Implementation of a Gadolinium Burnable Absorber in the Carbide LEU-NTR

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1. Introduction

The LEU-NTR (Low-Enriched Uranium Nuclear Thermal Rocket) has been shown to be neutronically viable and is able to perform at the level required for future manned and unmanned missions to Mars and the rest of the solar system [1,2]. However, as has been previously identified, the implementation of the LEU fuel in the standard NTR core design, while feasible, poses some unique challenges that need to be resolved before it can be successfully implemented instead of the traditional HEU-NTR designs. Among the most crucial are the rapid reactivity depletion during full-power operation and the positive reactivity insertion during the full-submersion criticality accident. In previous work, it has been suggested that both challenges can be mitigated through the successful implementation of a burnable absorber in the active core [3]. Of the poisons previously surveyed, one of the most promising is Gadolinium in the form of Gadolina (Gd2O4) [4]. This paper explores the possibility of different methods by which the Gadolinia can be implemented in the core and makes a preliminary study of its effect on the full submersion criticality accident and the reactivity depletion during operation.

2. Analysis Method

The analysis presented in this paper was done purely from a neutronics perspective. It was done by taking a reference Carbide LEU-NTR core design updated from previous work [2] and subjected to different parameter changes in order to verify their effect on the core neutronics. Core criticality calculations were all done using MCNP5-1.6 [5] on a laboratory Linux cluster at KAIST. All cross-sections were taken to be at room temperature, using the ENDF/B-VII library and 3 instances of natural composition cross-sections available in the ENDF/B-VI library distributed with the MCNP package [6]. All calculations, unless otherwise stated, were done using 50000 particles over 450 active cycles with 50 inactive cycles in order to achieve a typical standard deviation of about .00015, more than suitable for the purpose of this study both in terms of accuracy as well as calculation speed. In the analysis of the neutron poison, two parameters were varied: poison content, and the location of the neutron poison.

3. Reference Core Design

The reference core design is based on a current design being developed at KAIST for the implementation of the LEU Carbide fuel. The core measures 75 cm tall with an active core radius of 35 cm and 20 cm beryllium axial and radial reflectors. In this study we have looked at two active core configurations in order to capture the effects of having different moderator to fuel elements ratio. The two configurations are the inverse alpha (2:1) and the bulls-eye (1:1) configurations. This study also serves the purpose of providing additional information related to the possibility of reducing the moderator to fuel ratio in an attempt to reduce the fuel power density without unduly increasing the core's mass. Both configurations use the same baseline moderator and fuel element geometries presented in Table 1 and Fig. 1. The radial core geometries for both active core configurations are shown in Figs. 2 and 3.

Table 1. Moderator and Fuel element geometry

Component	Material	Inner Radius (cm)	Outer Radius (cm)
Inner Hydrogen	Hydrogen		.203
Inner tie tube	Zircaloy	.203	.254
Moderator	$ZrH_{1.8}$	.254	.684
Outer Hydrogen	Hydrogen	.684	.7605
Outer tie tube	Zircaloy	.7605	.786
Insulator tube	ZrC (50%TD)	.786	.9
Hexagonal element body	Graphite	1.905 cm face to face	
Fuel element coolant channel	Hydrogen	.1375 cm	
Fuel element body	(U,Zr)C	1.905 cm face to face	

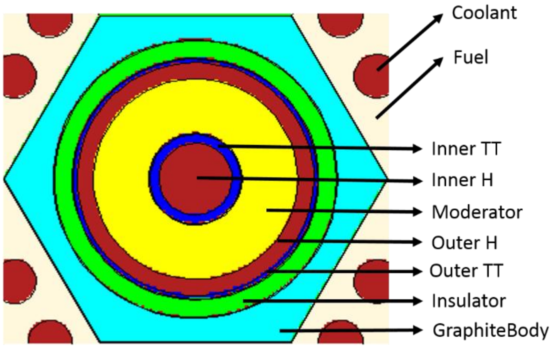

Fig. 2. Moderator and fuel element geometries.

The default configuration for the core for the purpose of this analysis is with the control drums in the "out" position, providing the maximum reactivity both when dry and submerged. The k-effectives for both conditions and relevant characteristics (void fraction, fuel fraction, and number of moderator and fuel elements) for both configurations are given in Table 2. An interesting point in this table is the increased k-effective for the bulls-eye core configuration relative to the inverse alpha configuration. In previous work, it has been established that the smallest critical core is achieved by maximizing the moderation in the core, which seems to run against the presented results. This seeming inconsistency is actually in agreement with the previous findings in that the increase in k-effective can be explained as a combination of the larger reflector worth and increased fissile content of the bulls-eye configuration relative to the more moderated inverse-alpha. If the reflector were to be reduced (resulting in a smaller and lighter core), we would find that the smallest and lightest critical configuration would still be the more heavily moderated inverse alpha.

Table 2. Key reference core parameters.

	Inverse Alpha (2:1)	Bulls-eye (1:1)
Dry k-eff	1.17237	1.21061
Flooded k-eff	1.23517	1.3572
Void Fraction	0.097	0.073
Fuel Fraction	0.195	0.303
No. of Moderator Elements	774	570
No. of Fuel Elements	379	589

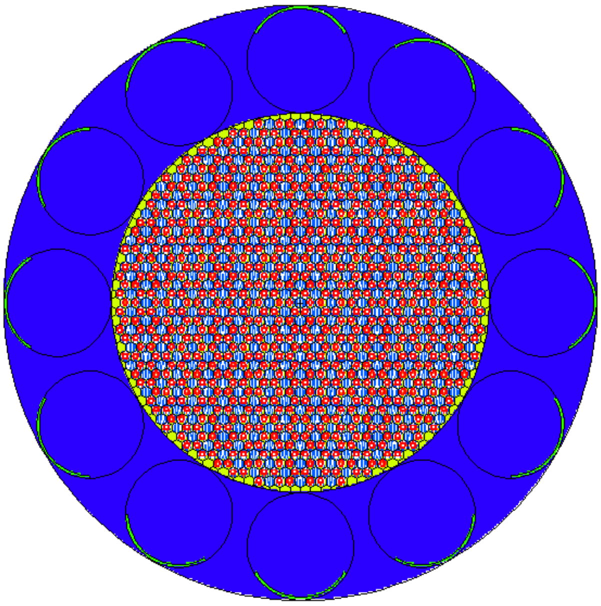

Fig. 2. Reference core radial geometry using the Inverse Alpha configuration (2:1).

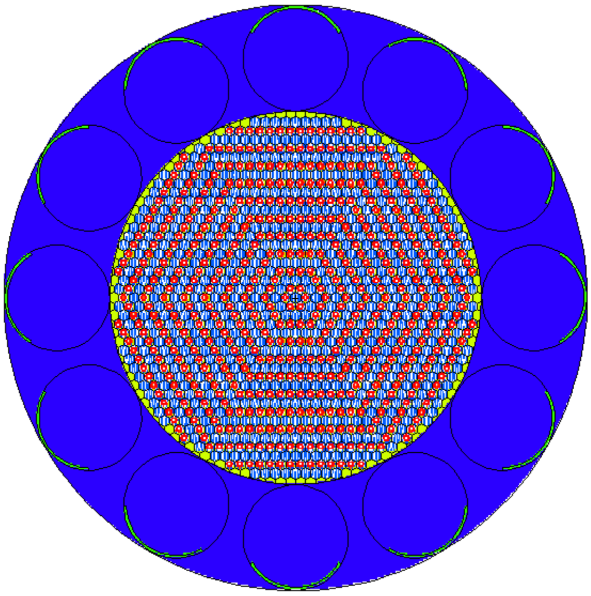

Fig. 3. Reference core radial geometry using the Bulls-Eye configuration (1:1).

4. Poison Placement

In the present study the poison was introduced in four different locations: the inner tie-tube, the outer tie tube, homogenously throughout the fuel element, and as a coating in the fuel coolant channels. In each of these locations it is introduced in the form of an addition of Gadolinia (Gd2O3) fully enriched in Gd-157 to the material of the component. In the instance of the fuel, the addition is minute, ranging from 10^{-6} to 10^{-5} weight percent. The small amount should ensure that the material properties of the fuel remain unchanged relative to those previously determined. In the case of the tie tubes, the concentration is higher, from 10^{-5} to 10^{-4} weight percent, but this is done also in hopes of improving the material properties of the zirconium alloy through oxide dispersion strengthening. Recent work done in Russia and South Korea [7] [8] in connection to accident tolerant materials for PWRs suggest that such a material is feasible and shows promising material properties. Throughout the study, the fissile content in the core was kept constant and the material composition of the tie-tubes determined so as to achieve a Gadolinia loading in the core ranging from 0 to 4.5 gram of Gadolinia.

5. Reactivity Loss

In the implementation of Gadolinia in the core, there is a linear relationship between the reactivity penalty and the amount of Gadolinia added to the core. This is evidence that the self-shielding effect of the Gadolinia is still rather limited in the proposed quantities, and suggests that further Gadolinia can be added to the active core without diminishing its initial effectiveness in reducing the reactivity of the core. Consequently, because the self-shielding effect is so small, the Gadolinia will be depleted evenly throughout the core, maximizing its depletion rate.

It is important to note the role of the local neutron spectrum on the reactivity loss due to the implementation of Gadolinia. In the location where there is a relatively harder spectrum (the fuel matrix), the absorption cross-section of the Gadolinium is reduced. Given the strong slope of the absorption cross-section in the energies surrounding the thermal peak, even small changes in the thermal neutron population will result in significant changes in the absorption by the poison. The reactivity loss due to the implementation of the poison is shown in Figs. 4 and 5. While the effect of the harder spectrum is relatively small, the difference between having the poison in the fuel and the inner tie-tube being about 900 pcm for the Bulls-Eye and 1000 pcm for the Inverse Alpha, it is nonetheless clearly noticeable, increasing as a function of the Gadolinium content in the core. This suggests that as increasing amounts of Gadolinium are added, this effect will become increasingly apparent making the appropriate placement of the poison a crucial aspect of its implementation.

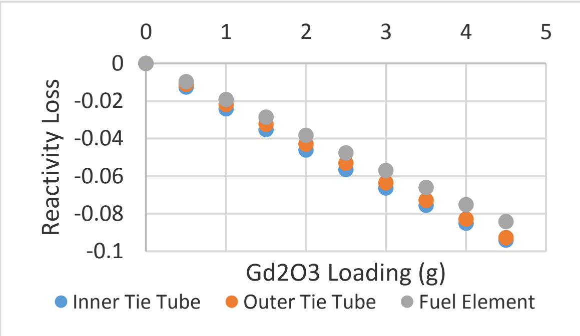

Fig. 4. Reactivity loss due to Gadolinium when inserted into different locations in the Bulls-Eye (1:1) core.

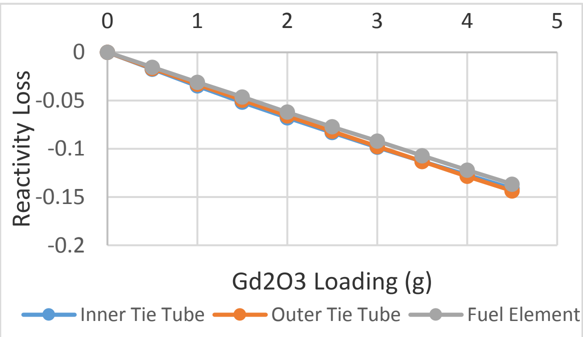

Fig. 5. Reactivity loss due to Gadolinium when inserted into different locations in the Inverse Alpha (2:1) core.

The absorption cross-section of ^{157}Gd plotted along with the fission cross-section of ^{235}U and the core average neutron spectrum for the Inverse Alpha (2:1) core is shown in Fig. 6. The tightly coupled relationship between the magnitude of the thermal peak and the microscopic absorption cross-section of the Gadolinium can be clearly seen where the thermal peak matches the point where the absorption cross-section approaches its peak. This means that any increase in the magnitude of the thermal peak will result in a significant increase in the absorption rate as the neutrons will have slowed down from faster energies with lower absorption cross-sections.

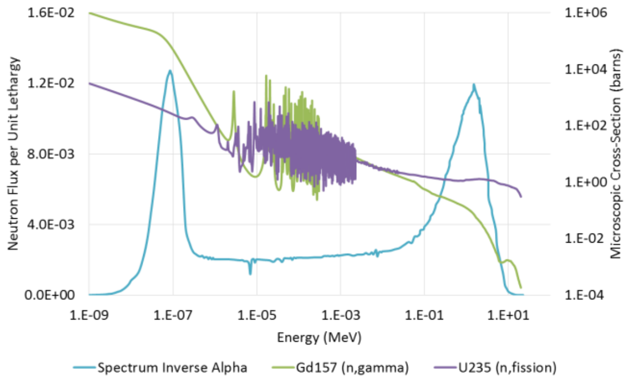

Fig. 5. Absorption cross-section of ^{157}Gd along with the fission cross-section of ^{235}U and the core average absorption neutron flux of the Inverse-Alpha (2:1) reference core.

Further analysis of the Inverse Alpha core included increasing the amount Gadolinia loaded into the core and placing it as a coating along the fuel coolant channels. The reactivity penalty for all four configurations is shown in Fig. 7. Here, as is expected, from the earlier study, the reactivity penalty is similar for all poison placements. The interesting point is that the increasing self-shielding of the poison in the central tie-tube element. Here, Fig. 7 shows how the reactivity loss with each additional amount of Gadolinia has an increasingly small effect. This could lend itself to future designs where taking advantage of the self-shielding potential of this particular location could result in a tailored burn-up.

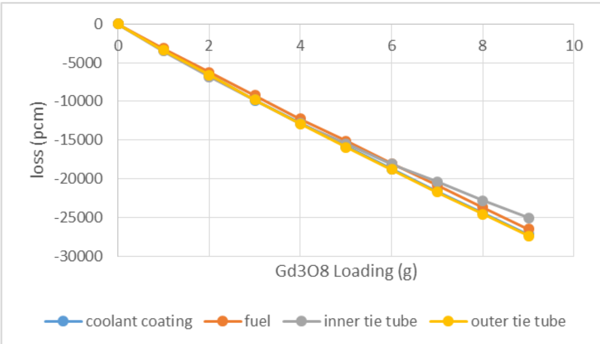

Fig. 7. Reactivity loss due to Gadolinium when inserted into different locations in the Inverse Alpha (2:1) core with loadings from 0 g to 9 g of Gadolinia.

6. Full Submersion Criticality Mitigation

The benefits of having a spectral shift absorber in the active core in order to mitigate the reactivity increase during the full-submersion accident have been previously shown to be significant in fast spectrum cores in previous work by King and El-Genk [4]. Its effectiveness is due to the significant change in the magnitude of the thermal peak between the "dry" (voided coolant channels in the fuel and moderator elements and surrounded by a vacuum) and "flooded" conditions (all channels filled with water and surrounded by water). In the Carbide LEU-NTR, the effect is less noticeable, but is present none-the-less.

6.1 Spectrum Hardening

In an attempt to increase the change in the thermal peak between the two conditions, the spectrum of the core was hardened to varying degrees by reducing the thickness of the moderator sleeve. While this resulted in the reduction of the reactivity loss due to the Gadolinium, the net result was actually an increase in the water worth during submersion. These can be seen in Table 3 and Table 4 for both core configurations.

Table 3. Effect of Gd on the water worth and clean core reactivity with different moderator sleeve thicknesses for the Bulls-Eye (1:1) core.

	Inner Tie Tube		Outer Tie Tube		Fuel Element	
Mod Thick (cm)	Water Worth	Loss/Gd(g)	Water Worth	Loss/Gd(g)	Water Worth	Loss/Gd(g)
0.44	0.0983	-0.0241	0.0918	-0.0238	0.0882	-0.0216
0.354	0.1164	-0.0294	0.1102	-0.0286	0.1073	-0.0266
0.268	0.1476	-0.0380	0.1422	-0.0371	0.1393	-0.0353
0.182	0.2052	-0.0540	0.2014	-0.0533	0.1994	-0.0518

Table 4. Effect of Gd on the water worth and clean core reactivity with different moderator sleeve thicknesses for the Inverse-Alpha (2:1) core.

	Inner Tie Tube		Outer Tie Tube		Fuel Element	
Mod Thick (cm)	Water Worth	Loss/Gd(g)	Water Worth	Loss/Gd(g)	Water Worth	Loss/Gd(g)
0.44	0.0533	-0.0362	0.0471	-0.0368	0.0421	-0.0350
0.354	0.0686	-0.0402	0.030	-0.0401	0.0576	-0.0383
0.268	0.0956	-0.0472	0.0908	-0.0468	0.0846	-0.0448
0.182	0.1488	-0.0616	0.1450	-0.0612	0.1384	-0.0590

The results of this show that while the effect of the spectral shift absorber is noticeable, the dominant effect reducing the impact of the full submersion accident is the over-moderation of the core. When the core is fully flooded with water, it is significantly over-moderated, a state that is achieved regardless of the spectrum prior to submersion. This is clearly seen when comparing the two core configurations. In the case of the Inverse Alpha configuration, the core spectrum is over-moderated, which results in a significant negative reactivity insertion with the further addition of moderator. In the case of the Bulls-Eye configuration, the core spectrum is under-moderated, introducing a positive reactivity insertion along with the negative reactivity from the final over moderated state. The situation is then worsened by hardening the spectrum through the removal of the ZrH moderator. In removing the moderator, the core becomes further under-moderated, increasing the positive reactivity insertion with the addition of the water during submersion, which then counters the effects of the final over-moderated state of the core. The net result is then an increase of the positive reactivity insertion with the flooding of the core.

6.2 Effect Due to Poison Placement

The placement of the poison has a noticeable effect on its ability to counter the increase in reactivity during the accident. In Fig. 8 the flood worth is shown for each position as a function of Gadolinia loading (the non-smooth nature of the curves is due to statistical error). Here, it can be seen that having the poison as a coolant along the fuel coolant channels is the most effective at reducing the reactivity increase. This can be explained by the fact that the spectrum is hardest in this location and will undergo the largest change in the thermal peak of locations studied. What is interesting, however, is the behavior of the poison when place in the inner and outer tie-tubes. Instead of providing a net negative reactivity insertion, the poison placement results in a net positive insertion. This is due to the shielding of the moderator by the poison. By having the poison in the moderator element, the moderating ability of the moderating sleeve is reduced, reducing the reactivity of the core while having only a small effect on the reactivity when the core is submerged. The final effect is to then have a net increase in the core reactivity.

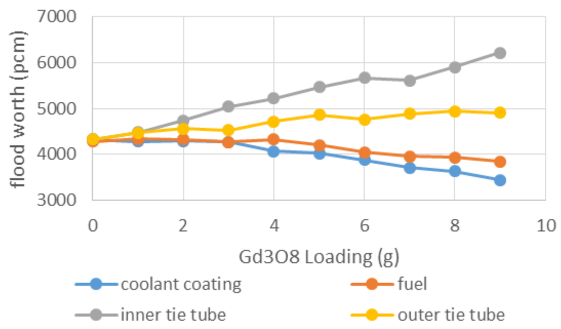

Fig. 8. Flood worth for different poison locations as a function of Gadolinia loading in the core.

7. Depletion Analysis

As previously mentioned, a consequence of the low self-shielding of the gadolinium is the maximizing of the rate of depletion of the poison in the core. This lends itself to the unique application of countering the combined reactivity reduction due to the depletion of the fissile material and the initial build-up of fission products in the core. A preliminary burn-up calculation was done to show that during operation the reactivity of the core actually increases rather than decreases during the first four hours of full-power operation. This is shown in Fig 9.

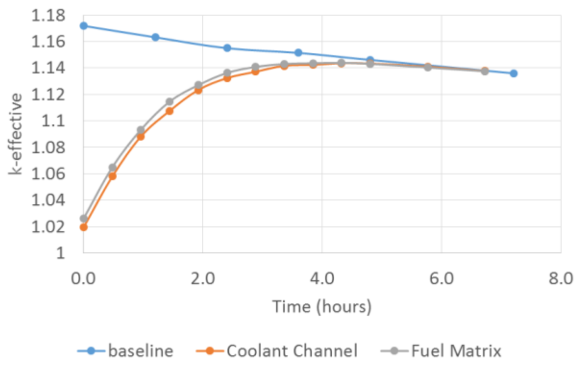

Fig. 9. Depletion of the core at 450 MW for 8 hours with the poison implemented in the fuel matrix and the coolant channel.

As the core is required to operate at full power for only two hours, the short duration of the effect of the Gd on the core is well within the operating time requirements of the core.

3. Conclusions

The application of a Gadolinium neutron absorber in the active core region of the LEU-NTR has been shown to be neutronically feasible. It can be introduced into the core in various locations without resulting in core performance loss. The utility of the poison in terms of mitigating the full-submersion reactivity accident and the rapid change in reactivity during full-power operation have been preliminarily shown and the first steps towards eventual implementation made.

Future work will consist of determining the maximum poison content in the core and tailoring the self-shielding effect in order to determine a specific Gd depletion rate. This will enable the operation of the core at full power with minimal control drum movement, significantly improving the ease of operation and reliability of the Carbide LEU-NTR.

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