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COMPARATIVE STUDIES ON PLUTONIUM AND ^{233}U UTILIZATION IN MINIFUJI MSR

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ABSTRACT

Molten salt reactor (MSR) has many merits such as safety enhancement and capability to be used for hydrogen production. A comparative evaluation of plutonium and ^{233}U utilization in miniFUJI MSR has been performed. Reactor grade plutonium (RGPu), weapon grade plutonium (WGPu), and super grade plutonium (SGPu) have been utilized in the present study. The reactors can obtain their criticality condition with the ^{233}U concentration in the Th-^{233}U fuel, RGPu concentration in Th-RGPu fuel, WGPu concentration in Th-WGPu fuel, and SGPu concentration in Th-SGPu fuel of 0.52%, 5.76%, 2.16%, and 1.96%, respectively. The Th-^{233}U fuel results in the soft neutron spectra of miniFUJI reactor. The neutron spectra turn into harder with the enlarging of plutonium concentration in loaded fuel where Th-RGPu fuel gives the hardest neutron spectra.

Key Words: **MSR, ^{233}U, reactor grade Pu, weapon grade Pu, super grade Pu,**

1. INTRODUCTION

Since they have many advantages, molten salt reactors (MSRs) designs have been endorsed as one of the six Generation IV nuclear power systems. Their merits amongst others are the waste burning capability, safety, and ability to be used for hydrogen production due to it can operate at high temperature [1-2]. MSR has a small excess reactivity and the refueling process can be accomplished online so that it has very low possibility for high power surges, which in sequence increases the safety performance [1].

At present, several countries such as USA, Russian Federation, France, Japan, and China, commonly under the frame of the Generation-IV International Forum (GIF) are developing many conceptual designs of MSR [3].

Nowadays, a thorium molten salt nuclear energy synergetic (THORIMS-NES) concept was being proposed for the safe and sustainable nuclear industry [2]. The THORIMS-NES concept consists of three stages. The building of a miniFUJI reactor, a small 10 MWe power reactor that may be developed during 7 years, is the first stage. The second stage is the construction of the 100-300 MWe FUJI reactor, a thorium molten salt reactor planned to go online in 12-14 years. The last stage is the setting up of regional breeding and chemical processing centers with production of ^{233}U by thorium spallation in an accelerator molten salt breeder (AMSB) [2].

Originally, the MSR designs consider Th-^{233}U or Th-Pu as main fuel. Recently, from the nuclear proliferation point of views, some experts suggest to avoid the separation of plutonium and minor actinides (MA) during the reprocessing of nuclear spent fuel. Moreover, the plutonium and MA recycling in thorium based reactor is an attractive answer for the nuclear wastes management since it will generate smaller amount of the high level nuclear waste (HLW) [4].

Preliminary study on plutonium and minor actinides utilization in miniFUJI reactor has been conducted [5]. In this previous study, 25 MW and 50 MW of the thermal power output of miniFUJI reactor have been evaluated. The power density of core are 3.98 W/cc and 7.96 W/cc for the 25 MW and 50 MW thermal power output, correspondingly.

In the present paper, a comparative evaluation of plutonium and ^{233}U utilization in miniFUJI MSR will be discussed. Three types of plutonium, namely: reactor grade plutonium (RGPu), weapon grade plutonium (WGPu), and super grade plutonium (SGPu) have been employed in the present study.

2. REACTOR DESIGN AND METHODOLOGY

General design parameters of studied small molten salt reactor of miniFUJI is presented in **Table 1**. The thermal power output is 25 MW with the power density of 3.98 W/cc. Assuming that the thermal efficiency of miniFUJI reactor is about 40%, this thermal output can be considered as the 10 MW of electric power output [5]. The corresponding core diameter and height are 2.0 m, and 2.0 m, respectively. Even though, MSR can be operated in long period, due to the graphite lifetime, the lifetime of reactor of about 20 years has been employed in this study. To substitute the graphite, the reactors should be shut down when the graphite achieves its time limit due to cracking and/or swelling [6].

As a matter of facts, in the present study, the neutronics aspect is the main consideration. The neutronics cell calculation [7] was performed by using PIJ (collision probability method code) routine of SRAC 2002 code [8], with the nuclear data library is JENDL-3.2 [9].

Table 1 Specification of miniFUJI MSR

Physics Parameters	**Specification**
Thermal power (MW)	25
Power density (W/cc)	3.98
Core geometry:	
Height (m)	2.0
Diameter (m)	2.0
Fuel	
Types	molten salt
Composition:	1) LiF, BeF_2, ThF_4, UF_4
	2) LiF, BeF_2, ThF_4, PuF_3
Inlet temperature (K)	840
Outlet temperature (K)	980
Lifetime (y)	20

The fuel salt composition is tabulated in **Table 2**. The total fraction of LiF and BeF_2 in the fuel salt is fixed at 71.78% and 16.00%, respectively. Mean while, the total fraction of ThF_4 and $^{233}UF_4$, as well as ThF_4 and PuF_3 are 12.22%, correspondingly. Here, the faction of the last two parts of fuel salts are changed gradually to adjust the criticality condition of reactors.

Table 2 Composition of fuel salt types

	LiF (%)	BeF_2 (%)	(Th-^{233}U)F_4 (%)	$ThF_4 + PuF_3$ (%)
Th-U fuel	71.78	16.00	12.22	0.00
Th-Pu fuel	71.78	16.00	0.00	12.22

The isotopic vector compositions of the reactor grade plutonium [10], weapon grade plutonium [11], and super grade plutonium [12] are listed in the following **Tables 3, 4,** and **5**, recpectively. These isotopic composition of the reactor grade plutonium has been taken from the spent fuel composition of the 3 GWth of pressurized water reactor (PWR) with 33 tons of annual loaded uranium oxide fuel, 33 GWd/t burnup, and 10 years cooling [10].

Table 3. Reactor grade plutonium vector (%)

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
1.58	57.76	26.57	8.76	5.33

Table 4. Weapon grade plutonium vector (%)

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
0.01	93.80	5.80	0.13	0.02	0.22

Table 5. Super grade plutonium vector (%)

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
0.00	98.00	2.00	0.00	0.00	0.00

3. RESULTS AND DISCUSSION

Figures 1 and **2** show the effective multiplication factor (*k-eff*) as a function of burnup for miniFUJI reactor with Th-^{233}U fuel, and Th-RGPu fuel, respectively. As shown in these figure, the reactors can achieve their criticality with the ^{233}U concentration in the Th-^{233}U fuel of 0.52% and RGPu concentration in Th-RGPu fuel of 5.76%, correspondingly. The maximum obtained burnup for the 20 years of lifetime is 18.41 GWd/ton and 18.05 GWd/ton for Th-^{233}U fuel, and Th-RGPu fuel, respectively. For obtaining the criticality conditions, the miniFUJI reactor requires high concentration of RGPu. One of the good points of MSR is a capability to incinerate the nuclear waste. This proof is obviously revealed in the **Figure 2**.

The effective multiplication factor as a function of burnup for Th-WGPu fuel and Th-SGPu fuel are ilustrated in **Figures 3** and **4,** in that order. As can be seen in these figures, the reactors can realize their criticality with the WGPu concentration of 2.16% and SGPu concentration of 1.96%, correspondingly. The maximum obtained burnup is 18.28 GWd/ton and 18.34 GWd/ton for Th-WGPu fuel, and Th-SGPu fuel after 20 years of reactor lifetime, respectively.

The maximum obtained burnup increases with the augmenting of fissile plutonium concentration in fuel salt.

Figure 5 demostrates the comparison of the effective multiplication factor as a function of operation time for all evaluated fuel types with criticality condition. Even though, this study focuses on the neutronics aspect of reactor, qualitatively, the Th-WGPu fuel reveals the safest condition with the lowest reactivity swing.

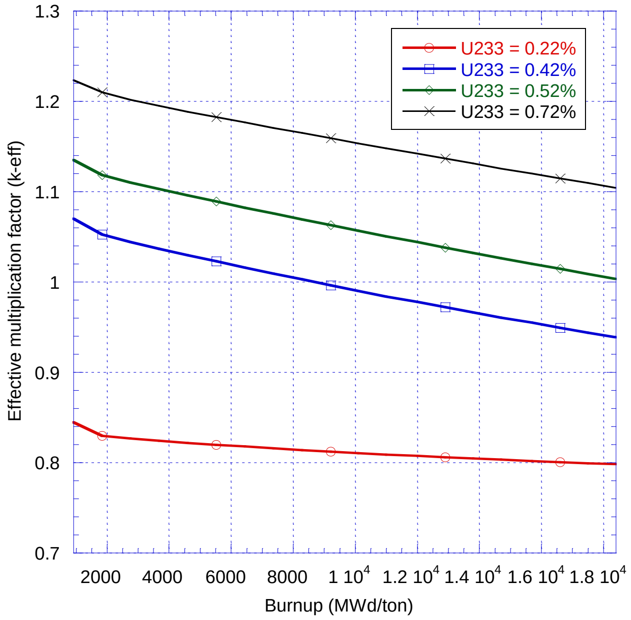

Figure 1. Effective multiplication factor of miniFUJI with Th-^{233}U fuel

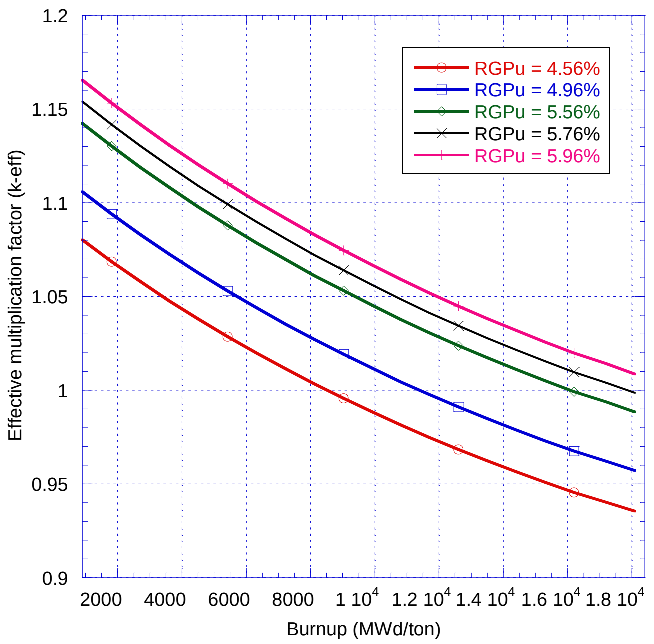

Figure 2. Effective multiplication factor of miniFUJI with Th-RGPu fuel

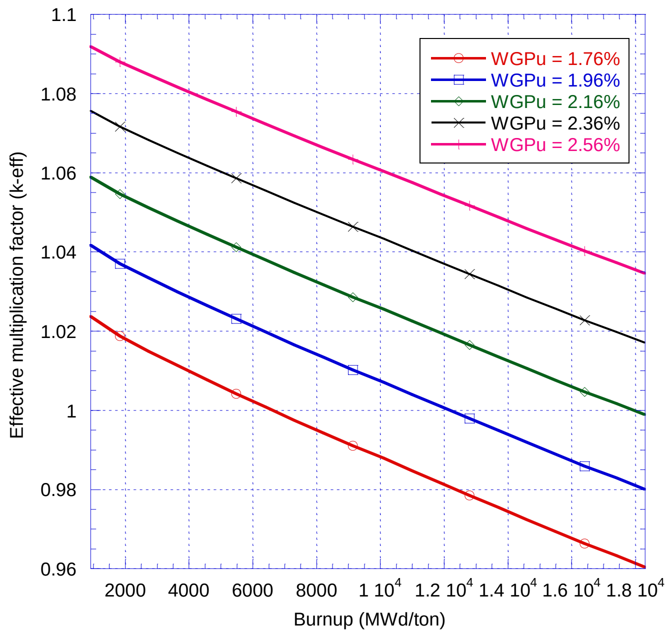

Figure 3. Effective multiplication factor of miniFUJI with Th-WGPu fuel

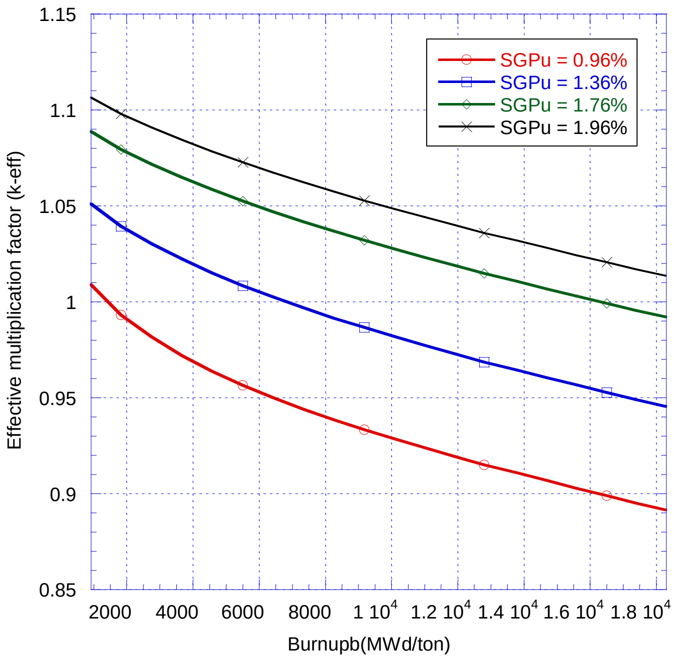

Figure 4. Effective multiplication factor of miniFUJI with Th-SGPu fuel

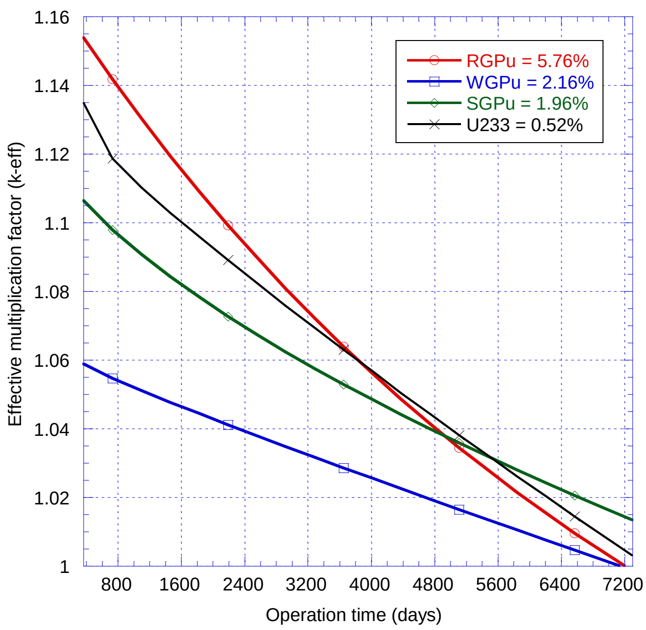

Figure 5. Comparison of effective multiplication factor of miniFUJI with various fuel types

The neutron spectra of miniFUJI MSR with Th-^{233}U fuel is presented in **Figure 6**. Clearly, the Th-^{233}U fuel results in the soft neutron spectra of miniFUJI reactor. The neutron spectrum becomes softer with the reducing of ^{233}U concentration in loaded fuel salt.

Figures 7, 8, and **9** exhibit the neutron spectra of miniFUJI reactor with Th-RGPu fuel, Th-WGPu fuel, and Th-SGPu fuel, correspondingly. For each fuel type, the neutron spectra become harder with the augmenting of plutonium concentration in loaded fuel. Th-RGPu fuel results in the hardest neutron spectra, while the Th-SGPu fuel gives the softest neutron spectra compared to that of the two others. These evidences may due to the higher concentration of absorber isotopes (such as ^{238}Pu and ^{240}Pu) in the reactor grade plutonium. These facts have also been reported in the references regarding the plutonium utilization in thermal reactor which results in the hardening of the neutron spectrum [13-15].

Figure 10 reveals the neutron spectra comparison of all evaluated fuel types with their criticality condition. Clearly from the figure that Pu utilization in miniFUJI MSR results in the hardening of neutron spectrum. The higher concentration of absorber isotopes in plutonium vector, the more harder of the neutron spectrum will be obtained.

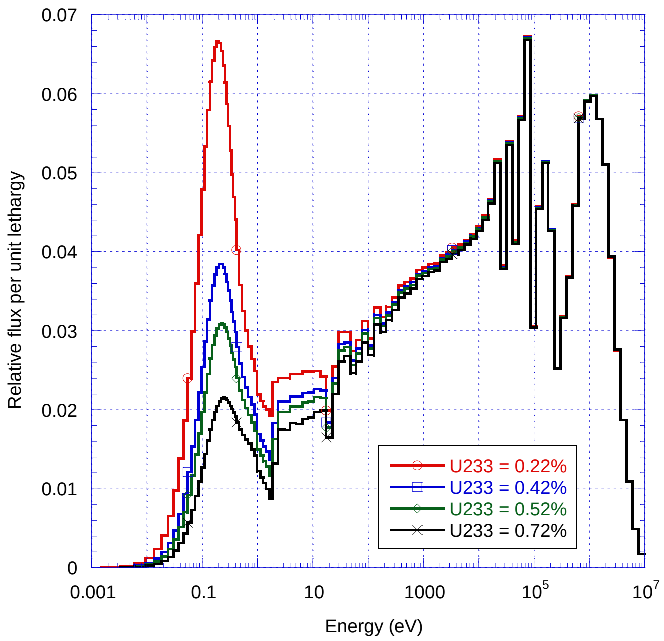

Figure 6. Neutron spectra of miniFUJI with Th-^{233}U fuel

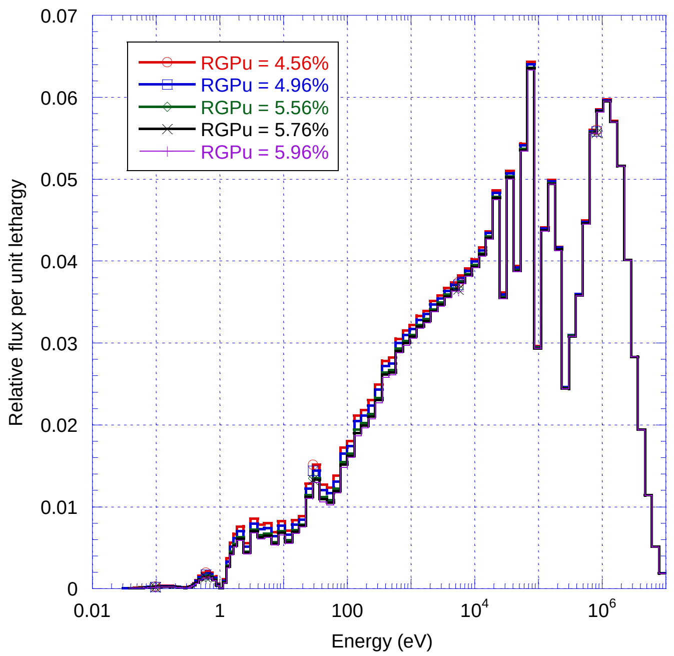

Figure 7. Neutron spectra of miniFUJI with Th-RGPu fuel

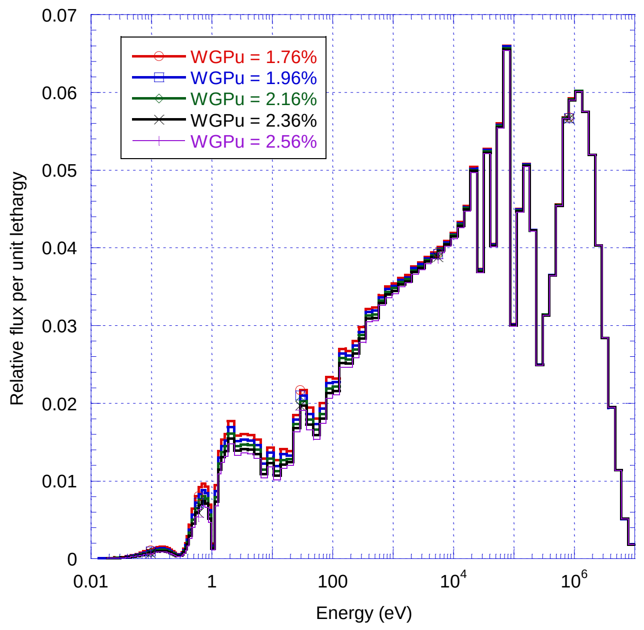

Figure 8. Neutron spectra of miniFUJI with Th-WGPu fuel

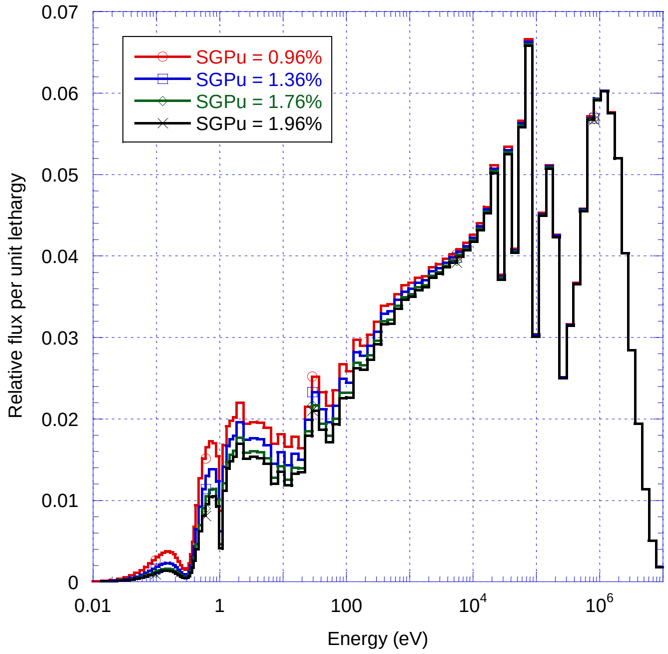

Figure 9. Neutron spectra of miniFUJI with Th-SGPu fuel

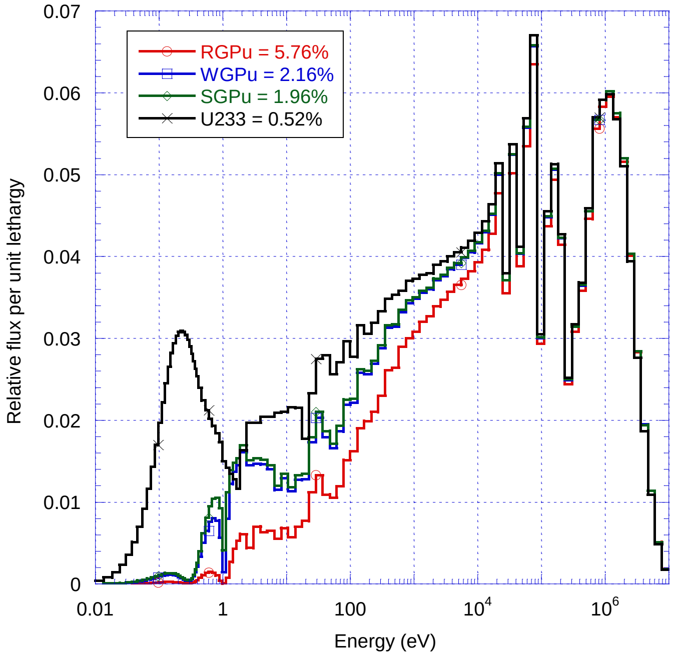

Figure 10. Comparison of neutron spectra of miniFUJI with various fuel types

4. CONCLUSIONS

Comparative studies on plutonium and ^{233}U utilization in miniFUJI MSR have been conducted. The reactor grade plutonium (RGPu), weapon grade plutonium (WGPu), and super grade plutonium (SGPu) have been employed. The reactors can achieve their criticality with the ^{233}U concentration in the Th-^{233}U fuel, RGPu concentration in Th-RGPu fuel, WGPu concentration in Th-WGPu fuel, and SGPu concentration in Th-SGPu fuel of 0.52%, 5.76%, 2.16%, and 1.96%, respectively. The final burnup levitates with the growing of fissile plutonium concentration in fuel.

The Th-^{233}U fuel results in the soft neutron spectra of miniFUJI reactor. The neutron spectra become harder with the augmenting of plutonium concentration in loaded fuel where Th-RGPu fuel results in the hardest neutron spectra. The last evidence may due to the higher concentration of absorber isotopes in the reactor grade plutonium.

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REFERENCES

[1] K. Furukawa, et. al., A Road Map for the Realization of Global-scale Thorium Breeding Fuel Cycle by Single Molten-Fluoride Flow, Molten salt reactor for sustainable nuclear power-MSR FUJI, Energ Convers Manage, 49, pp. 1832-1848, (2008)

[2] N. Suzuki N and Y. Shimazu, Reactivity-Initiated-Accident Analysis without Scram of a Molten Salt Reactor, J Nucl Sci Technol, 45 (6), pp. 575-581, (2008)

[3] IAEA, IAEA-TECDOC-1622, "Status and Trends of Nuclear Technologies", IAEA, Vienna, (2009)

[4] IAEA, IAEA-TECDOC-1319, "Thorium fuel utilization: Options and Trends", IAEA, Vienna, (2002)

[5] A. Waris, et. al., "Preliminary study on plutonium and minor actinides in thorims-nes minifuji reactor" , *Energ Convers Manage*, 72, pp. 27-32, (2013)

[6] R. W. Moir, "Recommendation for a restart of molten salt development", *Energ Convers Manage*, 49, pp. 1849-1858, (2008)

[7] N. Yamamoto, et. al., "Steady state analysis of small molten salt reactor (effect of fuel salt flow on reactor characteristics", *JSME Int J Ser B*, 48(3), pp. 610–617, (2005)

[8] K. Okumura, et. al., “SRAC: The Comprehensive Neutronic Calculation Code System”, Japan Atomic Energy Research Institute, Tokai-mura, Japan, (2002)

[9] T. Nakagawa T, et. al., Japanese Evaluated Nuclear Data Library Version 3 Revision-2: JENDL-3.2, *J Nucl Sci Technol*, 32 (12), pp. 1259-1271, (1995)

[10] C. H. M. Broeders, et. al., “Burning Transuranium Isotopes in Thermal and Fast Reactors”, *Nucl Eng Design*, 202, pp. 157-172, (2000)

[11] .Weston M Stacey, *Nuclear Reactor Physics*, John Wiley & Son, 2001

[12] http://en.wikipedia.org/wiki/Plutonium-239

[13] A. Waris and H. Sekimoto, “Characteristics of Several Equilibrium Fuel Cycles of PWR”, *J Nucl Sci Technol*, **38 (7)**, pp. 517-526, (2001)

[14] A. Waris, et. al., “Influence of moderator-to-fuel volume ratio on Pu and MA recycling in equilibrium fuel cycles of PWR”, *Proc. Int. Conf. On the New Frontiers of Nuclear Technology, PHYSOR 2002*, 7-10 October 2002, Seoul, (2002)

[15] Waris A, et. al., “Comparative Study on ^{233}U and Plutonium Utilization in Molten Salt Reactor”, *Indonesian J Phys*, **21(3)**, pp. 77-81, (2010)