types of super alloys have identified GEANT 4 code generated by quasi-experimental the macroscopic cross section of 7 MeV gamma and 4.5 MeV neutron radiation.

2.1. Monte carlo simulation code
Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. In the GEANT4 code system, neutrons have been modeled by using high-precision (HP) data-driven hadronic physics models (G4Neutron HPElastic, G4Neutron HPInelastic, G4Neutron HPCapture, and G4Neutron HPFission). So neutrons are simulated from thermal neutron energies (0.025 eV) up to 20 MeV. The neutron cross-section data are taken from the GEANT4's G4NDL4.0 library, in which data comes largely from the ENDF/B-VII evaluated data library which explicitly includes all nuclear

resonances in the form of point-like cross-sections rather than in the form of parameterizations. In the present study 4.9.4.p01 released version was used to simulate interactions between neutrons and shield samples. As outputs absorbed doses and macroscopic cross sections were given.

We obtained cross section and neutron capture via GEANT4 Monte Carlo code. In the first place, atomic stoichiometry and densities of the samples have been entered. In second place simulation has been started for 1000000 primary neutron particles. Then in the practical section absorbed dose by the detector is obtained.

3. Results and discussion

Macroscopic cross-section shows the probability of collisions of atomic radiation target substance. This value higher can be said that the material well absorbs radiation. The macroscopic cross section with neutron capture is influential factors to determine neutron and gamma radiation shielding characteristics of the sample. Monte Carlo simulations, five sample were produced and the stainless steel 316LN reference sample, then equivalent dose rate measurements were performed. Table.3.1. shows experimental results.

Table 1. Percentage composition of manufactured samples by mass.

Sample code	Material	Geant4 4.5 MeV neutron total macroscopic cross sections (cm^{-1})	7 MeV gamma mass attenuation coefficient (cm^2/g)	Equivalent dose rates 4.5 MeV neutron $(\mu Sv/h)$	Melting point range (°C)
-	**Emp.**	-	-	1.38556	-
[a]**RNS** 316LN (reference samples)	Armor steel is used in nuclear reactors	0.269224	0.03008	0.97812	1345-1440
SA1[b]	40%Ni-20%Cr-30%Fe-1%B_4C-4%Re-5%W	0.337380	0.31794	0.590105	1480-1500
SA2	50%Ni-20%Cr-25W-5%Cu	0.354598	0.30594	0.391248	1480-1500
SA3	50%Ni-25%Cr-15%Fe-5%Re-5%W	0.371489	0.32393	0.525218	1480-1500
SA4	45%Re-40%B-10%Cr-5%Fe	0.418609	0.39377	0.876505	1480-1500
SA5	55%Re-38%B-2%Cr-5%Fe	0.446621	0.46391	0.733460	1480-1500

[a]**RNS:** References nuclear stainless steel
[b]**SA** : New super alloys material

Figure 1 and Figure 2 shows five types of super alloys have identified GEANT 4 code generated by quasi-experimental the macroscopic cross section of 7 MeV gamma and 4.5 MeV neutron radiation.
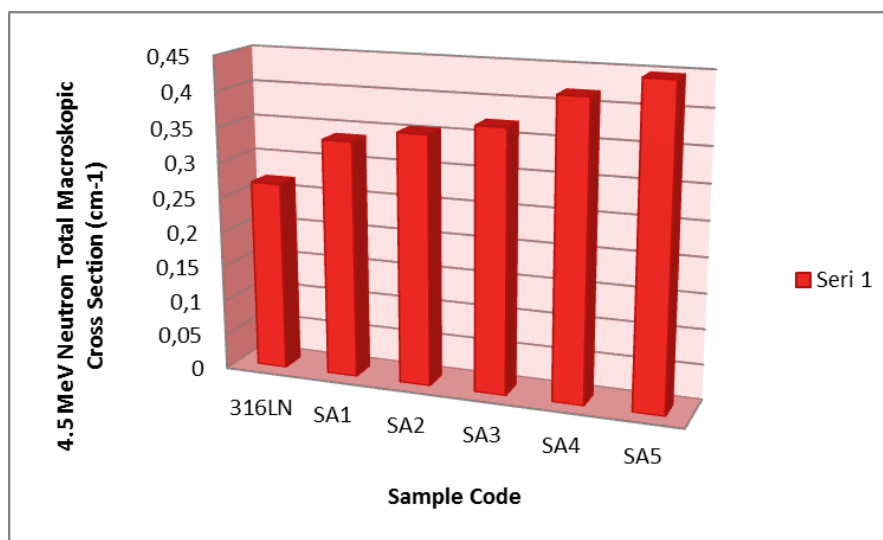
Figure 2. Total macroscopic cross sections by GEANT4 (4.5MeV neutron) of RNS 316LN.SA1.SA2.SA3.SA4.SA5
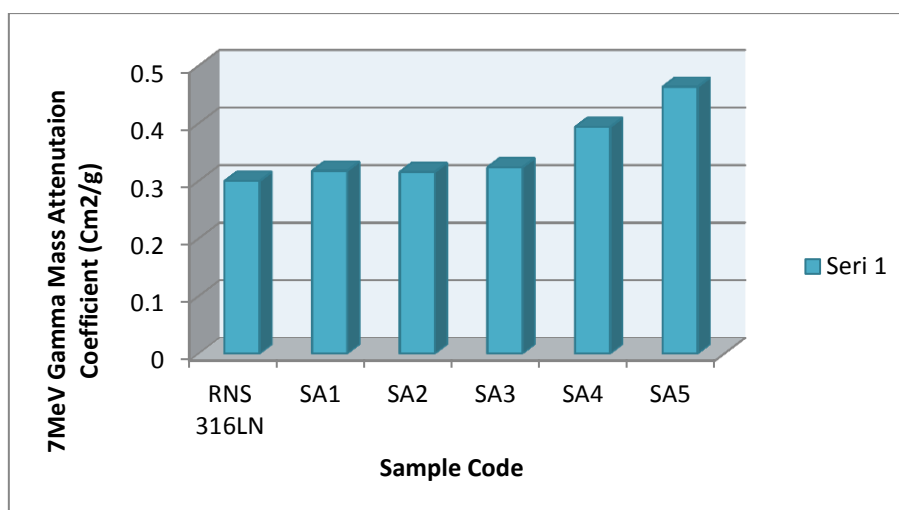

Figure 2. Gamma linear absorption coefficient by GEANT4 (7 MeV gamma) of RNS 316LN.SA1.SA2.SA3.SA4.SA5

These dose values mean that equivalent dose rates (μSv/h) by the detector. Decreased equivalent dose rate value indicates that this sample has high neutron shielding performance. As can be seen from Table 1 cross section is increasing with the using of boroncarpide (B$_4$C), wolfram (W) in the samples and decreasing absorbed dose by a detector of stainless steel. From table 3.1. that SA1, SA2, SA3, SA4, SA5 sample have high cross section value and low absorbed dose rate. The dose from the example source 1.38556 (μsv/ h), while the second sample supply SA2 front titled these values 0,391248 (μsv/h) decreased value. However, in the reactor, the commonly nuclear steels used dose value for the 0.97812 (μsv/h) decreased. Figure 3 shows 4.5 MeV neutrons for experimental dose measurement results. So SA2 has high neutron shielding properties in comparison to other samples.
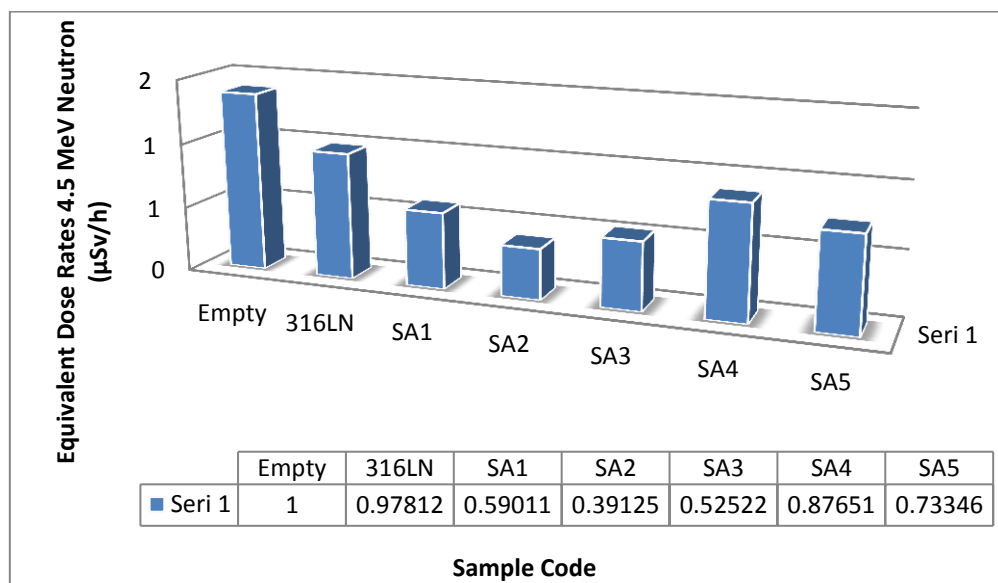
	Empty	316LN	SA1	SA2	SA3	SA4	SA5
■ Seri 1	1	0.97812	0.59011	0.39125	0.52522	0.87651	0.73346

Sample Code

Figure 3. 4.5 MeV neutrons for experimental dose measurement results.

Thus, as can be seen from table.1, is more effective shielding material because it has a high cross section, high neutron capture values and low absorbed dose rate.

SA1, SA2, SA3, SA4, SA5 WinXcom theoretical and experimental results for samples 276.389 (keV) 302.853 (keV) 356.017 (keV) 383.851 (keV) gamma radiation energy mass attenuation coefficient (cm^2/ g). This result is shown in Table 2.

Table 2 Experimental and theoretical (WinXcom) mass attenuation coefficients.

	Mass Attenuation Coefficient (cm^2/g)							
	276.389 keV Gamma		302.853 keV Gamma		356.017 keV Gamma		383.851 keV Gamma	
	*Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	Exp.	Theo.
SA1	0.088 ±0.0013	0.119	0.081 ±0.0054	0.112	0.073 ±0.0067	0.102	0.071 ±0.0010	0.098
SA2	0.090 ±0.0037	0.133	0.082 ±0.0010	0.123	0.071 ±0.0010	0.109	0.068 ±0.0017	0.104
SA3	0.109 ±0.0032	0.164	0.097 ±0.0010	0.147	0.083 ±0.0010	0.124	0.075 ±0.0020	0.116
SA4	0.099 ±0.0037	0.143	0.092 ±0.0010	0.133	0.081 ±0.0010	0.119	0.063 ±0.0017	0.114
SA5	0.121 ±0.0032	0.182	0.0107 ±0.0010	0.153	0.093 ±0.0010	0.134	0.085 ±0.0020	0.126

*Exp: experimental, Theo: Theoretical

Accordingly SA2 has greater value than standard steel and other samples from the prepared sample. As a result, samples prepared photon radiation can be used as an effective protective material.

4. Conclusions

We produced new super alloys samples having properties superior to the commonly used steel armor in this work in particular in nuclear power plants. In this production, we made largely dependent on international standards. We have identified materials ratio of combination of code using the Geant4 Monte Carlo Simulation mode. Produced made experimental measurements of the new super alloys which have proved to be better than the reference samples of materials by neutron shielding 316LN steel. These materials can be used for building walls of nuclear energy centrals, as moderator for nuclear reactors, in nuclear medicine departments and nuclear investigation centers, etc., to protect damages from neutron particle.

References

[1] Singh. V.P. and Badiger. N.M., 2014 Gamma ray and neutron shielding properties of some alloy materials.*AnnalsofNuclearEnergy,* 301-310

[2] Mawutorli Nyarku. Ramanathapura S. Venkata D., 2013 Experimental neutron attenuation measurements in possible fast reactor shield materials. *Annals of Nuclear,* **53**, 135-139.

[3] Schmidt. E. Schmieden, 2013, Search for long-lived stopped R-hadrons decaying out of time with pp collisions using the *ATLAS detector. Physical Review D* 88, 112003.

[4] Gilbert. MR. Sublet. JC., 2011. Neutron-induced transmutation effects in W and W-alloys in a fusion environment. *Nuclear Fusion,* **6**.

[5] Caldwell. Steven.. GWM Symposia.. 2013.. A Review of Tungsten Heavy Alloy Utilization in Isotope Transport Containers-13380 *Material science Waste Menagemnet.* United States.

[6] Kibata. M.. Saito.Y.. Tsubota. M.. Doken. Y.. Sato.M.. 2013. Neutron shielding material. method of manufacturing the same. and cask for spent fuel. US**8481986** B2 US 13/360.

[7] Zhao. L. Robinson. L. Paul. RL.. 2007. Application of cold neutron prompt-gamma activation analysis in environmental studies of aquatic plants. *Journal of Radioanalytical and Nuclear Chemistry.* Volume **271**. Number 3.

[8] Mizia. RE. Lister. TE. Pinhero. PJ. Swank. WD.2007. Neutron absorbing coating for nuclear criticality control. US Patent **6919576**.

[9] Blink. J. Choi. J. Farmer. J. 2007. Applications in the Nuclear Industry for Thermal Spray Amorphous Metal and Ceramic Coatings. Materials Science & Technology 2007 *Conference and Exhibition Detroit.* MI. United States September 16.Volume **40.**

[10] Choi. J-S. Farmer. J.C. Lee. C. Fischer. L. M. July 42007. Neutron-Absorbing Coatings for Safe. *Chemistry Materials and Life Sciences Directorate Lawrence Livermore National Laboratory* UCRL-TR-232463 Volume **1**.