

NEUTRONICS OF A LIQUID SALT COOLED - VERY HIGH TEMPERATURE REACTOR

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Abstract – *In the present studies, we have utilized the Monte Carlo MCNP code to investigate the neutronic and the safety parameters of the Liquid Salt cooled - Very High Temperature Reactor (LS-VHTR). More precisely, we focused on the void, fuel and moderator temperature reactivity coefficients for two fuel types, enriched uranium and spent LWR fuel, and five different molten salts, NaF, BeF₂, LiF, ZrF₄, Li₂Be₄F. The results show that the total void worth coefficient can be set negative provided that the fuel to moderator ratio is optimized and the moderating ratio of the coolant is sufficiently large; whereas the fuel and moderator temperature reactivity coefficients are negative at any fuel to moderator ratio.*

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I. Introduction

During last few years, the interest in the innovative, Liquid Salt cooled - Very High Temperature Reactor (LS-VHTR), has been growing. The preconceptual design of the LS-VHTR has been suggested at the Oak Ridge National Laboratory (ORNL) [1] and has originally been presented as the Advanced High Temperature Reactor (AHTR). The LS-VHTR design utilises a prismatic, High Temperature Reactor (HTR) fuel [2] in combination with liquid salt as a coolant. This connection of high-performance fuel and a coolant with enhanced heat transfer abilities enables efficient and economical operation. Main objective of the LS-VHTR operation may be either an efficient electricity production or a heat supply for a production of hydrogen or, combination of both. The LS-VHTR is moderated by graphite. The graphite matrix of the fuel blocks, as well as the inner and outer core reflectors serve as a thermal buffer in case of an accident, and they provide a strong thermal feedback during normal reactor operation. The high inherent safety of the LS-VHTR meets the strict requirements on future reactor systems, as defined by the Gen IV project.

First, an undermoderated core setup was found for both types of fuel by modifying the fuel to moderator ratio; then, the total void worth and the temperature coefficients of reactivity were investigated. Few single-component molten salts were involved in the study of the void effect, in order to estimate the worth of these components; NaF, BeF₂, LiF, ZrF₄. As a reference multi-component salt, Li₂Be₄F, referred to as FLiBe, was investigated. In the present study, neither burnable poison, nor control rods were used.

II. LS-VHTR Description

II. A Geometry

The LS-VHTR core, as illustrated in figure 1, contains 324x10 hexagonal fuel blocks assemblies in the horizontal and in the vertical direction respectively.

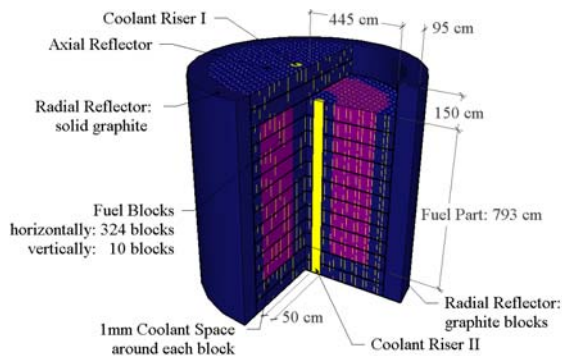


Figure 1: LS-VHTR core.

The blocks are arranged in annular concentric rings filled and surrounded by pure graphite hexagonal blocks which act as inner and outer reflectors. Around each hexagonal block, there is a 1 mm cooling space which yields 2 mm spacing between the walls of the assemblies. The core is sandwiched at the top and at the bottom by two axial pure graphite reflectors that contain the coolant channels. The latter ones are arranged exactly in the same pattern as in the fuel zone. The total thickness of both the axial and the radial reflectors is 150 cm.

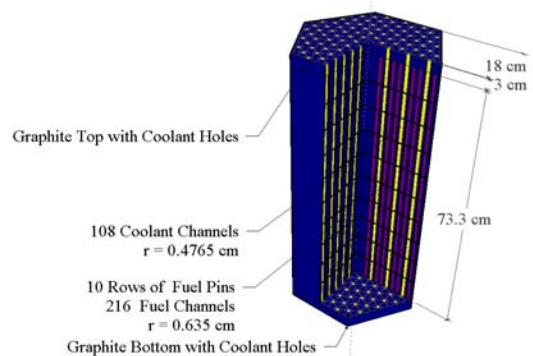


Figure 2: Fuel block.

The details of the fuel block assembly are depicted in figure 2. One hexagonal fuel block contains 216x10 fuel pins in xy - plane and along the z - axes, respectively, and 108 coolant channels. The latter ones continue also in the non-fueled bottom and top axial zones of the block, which extend 3 cm along the z axis from the vertical boundaries. Consequently, the active height of the block is 73.3 cm and the total height is 79.3 cm; the apothem is 18 cm. We neglected the modelling of the block handling hole, which is normally placed at the centre of the block.

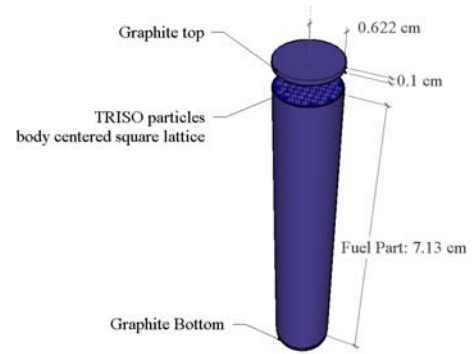


Figure 3: Fuel pin.

The fuel pin is illustrated in figure 3. The fuel pin has a radius 0.622 cm, an active height of 7.13 cm and 1 mm

layer of pure graphite both at the top and the bottom of the axial boundaries. Each fuel pin contains either 69x65, 69x83 or 97x79 TRISO particles, according to the core configuration. In all the configurations, the TRISO particles are disposed into a simple cubic lattice. Since MCNP5, a random placement of the TRISO particles in the fuel pin can be modeled. The regular lattice sets a difference of 200 pcm in the excess of reactivity compared to a random lattice [3]. In the present model the particles are not cut by the fuel pin boundaries.

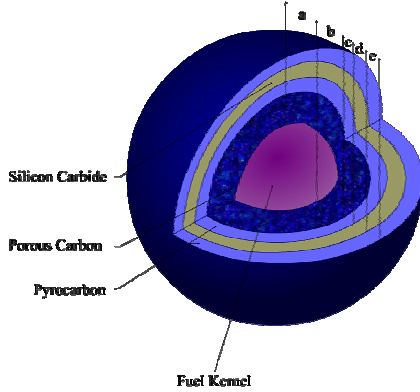


Figure 4: TRISO particle.

The TRISO packing fraction (*the fraction of the TRISO particles volume over the pin volume*) has been initially set to 14.53% for both fuel types. Later, this value was increased to 18.56 and eventually to 24.83%. The TRISO particle, as shown in figure 4, has a 150, 250 or 215 μm radius of kernel- depending on the core configuration, surrounded by coating layers of porous carbon, inner pyrocarbon, silicon carbide and outer pyrocarbon of outer radii 300, 335, 370 and 410 μm , respectively. The LS-VHTR core has been modeled with a high fidelity model, as described in table 1.

Table 1: Core Design Parameters.

| CORE | |
|--|-----------|
| Radius [cm] | 540 |
| Active Height [cm] | 793 |
| Axial Reflectors Height Top/Bottom [cm] | 150 |
| Coolant Riser Radius [cm] | 25 |
| Number of Fuel Blocks in the xy plane | 324 |
| Number of Fuel Blocks along the z Axis | 10 |
| Interstitial Gap between Hexagonal Blocks [cm] | 0.2 |
| Power [MW_{th}] | 2400 |
| Inlet Coolant Temperature [$^{\circ}\text{C}$]/[K] | 900/1173 |
| Outlet Coolant Temperature [$^{\circ}\text{C}$]/[K] | 1000/1273 |
| Inlet coolant pressure MPa | 0.23 |
| Outlet coolant pressure MPa | 0.10 |
| HEXAGONAL FUEL BLOCK | |
| Apothem [cm] | 18 |
| Height [cm] | 79.3 |
| Axial Reflectors Height Top/Bottom [cm] | 3 |
| Number of Fuel Pins in the xy Plane | 216 |
| Number of Fuel Pins along the z Axis | 10 |
| Radius of the Fuel Holes [cm] | 0.635 |
| Number of Coolant Channels | 108 |
| Radius of the Coolant Channel [cm] | 0.4765 |
| FUEL PINS | |
| Radius [cm] | 0.622 |
| Height [cm] | 7.33 |
| Graphite Top/Bottom [cm] | 0.1 |
| Number of TRISO particles – configuration 1 | 4485 |
| Number of TRISO particles – configuration 2 | 5727 |
| Number of TRISO particles – configuration 3 | 7663 |
| Graphite Density [$\text{g}\cdot\text{cm}^{-3}$] | 1.74 |
| TRISO PARTICLES | |
| kernel radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] – config. 1 | 150/10.2 |
| kernel radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] – config. 2 | 250/10.2 |
| kernel radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] – config. 3 | 215/10.2 |
| Porous carbon outer radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] | 300/1.0 |
| Pyrocarbon outer radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] | 335/1.85 |
| Silicon carbide outer radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] | 370/3.2 |
| Pyrocarbon outer radius [μm]/density [$\text{g}\cdot\text{cm}^{-3}$] | 410/1.85 |

II. B Molten Salts

We considered four single-component salts and one compound salt, FLiBe - with 66% of LiF and 34% BeF₂. In fact, as a reactor coolant only compound salts are considered because no single-component salt has sufficiently low freezing point. The survey and calculations carried out for other salts are aimed at understanding each component behavior, rather than suggesting it as a coolant. Densities, melting and boiling points and specific heats of the molten salts are summarized in table 2 ([1], [4]). Densities of the salts at 1200 K were calculated by the molar volumes additivity method described by Briggs [5]; the melting and the boiling points are given at the atmospheric pressure.

Table 2: Molten salt physical properties. [†] ZrF₄ sublimates at atmospheric pressure.

| | Li ₂ BeF ₄ | BeF ₂ | LiF | NaF | ZrF ₄ |
|---|----------------------------------|------------------|-------|-------|------------------|
| ρ [kg·m ⁻³] | 1827 | 1885 | 1765 | 2000 | 3209 |
| t_{melt} [°C] | 459 | 552 | 848 | 996 | --- [†] |
| t_{boil} [°C] | 1430 | 1169 | 1673 | 1704 | 912 |
| C_p [kJ kg ⁻¹ °C ⁻¹] | 2.371 | 2.138 | 2.583 | 1.595 | 1.002 |

In order to better illustrate the behaviour of the core during a total loss of coolant accident scenario, we used data from the JEFF3.0 library to evaluate the scattering to capture cross-section ratio and the moderating ratio of the molten salts. Figure 5 shows the data for Li₂BeF₄, BeF₂, LiF, NaF and ZrF₄. In the LS-VHTR core, graphite represents the major moderating material. It can be expected that the reactivity insertion, which follows after a total void of coolant will be related to the difference in the moderating abilities of the voided salt and the graphite. As might be seen from subplots in figure 5, the curves of BeF₂ are closest to those of graphite. This implies that BeF₂ is a relatively efficient moderator and a weak absorber, which results in more negative response on salt voiding comparing to the other salts.

In the numerical simulation, Li salts contained only the isotope ⁷Li, which in nature represents 92.5 % of lithium. Since ⁶Li has a relatively high absorption cross section in thermal region, it can significantly influence the void coefficient.

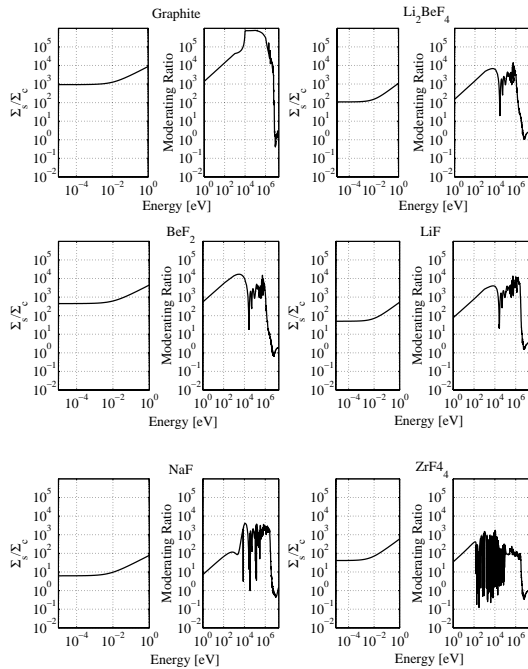


Figure 5: Elastic scattering to capture cross-section ratio, in the thermal region, and moderating ratio in the fast region, of graphite, Li₂BeF₄, BeF₂, LiF, NaF and ZrF₄.

III. C Fuels

In the present work, two different types of fuel have been used: neptunium - plutonium fuel, from the reprocessing of the spent LWRs fuel, in form of NpPuO_{1.7}, and enriched uranium in form of UO_{1.7}. The initial uranium fuel enrichment was set to be 6.965%, in order to provide the same initial reactivity excess as does the plutonium fueled, bare core (without the outer radial and axial graphite reflectors). However, this enrichment does not allow a long refueling time and therefore it has been increased by changing the Fuel to Moderator (FM) ratio, (the number of fuel atoms in the fuel pin divided by the number of moderator atoms in the pin) was examined. Table 3 reports the isotopic composition of both fuel types. Uranium fuel is listed in both analyzed enrichments.

Table 3: Atomic composition of the fuel.

| Plutonium Fuel | | Uranium Fuel | |
|-------------------|----------------|------------------|----------------|
| Isotope | Percentage [%] | Isotope | Percentage [%] |
| ²³⁷ Np | 1.91 | ²³⁵ U | 2.58 → 5.56 |
| ²³⁸ Pu | 0.56 | ²³⁸ U | 34.46 → 31.15 |
| ²³⁹ Pu | 21.11 | ¹⁶ O | 62.96 |
| ²⁴⁰ Pu | 8.5 | | |
| ²⁴¹ Pu | 3.09 | | |
| ²⁴² Pu | 1.87 | | |
| ¹⁶ O | 62.96 | | |

Figure 6 shows the capture to fission ratios of the plutonium and the uranium fuel mixtures [6]. Striking thermal peaks at 0.25 - 0.3 eV of ²³⁹Pu and ²⁴¹Pu and a peak at 1.056 eV, of ²⁴⁰Pu, which reflect in the capture to fission ratio curves of figure 6 strongly influence the neutron spectrum profile and the key safety parameters of the core. Similarly does the epithermal peak at 6.67 eV of ²³⁸U for the uranium fuel. Let us observe that the higher capture to fission ratio of for the plutonium fuel (about 0.5), compared to the uranium one (about 0.2), in the thermal energy range, from the numerical point of view of the MCNP simulations, translates into a shorter (approximately 5 times) computing time for the plutonium fueled core. The reason for this is, that the code needs to follow a smaller number of neutrons between two successive generations.

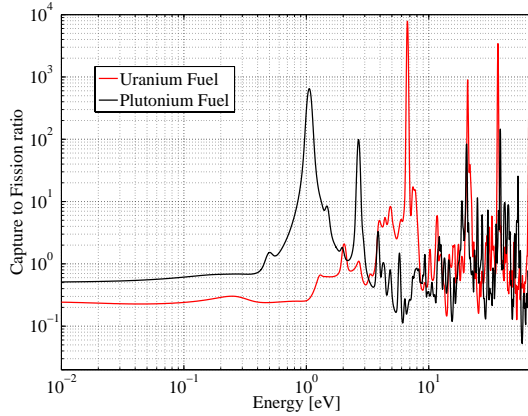


Figure 6: Capture to fission ratios of the fuel mixtures.

III. Results

III. A Moderation State

First, we determined, whether the initial core configuration for each fuel type was under- or overmoderated; consequently we were modifying the fuel to moderator ratio in order to set the core undermoderated. In an overmoderated core, an evacuation of coolant is always expected to cause an increase in reactivity (unless the leakage prevails in case of a compact core). In an undermoderated core, a coolant removal can cause either

- a reactivity drop (moderation abilities of the salt prevail over its absorption abilities)
- or
- a reactivity increase (absorption abilities of the salt prevail over its moderation abilities).

The initial core configuration was: TRISO kernel radius 150 μm and TRISO packing fraction (pf) 14.53% for both the uranium and plutonium fueled cores. For the uranium fueled core, the uranium fuel enrichment was 6.965%. First, we modified the TRISO packing fraction, by adding 1242 fuel particles to each fuel pin. This change caused a k_{eff} drop of -0.044 (± 0.001) in the plutonium fueled core, which demonstrates that the plutonium fueled core was initially undermoderated. The same change in the uranium fueled core yielded a k_{eff} increase of + 0.048 (± 0.001), which demonstrates, that the core was initially overmoderated. Second, we studied the k_{eff} as a function of the TRISO kernel radius, when the TRISO pf has been kept constant. The radius of the TRISO kernel varied from 100 to 250 μm and the porous carbon layer altered accordingly, to keep the radius of the TRISO particle constant. According to figure 7, the

uranium curve exhibits a maximum at about 200 μm . Then the core turns undermoderated and further adding of the fuel causes a k_{eff} drop. In the case of the plutonium fueled core, which is initially undermoderated, the curve declines from the beginning. A shallow dip occurs when the kernel radius reaches 225 μm . Thereafter, the k_{eff} grows modestly. This behaviour might be a consequence of the spectral peak passing a region, where a capture to fission ratio peak of the plutonium fuel (figure 6) is situated. Proof of this claim should be addressed in further studies.

Let us point out that the FM ratio depends mainly on the TRISO kernel radius and the packing fraction. However, the TRISO kernel radius plays major role because the dependence is according to the third power of r .

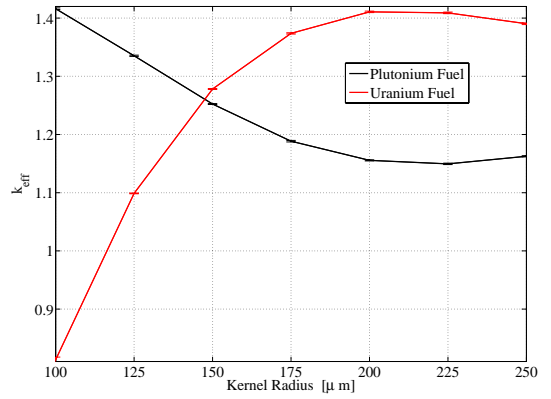


Figure 7: k_{eff} as function of the TRISO kernel size; TRISO pf has been constant, 14.53%. Confidence interval of one standard deviation is depicted.

III. B Total Void Worth

The Total Void Reactivity coefficient (TVR) represents the reactivity introduced in the core when the coolant is removed.

$$TVR = \rho^{void} - \rho = \frac{1}{k_{\text{eff}}} - \frac{1}{k_{\text{eff}}^{void}} \quad (1)$$

The calculation of the CVR has been performed for three core configurations and five molten salts for each of the configurations. The key parameters of three core configurations are listed in table 4.

Table 4: Key parameters in the CVR calculations.

| Core configuration | 1 | 2 | 3 |
|---------------------------------|-------|-------|-------|
| Kernel size [μm] | 150 | 250 | 215 |
| TRISO pf [%] | 14.53 | 18.56 | 24.83 |
| ^{235}U Enrichment [%] | 6.965 | 6.965 | 15 |
| FM Ratio [%] | | | |
| - Uranium Fuel | 0.53 | 3.08 | 2.46 |
| - Plutonium Fuel | 0.44 | 2.56 | 2.05 |
| β_{eff} [pcm] | | | |
| - Uranium Fuel | 659 | 674 | 741 |
| - Plutonium Fuel | 267 | 225 | 303 |

The first core configuration uses the fuel particle dimensions and the packing fraction of GA that were used previously in the deep burn analyses of the GT-MHR [2]. The uranium enrichment was regulated to provide the same k_{eff} as the plutonium fueled bare core. The second set of calculations uses a higher pf, a bigger kernel radius and the same uranium enrichment as the first case. The third set of calculations was performed with a kernel size, a TRISO packing fraction and a uranium enrichment, which sets a three- year life time for the uranium fueled core.

The void coefficients are related to the ability of the individual molten salts to act in the core as a moderator or a parasite absorber. This is given by the core geometry and the fuel, the moderator and the molten salt macroscopic cross sections.

Configuration one - Pu core undermoderated, U core overmoderated

Table 5 summarizes the total void worth coefficients, calculated according to equation 1, for the five different molten salt candidates. The TRISO particle packing fraction was set to 14.53%, the kernel radius to 150 μm for both fuel types and the uranium enrichment to 6.965%. This configuration yields a FM ratio of 0.53% for the uranium fueled core and of 0.44% for the plutonium fueled core.

In case of the undermoderated, plutonium fueled core, voiding FLiBe and BeF_2 is equivalent to a negative reactivity insertion, because the moderation abilities of the salts prevail over their parasitic absorption; salts behaves in the core more as a moderator rather than an absorber. A different situation occurs when voiding LiF, NaF and ZrF_4 . These salts are rather strong absorbers and therefore their removing leads to a positive reactivity insertion. In case of the overmoderated, uranium fuelled core, voiding any salt results in a positive reactivity introduction.

Table 5: Total void worth coefficients for a TRISO particle packing fraction of 14.53%, a kernel radius of 150 μm and a uranium fuel enrichment of 6.97%. [†] The core results subcritical with uranium fuel.

| Molten Salt | Plutonium Fuel | | Uranium Fuel | |
|---------------------------|----------------|----------------|--------------|-----------------|
| | [\$] | [pcm] | [\$] | [pcm] |
| Li_2BeF_4 | -2.40 | -641 \pm 60 | +5.95 | +3920 \pm 43 |
| BeF_2 | -5.26 | -1405 \pm 52 | +0.43 | +280 \pm 40 |
| LiF | +0.31 | +83 \pm 52 | +10.51 | +6920 \pm 38 |
| NaF [†] | +9.48 | +2530 \pm 51 | +74.66 | +49170 \pm 33 |
| ZrF_4 | +4.61 | +1230 \pm 50 | +13.80 | +9090 \pm 37 |

Generally, the difference between the CVR of the examined salts reflects the difference in their scattering to capture cross section (and moderating) ratios. The subplots of figure 5 coupled to table 8 show that the lower is the scattering to capture ratio of the coolant, the higher is the void coefficient. For instance, one can observe, that the scattering to capture and the moderating ratios of BeF_2 and FLiBe are pretty similar to those ones of graphite, for they induce, in the case of coolant removal, a decrease of reactivity (for an undermoderated core configuration). Amid all coolant candidates, NaF is the strongest absorber; consequently, the configuration with the uranium fuel and NaF becomes subcritical. All the delayed neutron fractions have been calculated with the FLiBe coolant.

Configuration two - Pu core locally overmoderated, U core undermoderated

Table 6 reports the total void worth void coefficients for a higher TRISO packing fraction, 18.56% and larger kernel radius, 250 μm . The FM ratio has been increased up to 3.08% for the uranium fueled core and up to 2.56% for the plutonium fueled core. In the present configuration, the fuel pin contains 69 particles in the xy - plane and 83 along the z - axis (yielding a total of 5727 particles).

Table 6: Total void worth coefficients for a TRISO packing fraction of 18.56 %, a kernel radius of 250 μm and a uranium fuel enrichment of 6.97%.

| Molten Salt | Plutonium Fuel | | Uranium Fuel | |
|--------------------------------------|----------------|----------------|--------------|-----------------|
| | [\$] | [pcm] | [\$] | [pcm] |
| Li₂BeF₄ | +2.31 | +520 \pm 90 | -0.19 | -129 \pm 111 |
| BeF₂ | +0.68 | +152 \pm 111 | -1.97 | -1327 \pm 114 |
| LiF | +4.02 | +904 \pm 81 | +1.64 | +1105 \pm 143 |
| NaF | +7.60 | +1708 \pm 89 | +15.18 | +10234 \pm 88 |
| ZrF₄ | +7.49 | +1685 \pm 85 | +3.56 | +2402 \pm 109 |

The previous changes set the uranium fuelled core undermoderated, which amplifies the moderating role of the coolant according to its moderating ratio. Also, the relative importance of the absorption in the fuel has increased. It can be expected, that the CVRs shift towards negative values in the uranium fuelled core.

As shown in table 9, the core exhibits a negative coolant void reactivity feedback for Li₂BeF₄ and BeF₂. The latter one is in absolute value bigger, in agreement with figure 5. In the plutonium fuelled core, most of the void coefficients shifted towards positive values, as the FM increased and the core became locally overmoderated. When a coolant, which acts partly as a moderator, is removed, spectra hardens. If this occurs in a region, where the spectral peak passes over a peak in the capture to fission ratio, a positive reactivity is introduced to the core.

For NaF, the CVR moved towards negative values; NaF is so strong absorber, that its moderating abilities is negligible. Changing the FM ratio influences the system by the drop of the relative importance of the neutron capture in the salt.

Configuration three - Pu core undermoderated, U core undermoderated

Table 7 lists the void coefficients for a TRISO packing fraction of 24.83%, a kernel radius of 215 μm and a 15% ²³⁵U enrichment. That gives a FM ratio of 2.46% and 2.05% for the uranium and for the plutonium fuelled core, respectively. In this configuration, a fuel pin contained 97 particles in the xy - plane and 79 particles along the z - axis (yielding a total of 7663 particles). Table 7 shows that for the uranium fuelled core, the decrease of the FM ratio shifted the CVR towards negative values.

Table 7: Total void worth coefficients for a TRISO packing fraction of 24.83 %, a kernel radius of 215 μm and a uranium fuel enrichment of 15%.

| Molten Salt | Plutonium Fuel | | Uranium Fuel | |
|--------------------------------------|----------------|----------------|--------------|----------------|
| | [\$] | [pcm] | [\$] | [pcm] |
| Li₂BeF₄ | +1.40 | +423 \pm 44 | -0.42 | -308 \pm 56 |
| BeF₂ | -1.99 | -60 \pm 38 | -1.61 | -1194 \pm 57 |
| LiF | +2.70 | +816 \pm 39 | +0.61 | +449 \pm 58 |
| NaF | +5.64 | +1707 \pm 37 | +7.50 | +5545 \pm 49 |
| ZrF₄ | +5.43 | +1642 \pm 39 | +2.09 | +1551 \pm 53 |

By drop of the FM ratio, the core has essentially returned towards the vicinity of the state, when it turns under/ overmoderated. For the plutonium fuel and the BeF₂ coolant, the void coefficient returned to negative values, and for the other salts, its positive values decreased.

In all the calculations, the coolant volume fraction (*the total coolant volume divided the core volume*) was 8.9%. From the presented configurations (table 4), the first one has been assumed as a reference for the plutonium fuelled core and the last one (with the enhanced FM ratio) for the uranium fuelled core for the rest of this study. Last but not least, it is worth to point out, that an event with a total coolant voiding is in the assumed LS-VHTR plant design very improbable, since the reactor vessel and the containment vessel are placed in a concrete silo which prevents the salt evacuation even in case of vessel melting. Furthermore, the primary pumps inlets are situated above the core, which excludes a total loss of coolant from damaged primary pipes. However, under less severe accident conditions, a local salt boiling may occur.

III. C Moderator temperature coefficient of reactivity

For the plutonium fuelled core, the kernel radius was set to 150 μm and the TRISO packing fraction to 14.53%. For the uranium fuelled core, the kernel radius was set to 215 μm , the TRISO packing fraction to 24.83% and the enrichment to 15%.

The Moderator Temperature Reactivity coefficients (MTR), have calculated according to equation:

$$MTR = \frac{\rho^{T_2} - \rho^{T_1}}{T_2 - T_1} = \frac{\frac{1}{k_{eff}^{T_1}} - \frac{1}{k_{eff}^{T_2}}}{T_2 - T_1} \quad (2)$$

For the plutonium fuelled core, the MTC in the operation temperature region (graphite, 1200 K) is large and negative, -6.53 ± 0.12 pcm/K ($\$/K -2.45e-2$). For the uranium fuelled core, the value becomes -0.21 ± 0.08 pcm/K ($\$ -2.78e-4$).

III. D Fuel Temperature Coefficient of Reactivity

The Fuel Temperature Reactivity coefficients (FTR) have been calculated analogically to the MTR, according to equation 2. At the operational temperatures, the FTR coefficients are -1.24 ± 0.12 pcm/K ($\$/K -4.65e-3$) for the plutonium fuelled core and -2.26 ± 0.08 ($\$/K -3.05e-3$) for the uranium fuelled core.

VI. Conclusions

In the present work, we have investigated the neutronic and safety performance of the Liquid Salt cooled - Very High Temperature Reactor (LS-VHTR), fueled with two types of fuel. The study is based on the preconceptual AHTR design [1] and it offers a comparison of the core performance fueled with spent LWR fuel and enriched uranium fuel.

The results showed that the total void worth coefficient can be set negative for both fuel types and FLiBe with an optimized fuel to moderator ratio that sets the core undermoderated. At this fuel to moderator ratio, the total negative feedback from the moderator and fuel at the operational temperatures is -7.82 pcm/K for the plutonium fueled core and -2.47 pcm/K for the uranium fueled core. This ensures a total negative temperature feedback. The effective delayed neutron fraction (table 4) is approximately 2.5 times higher for the uranium fueled core and it changes negligibly with the increase of the fuel to moderator ratio. The low value for the plutonium fueled core may present a challenge to the LS-VHTR concept.

References

- [1] D. T. Ingersoll, L. J. Ott, J. P. Renier, S. J. Ball, W. R. Corwin, C. W. Forsberg, D. F. Williams, D. F. Wilson, L. Reid, G. D. Del Cul, P. F. Peterson, H. Zhao, P. S. Pickard, E. J. Parma. Status of Preconceptual Design of the Advanced High-Temperature Reactor. (ORNL, The United States of America, Tennessee 2004).
- [2] A. Talamo, W. Gudowski, F. Venneri, *Annals of Nuclear Energy*, **31**, 173-196 (2004), The burnup capabilities of the Deep Burn Modular Helium Reactor analyzed by the Monte Carlo Continuous Energy Code MCB.
- [3] F. Brown, *Annals of Nuclear Energy*, **31**:2039–2047, (2005), Stochastic geometry capability in mcnp5 for the analysis of particle fuel.
- [4] D. R. Lide. Handbook of Chemistry and Physics, 84th edition. CRC Press, (2004).
- [5] R.B.Briggs. Molten-salt reactor program, semiannual progress report for period ending February 28. Technical Report ORNL-3936, Oak Ridge National Laboratory, 1966.
- [6] J. Zakova, Analysis of an Advanced Graphite Moderated and Molten Salt Cooled High Temperature Reactor. *Master thesis, KTH, Sweden*, (2007).