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Neutronic Analysis of the NuScale Fuel Assembly using Accident Tolerant Fuel with SiC-Coated Alumina Cladding

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A B S T R A C T

Nuclear fuel design influences a nuclear reactor's performance and safety. Accident Tolerant Fuel (ATF) is a novel concept in nuclear fuel technology developed to improve the performance and safety of a nuclear power reactor. Different ATF materials can impact the neutronic aspect of a nuclear reactor and thus must be analyzed accordingly. This research is a neutronic analysis of an ATF design using alumina (Al_2O_3) and outer silicon carbide (SiC) coating implemented in NuScale SMR fuel assembly. MCNP6.2 code was utilized to perform the neutronic calculations. Standard M5 cladding in NuScale was compared with Al_2O_3 and Al_2O_3+ SiC cladding. Analyzed parameters were fuel burnup, kinetic parameters, Doppler temperature coefficient, moderator temperature coefficient, and the evolution of several radionuclides. The results show no significant differences in the neutronic performance of the Al_2O_3 cladding compared to the standard M5 cladding. Therefore, Al_2O_3 cladding has the potential for application in pressurized water reactor (PWR) fuel.

1. INTRODUCTION

The Tohoku tsunami in Japan, in 2011, initiated a severe accident in the Fukushima Daiichi nuclear power plant. The seawater disabled the post-shutdown cooling system, resulting in a loss of coolant accident (LOCA). The increased core temperature caused damage to the fuel cladding. The high-temperature reaction of zirconium with water produced hydrogen gas, which accumulated in the reactor building and caused a hydrogen explosion. The explosion breached the reactor building and released a significant amount of volatile radioactive materials into the atmosphere. This accident was categorized INES Level 7, the most severe accident in a nuclear reactor [1–3].

After this accident, the research on accident-tolerant fuel (ATF) found its momentum. ATF is a novel fuel cladding design developed to improve the safety, flexibility, and efficiency of a nuclear power reactor. ATF is expected to be able to prevent severe nuclear accidents and increase the efficiency of fuel utilization during normal and transient conditions. The primary focus of the ATF design is on optimizing both cladding and fuel material so that the reactor can be operated for a longer time for each cycle and improve performance during various operational conditions [1–3].

Generally, light water reactors (LWRs) use uranium dioxide (UO_2) as the fuel, with zirconium alloy (Zircaloy) used as the fuel cladding. Zircaloy

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has a good performance as cladding for nuclear fuel but judging from what happened in Fukushima Daiichi, it has a potentially severe drawback during accident conditions. During LOCA, the lack of coolant results in increased zirconium temperature and results in accelerated steam-oxidation reaction with water. Hydrogen gas is generated from this reaction, which poses a significant hazard [3]. The ATF is expected to improve the safety of a nuclear power plant by preventing this accident from occurring, to begin with, using cladding material with good physical and chemical characteristics that consider the melting point, high thermal conductivity, better degradation resistance, and lower oxidation rate [4].

Cheng Ting et al (2012) mentioned several alternative materials for replacing zircaloys, such as alumina (Al_2O_3) and silicon carbide (SiC). Both are hard ceramics used as a coating for various systems due to their high resistance to corrosion. Alumina has a fairly high hardness, which makes its mechanical strength fairly strong. Other characteristics are high melting point and high-temperature stability, making it a promising candidate for cladding material [5].

SiC, on the other hand, is a crystal-structure material with high hardness and high melting point at 2837^{o}C [6]. Among several alternative cladding materials, SiC is the most promising for LWR. SiC has a decent mechanical strength even in a high-temperature system. This material also possesses several interesting characteristics such as good stability under neutron irradiation, low neutron absorption, low decay heat, and slow steam-oxidation kinetics. Therefore, SiC is expected to be able to prevent the accident progression that occurred in Fukushima Daiichi [7–9].

From the above explanations, Alumina and SiC have potential for ATF cladding. However, its application in LWR must be assessed, especially regarding its neutronic aspect.

NuScale is a pressurized water reactor (PWR) type reactor with a net electrical output of 570 MWe for a 12-module plant, each module containing one reactor core unit. Each NuScale reactor core has a thermal power of 160 MWt, with an operating pressure of 12.7 MPa. NuScale employs a 17 × 17 fuel assembly with uranium dioxide (UO_2) as the fuel material and zirconium-based M5 cladding. Research involving NuScale reactor using ATF was performed previously with different materials, but presently none using alumina in conjunction with SiC [1, 10, 11].

This research performs neutronic analysis on this NuScale fuel assembly with ATF cladding materials using MCNP code. The ATF materials used in this study are alumina and SiC-coated alumina. Both materials were compared with regular M5 cladding as comparison. Cladding materials are described in Section 2. The analyzed neutronic parameters were burnup calculation, neutron spectra, kinetic parameters, and temperature coefficient, all discussed in Section 4.

2. MODEL DESCRIPTION

Fuel assembly (FA) modeling and neutronic simulation were conducted using MCNP6 radiation transport code and ENDF/B-VIII neutron cross-section library [12–14]. FA design parameters and cladding materials are described in Tables 1 and 2, respectively. As previously mentioned, NuScale FA is a rectangular 17 × 17 assembly with 264 fuel rods and 25 guide tubes (see Fig. 3). The total length of the fuel rod is 200 cm, with upper and lower blankets measuring 8 cm each. The fuel is 4.3% enriched at active pin length and 1.87% at blankets. Light water is used as a moderator and coolant [14].

The three FA NuScale models taken in this study are the burnable absorber-free FA, separated into three models. The first model is the standard M5-cladding FA, as shown in Fig. 1. For the second model, the M5 cladding is replaced with alumina with identical thickness. The third model is based on alumina but with additional SiC coating on the outside of alumina cladding, to provide additional barrier during accidents (Fig. 2).

Table 1. Design Specification of NuScale FA

Parameter	Value
Number of pins	17 × 17
Number of fuel rods	264
Number of guide tubes	25
Fuel rod length (cm)	200
Cladding outer diameter (cm)	0.94996
Cladding inner diameter (cm)	0.82804
Helium gap thickness (cm)	0.01651
Cladding thickness (cm)	0.06096
FA Pitch (cm)	21.503
Fuel enrichment (%)	Blanket: 1.87 Active: 4.3

Table 2. Material specification

Variable	Model 1	Model 2	Model 3
Assembly geometry	Square	Square	Square
Coolant	H_2O	H_2O	H_2O
Fuel	UO_2	UO_2	UO_2
Cladding	M5	Al_2O_3	Al_2O_3
Coating	-	-	SiC
Gas gap	He	He	He

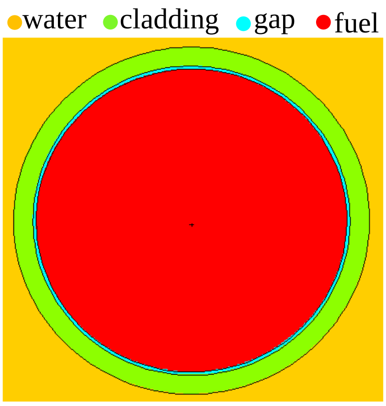

Fig. 1. NuScale fuel pin without coating

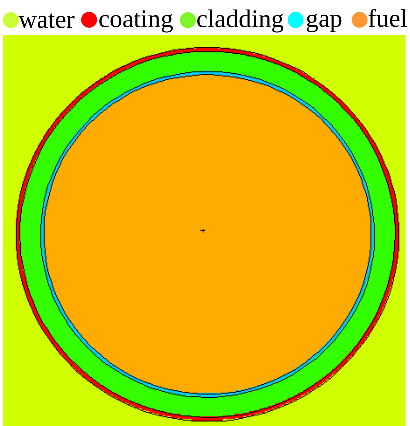

Fig. 2. NuScale fuel pin with outer coating

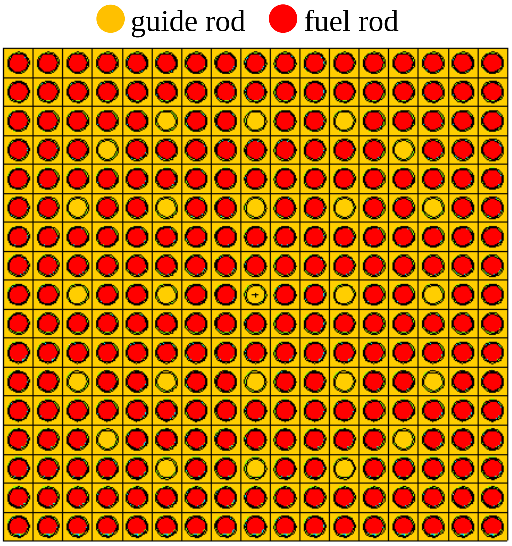

Fig. 3. NuScale FA geometric configuration

3. METHODOLOGY

Modeling and analysis of NuScale FA were performed using MCNP6.2 radiation transport code and ENDF/B-VIII neutron cross-section library. The input was written using a notepad++ text editor and visualisation was created using VISEDX24E. All FA models were simulated using 25,000 neutron particles per cycle, a total of 250 cycles, and the first 50 cycles discarded for neutron source convergence. Burnup calculation was done for 360 days, divided into 5 steps.

4. RESULTS AND DISCUSSION

4.1. Fuel burnup

Burnup calculation is depicted in Fig. 4. There is no notable difference in fuel burnup, indicating that both alumina cladding and alumina cladding+SiC coating have little impact on fuel burnup. Although different cladding affects criticality, fuel burnup does not seem to be significantly affected.

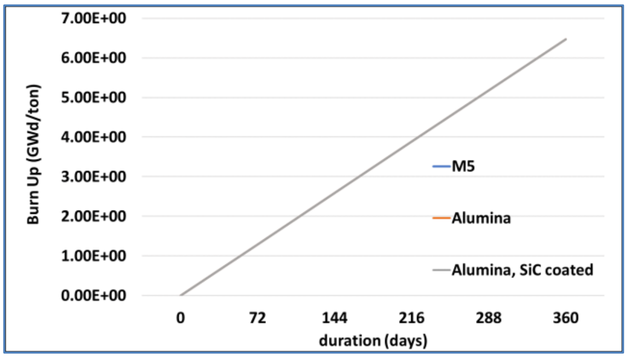

Fig 4. Fuel burnup across three variations

4.2. Neutron Spectra

Figure 5 displays the neutron spectrum per unit lethargy for all fuel variations. In the thermal energy region, there is no distinction between M5 cladding and proposed ATF cladding materials. However, a small difference can be noticed in the fast energy region, especially around 2.73 MeV, where alumina and SiC-coated alumina both have higher peaks than M5 cladding. This means that the neutron spectra in alumina-based claddings are slightly harder but not necessarily significant.

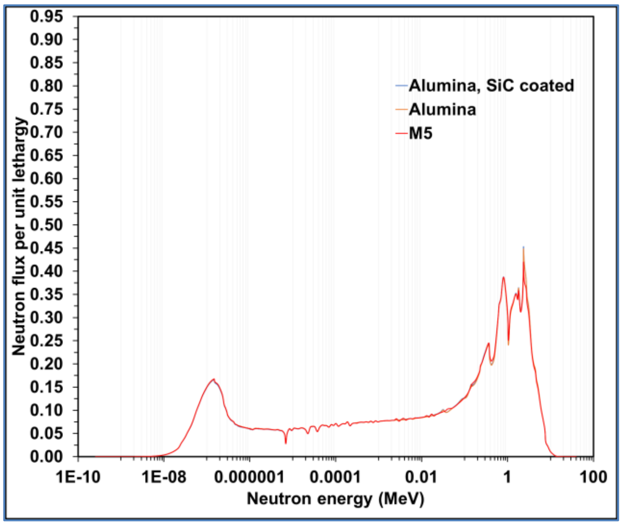

Fig. 5. Neutron spectra

4.3. Infinite multiplication factor

Fuel burnup decreases the infinite multiplication factor (k_{inf}) over time. The evolution of k_{inf} is shown in Fig. 6. At the beginning of the cycle (BOC), the fuel assembly is supercritical, so that the neutron population is sufficient to self-sustain the fission reaction. The k_{inf} are then depleted due to the consumption of fissile material and the buildup of fission products with large neutron capture cross-sections.

The addition of SiC coating quite notably affected the k_{inf} at the BOC, due to lowered moderator volume with the addition of SiC coating and silicon has a higher neutron capture cross section than zirconium. Outer SiC coating means that neutrons are partially captured in the coating before actually reaching the fuel. Meanwhile, k_{inf} in alumina without SiC improved the k_{inf}, due to a smaller capture cross-section of alumina compound compared to zirconium. As the difference in k_{inf} is quite significant, adding SiC coating is rather detrimental to the criticality of the fuel assembly system.

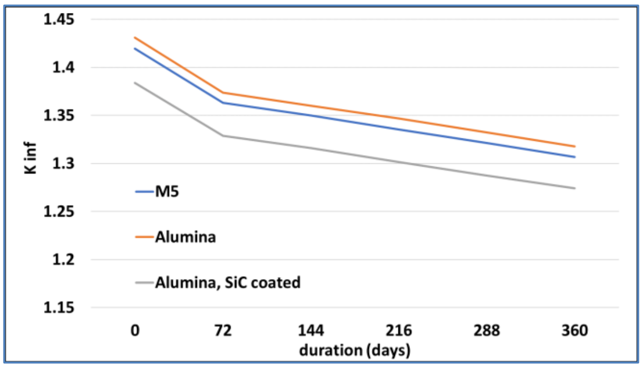

Fig. 6. Evolution of infinite multiplication factor

4.4. Effective delayed neutron fraction

Effective delayed neutron fraction (β_{eff}) is an important kinetic parameter that determines the reactor's controllability after reactivity insertion. Higher β_{eff} results in a longer reactor period, slowing down the change in reactor power after reactivity insertion. From Fig. 7, it can be seen that the trend of β_{eff} is generally decreasing over time, as the plutonium-239 isotope, which has a smaller delayed neutron fraction, builds up. The trend is inconsistent, but still within normal range. β_{eff} in M5 cladding tends to be lower, but the difference is insignificant. Therefore, using alumina-based ATF does not severely impact β_{eff} values. Fluctuations in the delayed neutron fraction can be caused by temperature and reactivity changes in the reactor.

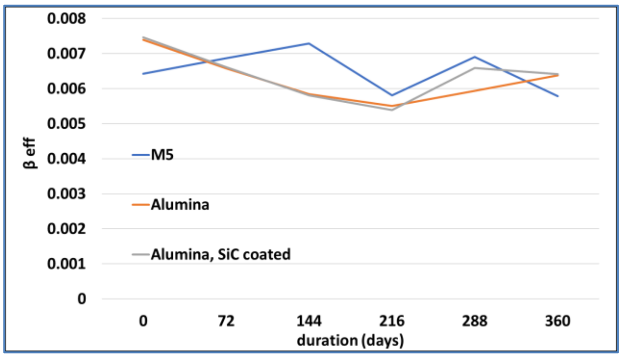

Fig. 7. Effective delayed neutron fraction

4.5. Mean Neutron Generation Time

Figure 8 shows the mean neutron generation time (λ), another important kinetic parameter. Alumina-SiC ATF tends to have slightly longer λ, which shows that the neutrons have to roam the fuel assembly for longer before interacting with fuel material. This is understandable since neutron capture is higher in this ATF configuration. Meanwhile, alumina ATF has a shorter λ, which correlates with low neutron capture by the cladding material.

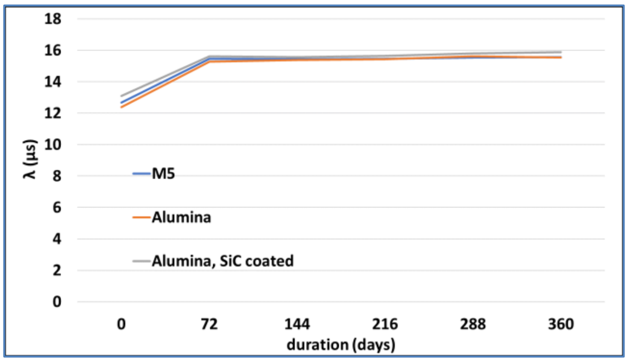

Fig. 8. Mean neutron generation time

4.6. Fuel Temperatur coefficient

Fuel temperature coefficient (FTC) is a unit representing the change of core reactivity against temperature. A negative FTC value represents a negative correlation of core reactivity against temperature, where the reactivity goes down when the temperature is increased. All FTC is shown to be negative both in BOC and end of cycle (EOC), as summarized in Table 3.

Table 3. Fuel temperature coefficient (pcm/K)

Cladding material	BOC	EOC
M5	-1.4511	-1.6157
Alumina	-1.3579	-1.6729
Alumina + SiC coating	-1.4881	-1.4939

The FTC is more negative in EOC as fissile material is depleted and fission products build up. Alumina ATF slightly weakened the FTC in the BOC but improved significantly in the EOC. Adding SiC in alumina improves FTC in the BOC, but the effect is less apparent in EOC. Overall, negative FTC is maintained.

4.7. Moderator temperature coefficient

The moderator temperature coefficient (MTC) represents the change in core reactivity against moderator temperature. As shown in Table 4, the MTC has less impact on reactivity compared to FTC, as a change of fuel temperature is more prominent in decreasing neutron cross-section than moderator temperature alone. Change in moderator density will have a higher impact on reactivity, as will be discussed further.

MTC in alumina seems to work differently than other cladding materials, weakened so much until became positive at EOC. However, it can be compensated with a void coefficient.

Table 4. Moderator temperature coefficient

Cladding material	BOC	EOC
M5	-0.4516	-0.8209
Alumina	-0.7909	0.5535
Alumina + SiC coating	-0.2750	-0.9520

4.8. Void Coefficient

Void coefficient denotes the change in reactivity against the change of moderator density (void), due to heating or bubble formation. As seen in Fig. 9, the void coefficient is negative for all conditions, and higher void fraction results in stronger negative feedback. The void coefficient in EOC is more negative due to a higher abundance of fission products increases neutron capture and lowers the probability of fission reaction. Alumina ATF has a slightly weaker void coefficient as its compound has a lower neutron capture cross-section, which increases the probability of a fission reaction. Meanwhile, SiC-coated alumina has generally a similar void coefficient with M5 since it has a higher neutron capture cross-section.

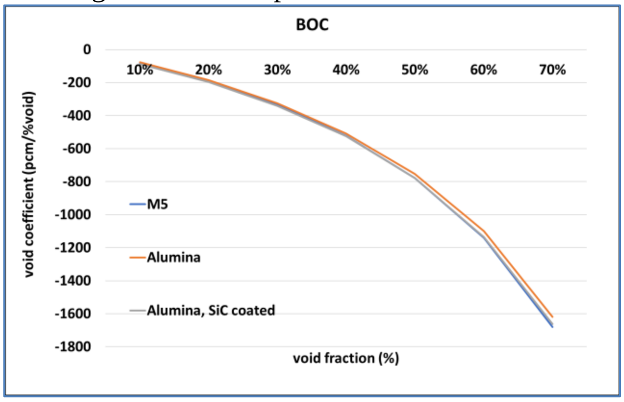

Fig. 9. Void coefficient at BOC

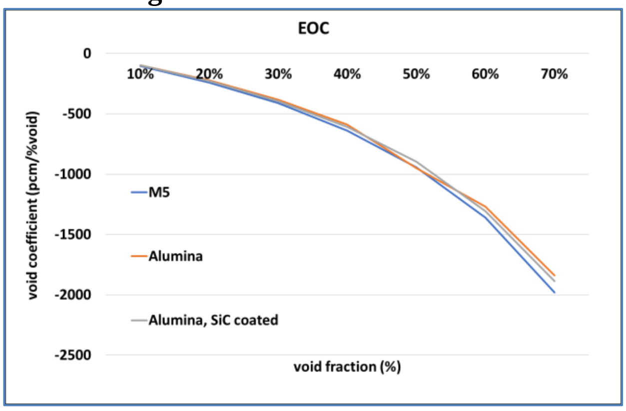

Fig. 10. Void coefficient at EOC

4.9. Nuclide Evolution

Figures 11-13 show the evolution of several important radionuclides (U-235, U-238, and Pu-239) for each fuel cladding variation. There are no significant differences in U-235 and U-238 evolution, meaning that fission and capture rates are not significantly impacted by the use of ATF cladding. For Pu-239, the pattern slightly deviates to be higher, as high neutron capture tends to increase U-235 consumption and lower Pu-239 self-consumption, thereby increasing the latter's accumulation.

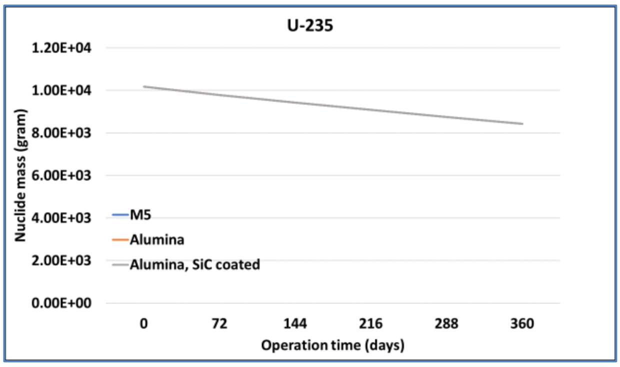

Fig. 11. U-235 mass evolution

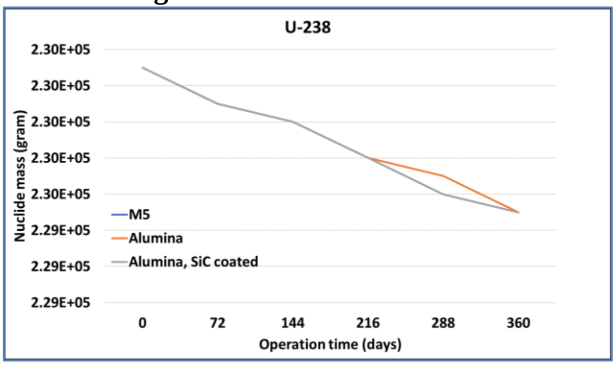

Fig. 12. U-238 mass evolution

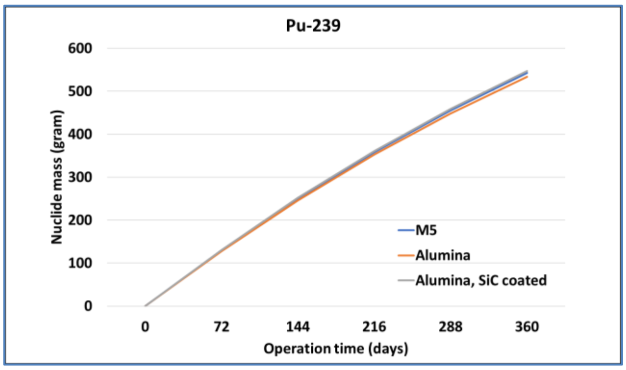

Fig. 13. Pu-239 mass evolution

Cs-137 and I-129 are two important fission products, both are volatile with Cs-137 emitting high gamma energy and I-129 having an extremely long half-life. From Figs. 14-15, replacing M5 cladding with alumina-based cladding results in only an insignificant change of Cs-137 and I-129, with both more prominent in later operational days. Therefore, there is no increased potential radiological risk from replacing M5 cladding with alumina-based cladding.

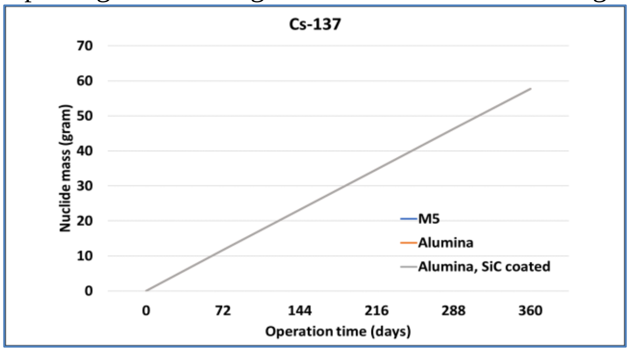

Fig. 14. Cs-137 evolution

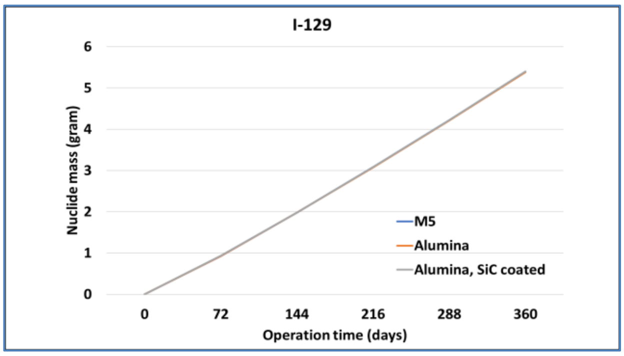

Fig. 15. I-129 mass evolution

5. CONCLUSION

From neutronic calculations on alumina-based ATFs, it can be concluded that apart from k_{inf} evolution, there are no significant differences in neutronic aspects between using M5 and ATF claddings. K_{inf} is most notably suppressed when alumina is coated by SiC but improved from regular M5 cladding without coating. Other parameters such as FTC, MTC, kinetic parameters, and void coefficient show small changes but are not particularly notable. Additionally, there is no significant difference in Cs-137 and I-129 production. Therefore, alumina cladding has the potential to be applied as ATF in NuScale FA.

AUTHOR CONTRIBUTION

Rahmania Serli Assifa contributed to data curation, investigation, formal analysis, and writing - original draft. R. Andika Putra Dwijayanto contributed to conceptualization, supervision, writing - Review, and editing; Fajar Arianto contributed to software, supervision, writing -

review, and editing. All authors read and approved the final version of the manuscript.

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