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Determining Gamma Source in Uranium Molybdenum of Fuel in G.A Siwabessy Multi-Purpose Reactor

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A B S T R A C T

Nuclear fission reactions produce a lot of radionuclides that release energy, one of which is in the form of gamma radiation. Gamma radiation is produced by various types of radionuclides, and nuclear reactor fuel will produce different values of gamma intensity. Uranium Molybdenum (U_7Mo-Al) is the type of nuclear fuel for future research reactors that possesses many advantages. For the application of molybdenum-based fuel, it is necessary to determine the resulting gamma radiation. The purpose is to determine the gamma radiation produced from molybdenum-based fuel with various densities. This study begins with the determination of the mass composition of the reactor component, calculations with ORIGEN2.1, and data output analysis. The U_7Mo-Al density was varied, namely 2.96 gU/cm^3, 3.85 gU/cm^3, 4.44 gU/cm^3, 5.43 gU/cm^3, 6.91 gU/cm^3, and 8.29 gU/cm^3. The gamma radiation yield of U7Mo-Al is lower than that of uranium silicide (U_3Si_2) with the same density of 2.96 gU/cm^3. The result will add to the justification for the superiority of U_7Mo-Al compared to U_3Si_2/Al. For U_7Mo-Al with densities of 3.85 gU/cm^3, 4.44 gU/cm^3, 5.43 gU/cm^3, 6.91 gU/cm^3, and 8.29 gU/cm^3, the one that produced the lowest gamma radiation intensity is 3.85 gU/cm^3 while the highest is 8.29 gU/cm^3. This explains that the intensity of the gamma radiation produced is directly proportional to the fuel density. The low intensity of gamma radiation in molybdenum-based fuel can be used as a suggestion in shielding design to ensure the operational safety of reactors.

1. INTRODUCTION

Gamma radiation is produced from the decay process of radioactive substances that occur in atomic nuclei. The radiation is emitted from an unstable atomic nucleus or at a nucleus in an excited state which then returns to the ground state. One way of producing gamma radiation is through nuclear fission reactions in the research reactor. This reaction will produce many radionuclide products and radiation sources, one of which is gamma radiation [1-2].

The gamma radiation in the reactor is an essential factor in radiation safety, mainly when used to calculate the thickness of the shield and the gamma heating [2]. The determination of gamma radiation is mandatory to determine how much of it

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will be produced in a new type fuel with different composition. The study of gamma radiation has been determined in the research of Rohanda [1] and Ardani [2]. The simulations were carried out by ORIGEN2.1 to produce three groups of nuclides, each of which was summed to obtain the total gamma radiation. The total decay gamma radiation consists of activation products, actinides and daughters, and fission products [3].

Over time, the nuclear reactor fuel is upgraded to increase the utilization of the reactor. Uranium molybdenum (U_7Mo-Al) is a type of fuel that has been studied as a future fuel for uranium silicide (U_3Si_2/Al) replacement in research reactors. Several studies stated the advantages of U_7Mo-Al compared to U_3Si_2-Al and uranium dioxide (UO_2), such as higher fuel density, corrosion resistance, and low neutron absorption cross-section. One of the U_7Mo-Al compositions that can increase reactor operating cycle is U_7Mo/Al [4].

Based on the many advantages of using U_7Mo-Al fuel, the RSG-GAS reactor is proposed to convert its fuel from U_3Si_2/Al-fuel into U_7Mo/Al-fuel. Changing the type of fuel in a reactor need various studies, one of the supporting studies is the analysis of gamma radiation. The purpose of this study is to determine the gamma radiation produced from molybdenum-based fuels with various densities. This study begins with the determination of the mass composition of the fuel component, calculations with ORIGEN2.1, and data output analysis. This research used the RSG-GAS equilibrium core with 15 and 30 MWth power. Variations in fuel densities in U_7Mo/Al materials are needed to determine the best option. The chosen densities are 2.96 gU/cm^3, 3.85 gU/cm^3, 4.44 gU/cm^3, 5.43 gU/cm^3, 6.91 gU/cm^3, and 8.29 gU/cm^3. Then, the intensity of the gamma radiation source from U_7Mo/Al fuel was compared to U_3Si_2/Al fuel with a density of 2.96 gU/cm^3. This result is used to complement the advantages of U_7Mo/Al data, especially in operational safety of RSG-GAS.

2. THEORY

a. G.A Siwabessy Multi Purpose Reactor

RSG-GAS is the world's first Material Testing Reactor (MTR)-type research reactor operated directly using Low Enriched Uranium (LEU). RSG-GAS was initially designed to use LEU oxide (U_3O_8-Al) fuel, with a density of 2.96 gU/cm^3 and U-235 enrichment of 19.75%. Light water is used as the reactor coolant and moderator. The RSG-GAS core configuration is composed of 40 fuel elements (EB) and 8 control elements (EK), and beryllium (Be) reflector elements in a 10×10 grid. A core casing surrounds this grid to direct flow cooling the core components. Outside the core casing, an L-shaped reflector block made of beryllium is positioned adjacent to the reactor core. The reactor core consists of 100 grid which serves as fuel elements, control elements, beryllium reflector elements, and irradiation positions. Each fuel element consists of 21 plates with a dimension of 7.71×8.1×60 cm. The control element in the RSG-GAS core has the same size as the fuel element [5, 6]. This reflector arrangement covers both sides of the reactor core. The configuration of the RSG-GAS reactor core is shown in Fig. 1.

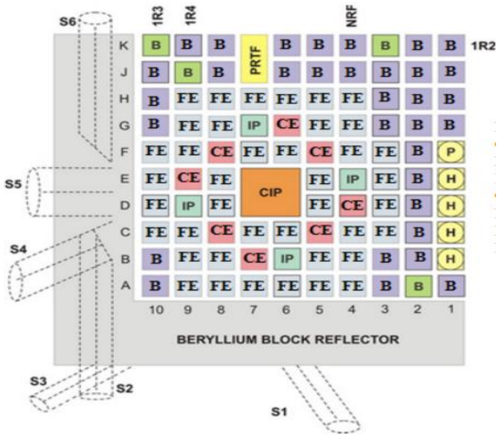

Fig. 1. RSG-GAS Core Configuration [7]

There are 8 holes intended for irradiation facilities for radioisotope production located at the irradiation position (IP) and central irradiation position (CIP). The irradiation holes can be seen on grids B6, D6, D7, D9, E4, E6, E7 and G7 [7]. Radioisotope production in RSG-GAS is carried out by placing the material or sample in a coated capsule.

Table 1. Charactersitics of the RSG-GAS equilibrium core of of U_3Si_2Al fuel [8]

Parameter	Description
Reactor type	Open pool
Fuel element	Uranium silicide (U_3Si_2Al)
Moderator material	H_2O
Reflector	Be and H_2O
Nominal power	30 MWth
Number of fuel elements (EB)	40
Number of control elements (EK)	8
Dimensions EB and EK	7.71×8.1×60
U-235 enrichment	19.75%
U-235 weight per fuel element	250 grams
U-235 weight per control element	178.6 grams

b. Sources of Gamma Radiation in The Reactor

One of the products of nuclear fission reactions is gamma radiation. There are two critical components for a fission reaction: the presence of neutrons and nuclear fuel [9]. U-235 is a fissile element that is often used as reactor fuel. When the nucleus of the U-235 atom captures a neutron, a fission reaction occurs. The probability of splitting the U-235 atomic nucleus when capturing thermal neutrons is about 82%. The remaining 18% possibility is the formation of U-236 accompanied by gamma (γ) radiation release. The U-235 cleavage reaction equation can be seen in Eq. 1.

$$U^{235} + {}_0n^1 \rightarrow (X_1 + X_2) + (2/3)_0n^1 + \gamma \qquad (1)$$

Based on Eq. 1, U-235 splits into new isotopes (X_1 & X_2), accompanied by the release of gamma (ɣ) and forming 2 or 3 new neutrons. The isotopes X_1 and X_2 are radioactive elements that emit gamma radiation whose intensity varies according to their half-lives. The new neutrons are partly used to continue the subsequent fission reaction, which among the resultants is gamma radiationThese gamma emission produced through fission reaction will be a source of gamma radiation in the reactor.

One of the essential characteristics of the gamma radiation source in the reactor is the intensity. The intensity of the gamma radiation source is a quantity that describes the ability of the gamma radiation rate to interact with the surrounding materials [11]. The amount of scattered photons per second in a unit area expresses the flux of the reactor. Thus, the unit of gamma radiation flux in the reactor is photon/cm^2.s [10]. We can only observe the power of the source of gamma radiation in the reactor by simulating using a computer program recognized by IAEA due to its radioactive nature.

c. Gamma Radiation Intensity

Fig. 2 shows a material with a certain thickness (x) exposed to gamma radiation with a certain intensity. The intensity of gamma radiation before penetrating material I_0 is greater than the intensity of gamma radiation after penetrating material I. Gamma energy before penetrating material E_1 has a greater value than the energy after penetrating material E_2 [11]. The linear attenuation equation can express this decrease in gamma radiation intensity as shown in Eq. 2.

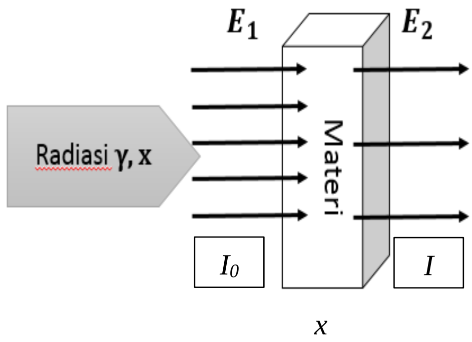

Fig 2. Illustration of photon radiation passing through material with a thickness of *x*

$$\Delta I(x) = -I_0(x)\mu\Delta x \qquad (2)$$

d. ORIGEN2.1

Oak Ridge Isotope Generation (ORIGEN) is a module of the reactor physics code package developed by Oak Ridge National Laboratory. The ORIGEN2.1 computer code simulates the nuclear fuel cycle and calculates the nuclide composition and the production and decay of radioisotopes in the reactor. The primary use of ORIGEN2.1 is to calculate the nuclide composition and other properties related to the nuclear material. The output ORIGEN2.1 will display the contribution of each nuclide in detail to the overall total for each experiment. One output data is regarding the spectrum and release rate of gamma radiation emitted from irradiated nuclear fuel at operating conditions according to certain reactors with their irradiation history [3, 12].

The libraries listed in ORIGEN2.1 are decay, photons, and cross sections. The decay and photon libraries are used to determine the spectrum and intensity of the gamma radiation source. For ease of calculation, the photon energies in ORIGEN2.1 are divided into 18 groups [3]. Table 2 describes the grouping of photon energies in ORIGEN2.1. The average gamma energy in Table 2 is the output result of ORIGEN2.1.

In ORIGEN2.1, calculating the spectrum and intensity of gamma is done by accumulating nuclide during the fission process. The number of Ni nuclides changes as a function of time is explained by the first-order ordinary differential equation in Eq. 3.

Table 2. Photon energy group structures of ORIGEN2.1 [15]

Group	Lower boundary (MeV)	Upper boundary (MeV)	Average (MeV)
1	0.0000E-02	2.0000E-02	1.0000E-02
2	2.0000E-02	3.0000E-02	2.5000E-02
3	3.0000E-02	4.0000E-02	3.7500E-02
4	4.0000E-02	7.0000E-02	5.7500E-02
5	7.0000E-02	1.0000E-01	8.5000E-02
6	1.0000E-01	1.5000E-01	1.2500E-01
7	1.5000E-01	3.0000E-01	2.2500E-01
8	3.0000E-01	4.5000E-01	3.7500E-01
9	4.5000E-01	7.0000E-01	5.7500E-01
10	7.0000E-01	1.0000E 00	8.5000E-01
11	1.0000E 00	1.5000E 00	1.2500E 00
12	1.5000E 00	2.0000E 00	1.7500E 00
13	2.0000E 00	2.5000E 00	2.2500E 00
14	2.5000E 00	3.0000E 00	2.7500E 00
15	3.0000E 00	4.0000E 00	3.5000E 00
16	4.0000E 00	6.0000E 00	5.0000E 00
17	6.0000E 00	8.0000E 00	7.0000E 00
18	8.0000E 00	1.0000E 01	9.5000E 00

$$\frac{dN_i}{dt} = \sum_{j=1}^{N} I_{ij}\lambda_j N_j + \phi \sum_{k=1}^{N} f_{ik}\sigma_k N_k - (\lambda_i + \phi\sigma_i + r_i)N_i + F_i\,, \quad i = 1 \ldots N \qquad (3)$$

N_i is the i nuclide concentration. I_{ij} is a fraction of the radioactive disintegration by other nuclides, leading to the formation of nuclide i. λ_i is the radioactive decay constant. ϕ is the position and average energy of the neutron flux, and f_{ik} is the fraction of absorption of neutrons by other nuclides, leading to the formation of nuclides. σ_k is the average of the neutron absorption spectra of the cross-section of nuclide k. r_i is the release rate of nuclide i from the system. F_i is the rate of nuclide i [3]. By solving N, ORIGEN2.1 can calculate the rate of photon release from nuclide i using the DEC command card, where the calculation equation is determined as follows.

$$P_i = g_i \lambda_i N_i \qquad (4)$$

P_i is the rate of photon release from nuclide i, g_i is the photon released per decay (in ORIGEN2 using the photon library) [3]. The ORIGEN2 database includes three nuclide families: 130 nuclides belong to actinides, 850 nuclides belong to fission fragments, and 720 nuclides belong to activation products (1,700 nuclides in total), each with a different library.

3. METHODOLOGY

This study begins with calculating the U7Mo/Al fuel composition for the RSG-GAS equilibrium core. This composition follows the pattern of the amount of U-235 mass in each fuel element. The total mass of U-235 used is 300, 390, 450, 550, and 700 grams for each fuel element. RSG-GAS core components data was obtained from the literature [1]. The mass distribution of the constituent parts of the various RSG-GAS fuels can be tabulated in Table 3.

Table 3. Mass distribution of elements for the preparation of various RSG-GAS core fuels

Fuel	U3Si2/Al (g)	U7Mo/Al (g)					
Density	2.96 gU/cm^3	2.96 gU/cm^3	3.85 gU/cm^3	4.44 gU/cm^3	5.43 gU/cm^3	6.91 gU/cm^3	8.29 gU/cm^3
U-235 mass per element	250 (gU)	250 (gU)	300 (gU)	390 (gU)	450 (gU)	550 (gU)	700 (gU)
U-235	11428	11428	13428	17028	19428	23428	29428
U-238	46435.296	46435.296	54561.87	69189.72	78941.62	95194.78	119574.5
Si	4538.297	-	-	-	-	-	-
Mo	-	3473.187	4081.025	5175.133	5904.539	7120.215	8943.729
Al	2188.108	937.7604	1101.877	1397.286	1594.226	1922.458	2414.807

Mass Composition of elements in RSG-GAS core (g)

H	43214285.71
O	172857142.86
Mg	2181.76
Mn	536.40
Ti	128.00
Kr	326.40
Fe	549.60
Cu	312.00
Zn	255.60

The next step is to install the ORIGEN2.1 program, which consists of ORIGEN2.exe, library, input, and output. The four files must exist in the same folder. The next step is to make the input by entering data such as the research reactor cross section library, U_7Mo/Al fuel composition, target composition, and other data adapted to the operating conditions of the RSG-GAS.

The adjusted input data is in Table 3. Then a running program is carried out that generated an output file. The output on ORIGEN2.1 consists of three data: activation products, actinides + daughters, and fission products. These three data are included in the gamma energy release (photon/s).

4. RESULTS AND DISCUSSION

Gamma radiation on the RSG-GAS core fueled with uranium molybdenum (U_7Mo-Al) at a power level of 15 MWt and 30 MWt has been determined using the ORIGEN2.1 and summarized in Tables 4 and 5. The simulation has been done for 4 days. The gamma radiation intensity information is obtained from the output of ORIGEN2.1, which is divided into three nuclides: activation products, actinides + daughters, and fission products. The intensity of gamma radiation is divided into 18 energy groups from 0.01-9.8 MeV. The intensity of the gamma radiation source generated in the ORIGEN2.1 calculation follows the RSG-GAS reactor's operating history.

A comparison of the intensity of the gamma radiation in RSG-GAS for the fuel types of uranium silicide (U_2Si_3/Al) and uranium molybdenum (U_7Mo/Al) is shown in Fig. 3. The figure shows the difference in the intensity of the gamma radiation sources (photons/s) at density of 2.96 gU/cm^3 or 250 grams of U-235 per fuel element.

As shown in Fig 2.a, gamma radiation in the activation product in uranium silicide fuel has a higher intensity than uranium molybdenum fuel. In Figs. 2.b and 2.c, both fuels have the same intensity. Namely, the gamma radiation produced from actinide products, their decay products, and fission products in uranium silicide and molybdenum fuels has the same intensity.

The difference in the intensity of the activation products in the two fuels makes the total intensity of the gamma radiation sources different. This difference confirms that uranium molybdenum has a lower gamma radiation intensity than uranium silicide fuel. The lower intensity of gamma radiation can justify that uranium molybdenum has a better safety level than uranium silicide. The low intensity of gamma radiation will be suggested in the shielding design, so that it will ensure safe operation.

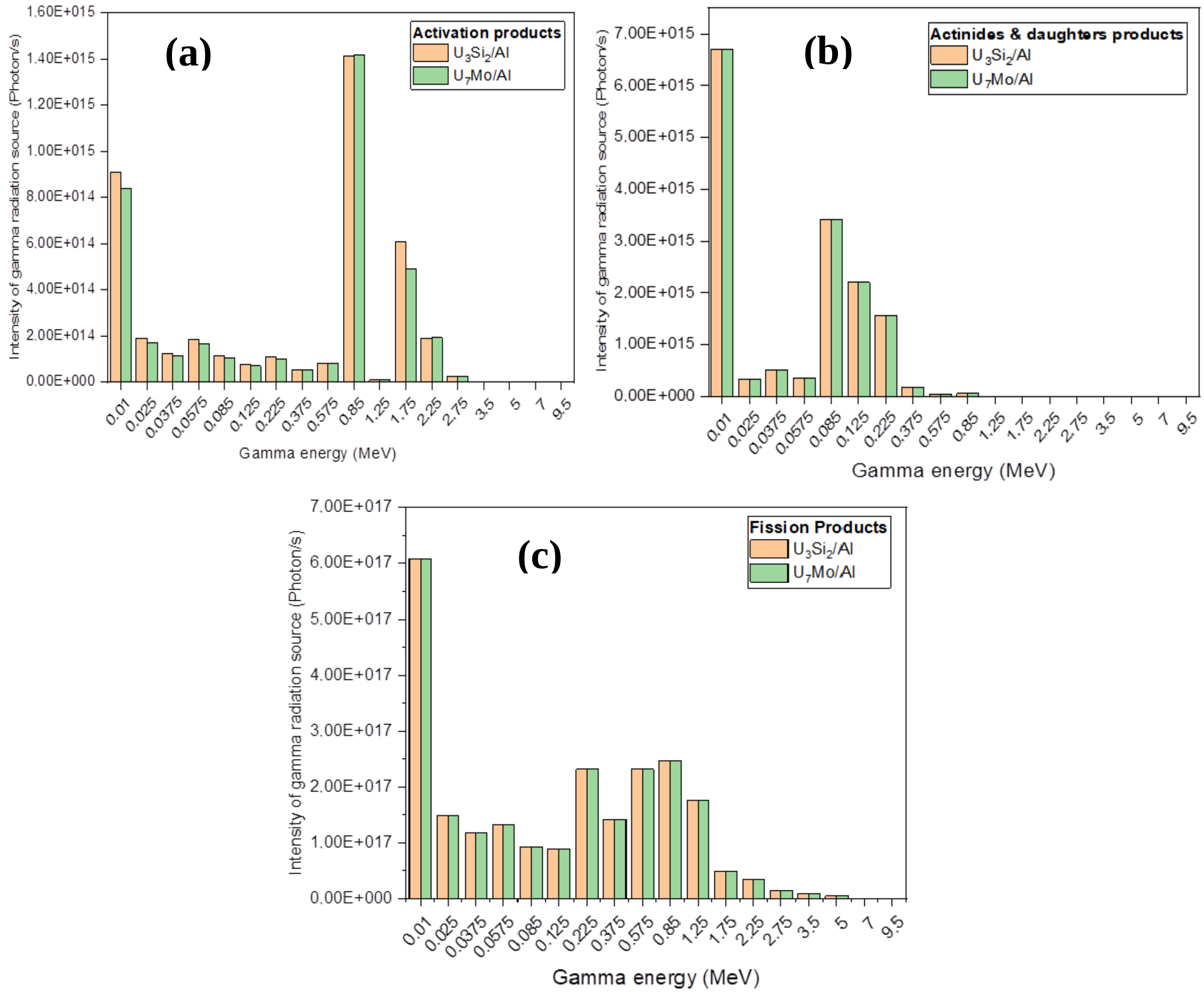

Fig. 3 Comparison of the intensity of gamma radiation sources on uranium silicide and uranium molybdenum RSG-GAS 2.96 gU/cm^3 fuels in various products (a) activation (b) actinides & daughters (c) fission

Each load of the U_7Mo/Al fuel has a different gamma radiation intensity. From the density of 3.85 to 8.29 gU/cm^3, as shown in Tables 4 and 5, it can be seen the intensity of the gamma radiation produced. U_7Mo/Al with a density of 3.85 gU/cm^3 produces the smallest gamma radiation intensity compared to other fuel densities, namely 2.3531E+18 (15 MWth) and 4.7063E+18 (30 MWth). Meanwhile, the highest gamma radiation intensity source from U_7Mo/Al fuel was obtained from a density of 8.29 gU/cm^3, namely 2.3594E+18 (15 Mwth) and 4.7188E+18 (30 MWth). From these results it can be seen that the effect of increasing density on increasing the intensity of gamma radiation is directly proportional. So it can be concluded that uranium molybdenum with 3.85 gU/cm^3 density provides better safety against radiation exposure than other higher densities. So from these results, the researchers suggested a fuel with the lowest density to be used as uranium molybdenum fuel. Although in previous studies making the density larger would increase the operating time [4,13].

The gamma radiation source from the ORIGEN2.1 calculation has 18 energy groups. The highest intensity of gamma radiation sources is in the energy group of 0.01 MeV. Meanwhile, the lowest intensity of gamma radiation sources is at a gamma radiation energy of 9.5 MeV. The intensity of this gamma radiation source produces an estimate of the dose and gamma heat [14].

Table 4. Intensity of gamma radiation sources at various U_7Mo-Al RSG-GAS fuel densities in 15 MWth

Intensity of gamma radiation sources on the U_7Mo-Al fueled RSG-GAS core (photons/s)					
Gamma energy (MeV)	**UMo-300**	**UMo-390**	**UMo-450**	**UMo-550**	**UMo-700**
Density (gU/.g^3)	**3.85 gU/cm^3**	**4.44 gU/cm^3**	**5.43 gU/cm^3**	**6.91 gU/cm^3**	**8.29 gU/cm^3**
0.01	6.1602E+17	6.1638E+17	6.1652E+17	6.1684E+17	6.1706E+17
0.025	1.4888E+17	1.4895E+17	1.4894E+17	1.4903E+17	1.4911E+17
0.0375	1.1831E+17	1.1849E+17	1.1849E+17	1.1858E+17	1.1867E+17
0.0575	1.3279E+17	1.3287E+17	1.3285E+17	1.3294E+17	1.3302E+17
0.085	9.6575E+16	9.6607E+16	9.6628E+16	9.6657E+16	9.6687E+16
0.125	9.2036E+16	9.2073E+16	9.2088E+16	9.2110E+16	9.2133E+16
0.225	2.3456E+17	2.3584E+17	2.3653E+17	2.3752E+17	2.3871E+17
0.375	1.4182E+17	1.4192E+17	1.4191E+17	1.4201E+17	1.4200E+17
0.575	2.3251E+17	2.3259E+17	2.3269E+17	2.3268E+17	2.3277E+17
0.85	2.4906E+17	2.4890E+17	2.4878E+17	2.4874E+17	2.4860E+17
1.25	1.7621E+17	1.7631E+17	1.7631E+17	1.7631E+17	1.7641E+17
1.75	4.9751E+16	4.9699E+16	4.9676E+16	4.9646E+16	4.9616E+16
2.25	3.5524E+16	3.5509E+16	3.5493E+16	3.5484E+16	3.5475E+16
2.75	1.4773E+16	1.4778E+16	1.4776E+16	1.4783E+16	1.4780E+16
3.5	9.2580E+15	9.2615E+15	9.2634E+15	9.2661E+15	9.2679E+15
5	5.0130E+15	5.0150E+15	5.0160E+15	5.0170E+15	5.0190E+15
7	4.0610E+13	4.0630E+13	4.0640E+13	4.0650E+13	4.0660E+13
9.5	7.6300E+09	7.6340E+09	7.6360E+09	7.6380E+09	7.6400E+09
Total	**2.3531E+18**	**2.3552E+18**	**2.3560E+18**	**2.3576E+18**	**2.3594E+18**

Table 5. Intensity of gamma radiation sources at various U_7Mo-Al RSG-GAS fuel densities in 30 MWth

Intensity of gamma radiation sources on the U_7Mo-Al fueled RSG-GAS core (photons/s)					
Gamma energy (MeV)	**UMo-300**	**UMo-390**	**UMo-450**	**UMo-550**	**UMo-700**
Density (gU/g^3)	**3.85 gU/cm^3**	**4.44 gU/cm^3**	**5.43 gU/cm^3**	**6.91 gU/cm^3**	**8.29 gU/cm^3**
0.01	1.2320E+18	1.2328E+18	1.2330E+18	1.2337E+18	1.2341E+18
0.025	2.9777E+17	2.9791E+17	2.9788E+17	2.9805E+17	2.9822E+17
0.0375	2.3663E+17	2.3699E+17	2.3697E+17	2.3715E+17	2.3733E+17
0.0575	2.6559E+17	2.6573E+17	2.6571E+17	2.6588E+17	2.6605E+17
0.085	1.9315E+17	1.9321E+17	1.9326E+17	1.9331E+17	1.9337E+17
0.125	1.8407E+17	1.8415E+17	1.8418E+17	1.8422E+17	1.8427E+17
0.225	4.6911E+17	4.7168E+17	4.7306E+17	4.7504E+17	4.7742E+17
0.375	2.8365E+17	2.8383E+17	2.8383E+17	2.8402E+17	2.8401E+17
0.575	4.6502E+17	4.6519E+17	4.6537E+17	4.6536E+17	4.6554E+17
0.85	4.9811E+17	4.9780E+17	4.9757E+17	4.9748E+17	4.9720E+17
1.25	3.5243E+17	3.5262E+17	3.5262E+17	3.5262E+17	3.5282E+17
1.75	9.9503E+16	9.9398E+16	9.9352E+16	9.9291E+16	9.9231E+16
2.25	7.1048E+16	7.1019E+16	7.0987E+16	7.0968E+16	7.0950E+16
2.75	2.9546E+16	2.9556E+16	2.9552E+16	2.9566E+16	2.9561E+16
3.5	1.8516E+16	1.8523E+16	1.8527E+16	1.8532E+16	1.8536E+16
5	1.0026E+16	1.0030E+16	1.0032E+16	1.0034E+16	1.0038E+16
7	8.1220E+13	8.1260E+13	8.1280E+13	8.1300E+13	8.1320E+13
9.5	1.5260E+10	1.5268E+10	1.5272E+10	1.5276E+10	1.5280E+10
Total	**4.7063E+18**	**4.7105E+18**	**4.7120E+18**	**4.7153E+18**	**4.7188E+18**

The intensity of the gamma radiation source can also be affected by the reactor power, as shown in Fig. 4. It shows that the intensity of U_7Mo/Al with a density of 8.29 gU/cm^3 gU at 30 MWt power is higher than that of 15 MWt power. The RSG-GAS uses a power of 15 MWt in its typical operations [7]. The impact of level reactor power with the intensity of the gamma radiation is directly proportional. That is, the intensity of the gamma radiation source will increase with increasing reactor power

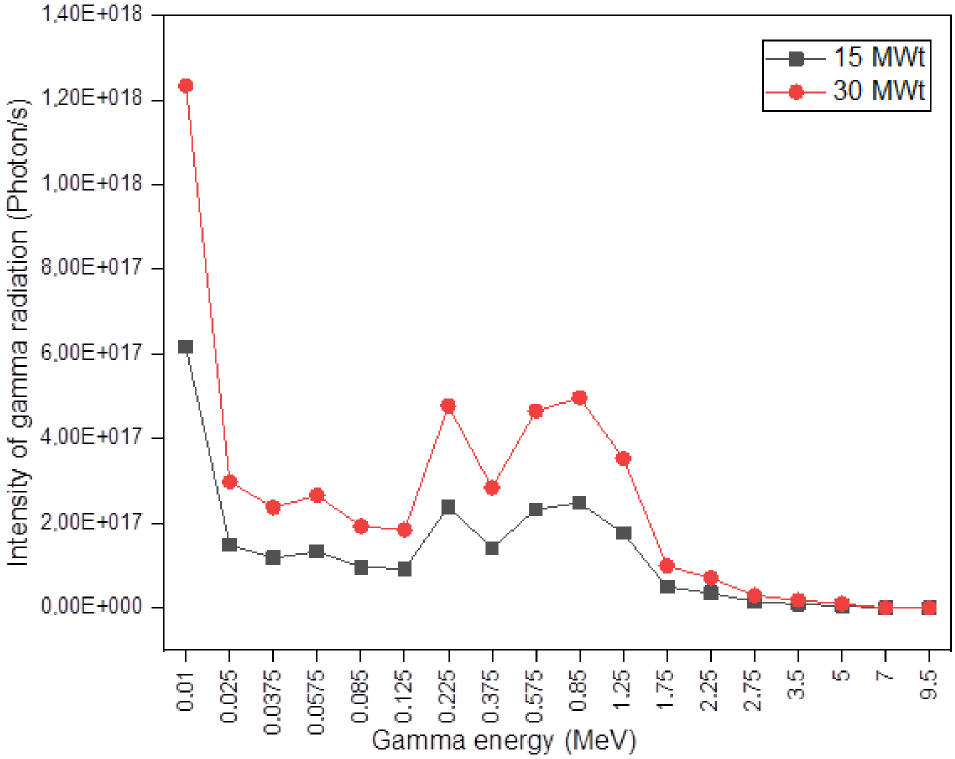

Fig 4. The intensity of the gamma source on U7Mo/Al 700 grams of RSG-GAS fuel at 15 and 30 MWt

The intensity of gamma radiation in RSG-GAS from the output of ORIGEN2.1 is the sum of activation products, actinides + its daughters, and fission products. As shown in Fig. 5, the three products produce different intensities of gamma radiation emission. Fission products have the highest intensity of gamma radiation emission compared to other groups of nuclides. This result is because the actinide nuclide group and its decays mostly consist of long-lived radionuclides. The radionuclide atoms split to form fission products and releasing neutrons to continue the chain reaction. A fission product with a short half-life is unstable and radioactive because it has more neutrons than a stable atom with the same atomic number. The initial unstable fission products undergo beta decay to become stable by converting a neutron to a proton with each beta emission. The first beta decay occurs rapidly with the release of high-energy gamma radiation. This results in the larger presence of gamma radiation in the fission products than in the nuclide activation products group and actinides + daughters, where there is gamma radiation of 168 MeV in each fission reaction [10, 15].

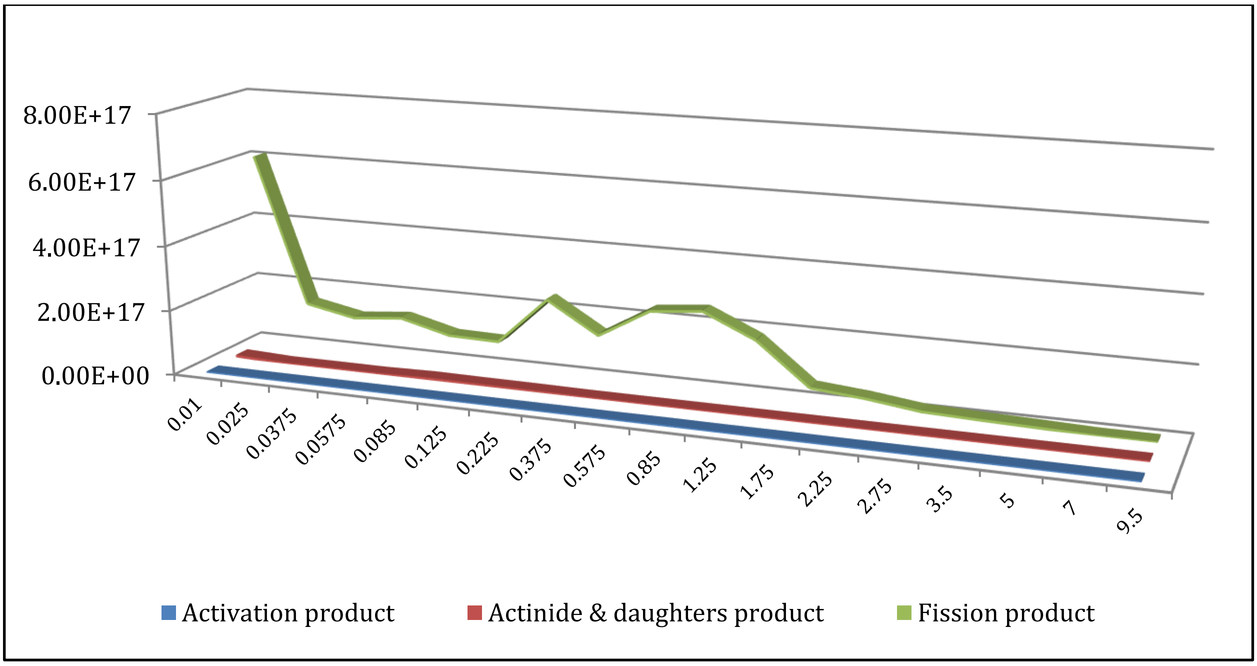

Fig 5. The intensity of the gamma source on U_7Mo/Al 8.29 gU/cm^3 RSG-GAS at 15 MWth

5. CONCLUSION

With the same mass composition, the intensity of the gamma radiation from U_2Si_3/Al fuel is larger than U_7Mo/Al. The difference in loading level affects the results of the gamma radiation intensity of the U_7Mo/Al fuel. The minimum intensity of gamma radiation is at fuel load of 300 gU. In comparison, the intensity of the largest gamma radiation source is at fuel load of 700 gU. The effect of power on the resulting gamma radiation intensity, thesmallest gamma radiation intensity, is U_7Mo/Al at 15 MW. The fission product nuclide group is the most significant constituent of this gamma radiation source.

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AUTHORS CONTRIBUTION

All authors contributed equally to this manuscript. All authors read and approved the final version of the paper.

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