ANL-GenIV-074

NEUTRONIC ASSSESSMENT OF STRINGER FUEL ASSEMBLY DESIGN FOR LIQUID-SALT-COOLED VERY HIGH TEMPERATURE REACTOR (LS-VHTR)

Nuclear Engineering Division

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Neutronic Assessment of Stringer Fuel Assembly Design for Liquid-Salt-Cooled Very High Temperature Reactor (LS-VHTR)

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Abstract

Neutronic studies of 18-pin and 36-pin stringer fuel assemblies have been performed to ascertain that core design requirements for the Liquid-Salt Cooled Very High Temperature Reactor (LS-VHTR) can be met. Parametric studies were performed to determine core characteristics required to achieve a target core cycle length of 18 months and fuel discharge burnup greater than 100 GWd/t under the constraint that the uranium enrichment be less than 20% in order to support non-proliferation goals. The studies were done using the WIMS9 lattice code and the linear reactivity model to estimate the core reactivity balance, fuel composition, and discharge burnup.

The results show that the design goals can be met using a 1-batch fuel management scheme, uranium enrichment of 15% and a fuel packing fraction of 30% or greater for the 36-pin stringer fuel assembly design.

INTRODUCTION

Evaluations of a liquid-salt- (molten-salt-) cooled version of the prismatic-block type VHTR, the LS-VHTR, are ongoing at U.S. national laboratories, universities, and industry. These evaluations have included core and passive safety studies and balance of plant conceptual designs. [1,2]

Earlier project studies had indicated that the LS-VHTR designs using fuel blocks similar to those employed for the Fort Saint Vrain and GT-MHR cores could result in the blocks floating during refueling. [3] This is because of the lower density of the fuel block relative to the liquid salt coolant. Consequently, it was decided to evaluate assembly designs that allow more effective restraint of the fuel assemblies. Based on this requirement, and the potential to reduce the number of fuel movements during refueling, it was proposed that effort be devoted to the stringer assembly design similar to that used in the U.K. advanced gas-cooled reactor (AGR) system. In this design, the graphite moderator and fuel material are decoupled, with the two removed from the core at different intervals. In the AGR design, this allows the on-line (at power) refueling of the core.

A study has been conducted to confirm the feasibility of the fuel stringer design from a neutronic viewpoint, with the design requirements satisfied. The target values for the fuel discharge burnup and cycle length that were used in the FY 2005 study [1] have been retained. Specifically, the discharge burnup and cycle length should be at least 100 GWd/t and 1-½ years, respectively, with the uranium enrichment constrained to less than 20% ^{235}U.

In Section 2, the characteristics of the LS-VHTR core and stringer fuel assembly are briefly described. The lattice physics tools and models employed in this study are discussed in Section 3. The results of sensitivity and parametric studies are summarized in Section 4. Finally, the conclusions from the work are provided in Section 5.

1.0 LS-VHTR CORE USING STRINGER FUEL ASSEMBLY

The core layout consists radially of 265 fuel assemblies, arranged similarly to the fuel columns evaluated in the FY 2005 LS-VHTR study (see Figure 1). The FY 2005 study used the GT-MHR fuel elements that are 79.3 cm high, of which ten are stacked vertically in each fuel column. The fuel assembly blocks have a pitch of 36 cm (measured across the flats). The GT-MHR standard assembly design contains holes for fuel compacts and liquid-salt coolant passage. In the current study, the fuel column consists vertically of hexagonal graphite blocks (moderators) that have a large central hole. The blocks in the column are restrained to ensure that they do not float in the liquid-salt coolant. The block pitch is still 36 cm, but each block now has a height of 1 m. The active core height is however 8 m (similar to the original design, 793 cm).

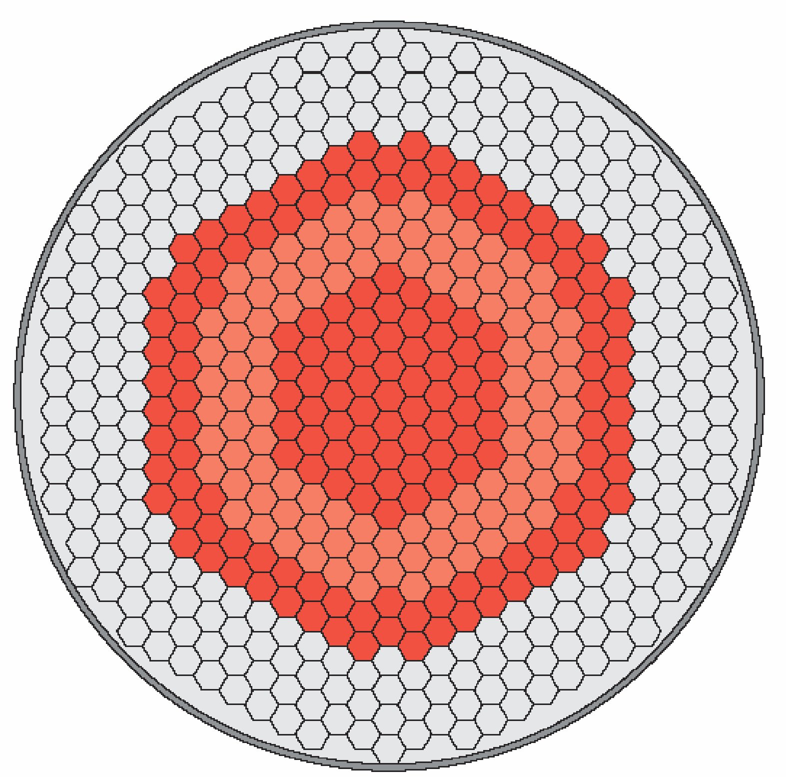

Figure 1. LS-VHTR Core Layout.

Fuel stringers pass through the large central holes. In the current study, graphite is assumed for the material of the stringer unit, but in reality might be carbon-carbon composites to provide the required strength. Each fuel stringer contains 8 fuel elements stacked vertically, each

1 m high. Figure 2 shows schematically the fuel stringers and graphite moderator (graphite block in a core column) for designs containing 18 and 36 fuel pins in the fuel stringer. For simplification of the current study, the stringer material and the graphite block have been modeled as a single graphite material. By separating the graphite block and the fuel stringer, the fuel stringer that sees much harsher conditions (temperature gradients, neutron dose, etc.) could be replaced periodically, while the blocks could stay longer in the core (note that in the U.K. AGRs the graphite blocks are permanent).

The reference assembly design has 18 fuel pins and a tie rod in the center (Figure 2). For this design, the inner diameter of the fuel stringer is 20 cm. The fuel rods are arranged in two circular rings. The inner ring has six rods that are displaced 60^{o} apart, while the 12 rods in the outer ring are displaced 30^{o} apart. The central tie rod shown in Figure 2 is used for forming the 8 fuel elements (arranged vertically) into a stringer unit. Due to high temperature considerations, the tie rod would not be made of metal (some alloys might be useable). It might however be a carbon-carbon composite due to potential material strength requirements for the LS-VHTR. In the current study, it is assumed to be graphite. In the U.K. AGRs the tie rod is made of stainless steel.

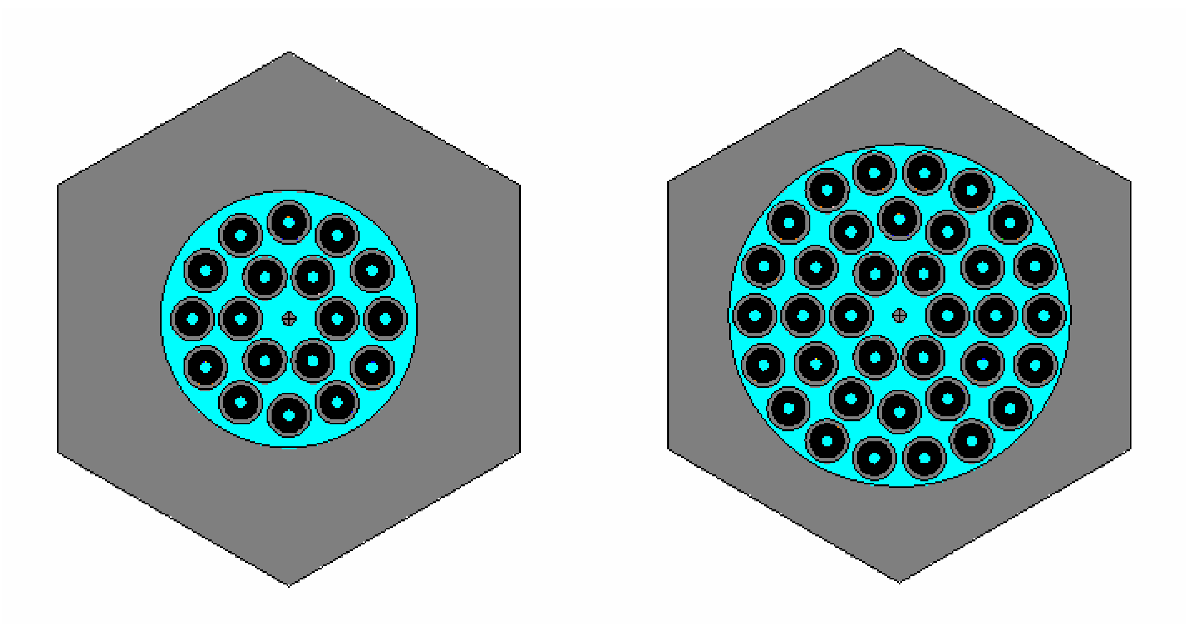

Figure 2. Radial Layouts of New 18-Pin (Left) and 36-Pin (Right) Stringer Assemblies.

An annular pin design similar to that used for the HTTR has been considered in this study to reduce the fuel center-line temperature. The pin contains annular fuel compacts that are stacked end-to-end vertically in a graphite or carbon-carbon composite sleeve (graphite assumed in this study). The inner diameter of the fuel compact is 1.0 cm and the outer diameter is 2.6 cm. The graphite sleeve outer diameter is 3.4 cm. The distance between each ring is 3.75 cm.

The fuel compact are assumed to contain TRISO coated fuel particles (CFPs) in a graphite matrix similar to that used for the FY 2005 design study. In the current work, the CFPs each have a central uranium oxycarbide fuel kernel and layers of carbon and silicon carbide. A kernel diameter of 425 μm is assumed. The CFP packing fraction in the compact graphite matrix is a variable that is determined in the current work. From a fuel performance point of view a conservative limit of 35% has been imposed in this study.

The liquid salt coolant passes through the space external to the fuel pins in the fuel stringer. The coolant assumed in the study is Flibe (Li_2BeF_4) that is enriched to 99.995% Li-7 in the lithium.

For design sensitivity study, a 36-pin design was also considered for the purpose of increasing the fuel loading. This configuration was obtained by adding an extra outer ring containing 18 fuel pins arranged 20^o apart on an imaginary circle 11.25 cm from the center of the assembly. Figure 2 also shows the configuration with 36 fuel pins. The pin dimensions are the same as those for the 18-pin design. To contain the 36 fuel pins in the fuel stringer, the inner diameter of the fuel stringer is increased to 26.6 cm; this radius was derived from an optimization study discussed in Section 4.6.

Design data for the stringer fuel assemblies used in the current study and the block design used in the FY 2005 study are summarized in Table 1. Finally, for calculations at hot, full-power condition, the material temperatures assumed are fuel = 1027°C, moderator = 977°C, and coolant = 927°C. These are also consistent with FY 2005 data. No thermal design calculations are planned for this year.

Table 1. Comparison of Design Data for LS-VHTR Cores Using Block and Stringer Fuel Assemblies.

	Block	18-pin Stringer	36-pin Stringer
Core power, MWt	2400	2400	2400
Core power density, MW/m^3	10.2	10.1	10.1
Active height, cm	793	800	800
Coolant	Li_2BeF_4	Li_2BeF_4	Li_2BeF_4
Fuel element			
- width across flats, cm - height, cm - density, g/cm^3 - fuel rod channel OD, cm -fuel rod inner/outer dia., cm - coolant channel OD, cm - fuel compact pitch, cm - number of fuel compacts	36.0 79.3 1.74 1.27 --/1.245 0.953 1.8796 216	36.0 100.0 1.74 n/a 0.5/1.3 20.0 3.75 18	36.0 100.0 1.74 n/a 0.5/1.3 26.6 3.75 36
Fuel compact			
- kernel - 1st coating - 2nd coating - 3rd coating - 4th coating	425 μm, $UC_{0.5}O_{1.5}$, 10.50 g/cm^3 Carbon buffer, 100 μm thickness, 1.0 g/cm^3 Inner pyretic carbon, 35 μm thickness, 1.90 g/cm^3 SiC, 35 μm thickness, 3.2 g/cm3 Outer pyretic carbon, 40 μm thickness, 1.87 g/cm^3		
Coolant temperature (inlet/outlet, ^oC)	900 / 1000	900 / 1000	900 / 1000
Average temperatures for core calculations (^oC) - fuel - graphite - coolant	 1027 977 927	 1027 977 927	 1027 977 927

2.0 COMPUTATION METHODS AND MODEL VERIFICATION

The calculations done for this study have mostly used the linear reactivity model (LRM) [4] and the lattice code WIMS9 [5] to represent the LS-VHTR core. WIMS9 does not explicitly allow treatment of the double heterogeneity effect of the coated fuel particles in the graphite matrix during assembly-level calculations, but this can be done in a two-step process described in Section 3.2. Prior to the final calculations, the performance of the code model was evaluated by comparing results with those obtained using the Monte Carlo code MCNP4C [6].

The LRM assumes that the core reactivity behavior with burnup (k_{eff} let-down) is linear and can be predicted using a series of unit assembly calculations. The approach is particularly useful for getting estimates of the enrichment requirements and fuel compositions with burnup. In this regard, estimates of the required fuel enrichment can be obtained for the critical burnup states. The LRM cannot, however, be used for accurately estimating the core power peaks.

In the following sections, the linear reactivity model and the WIMS9 lattice codes and models are briefly discussed. The results of the WIMS9 code model compared to the MCNP4C results are then presented.

3.1 Estimation of Core Reactivity and Cycle Length

If the assumption of a linear relationship between the core excess reactivity and burnup is acceptable, the linear reactivity model can be used to predict the reactivity behavior of various multi-batch fuel management schemes. In our approach, assembly-level calculations with reflective boundary conditions were utilized to model the performance of a reactor loaded entirely with LS-VHTR stringer fuel and reflector assemblies. In this case, the linear reactivity model [4] gives the relationship between the core critical burnup (B_c) and the assembly discharge burnup (B_d):

$$B_c = \frac{n+1}{2n} B_d \, , \tag{1}$$

where n denotes the number of fuel management batches.

In Equation (1) above, the critical burnup is equivalent to the core average burnup at the end of cycle (EOC). For example, in a three-batch core with a cycle length of 33.3 GWd/t, the discharge burnup is 100 GWd/t, and according to Equation 1, the critical burnup is 66.67 GWd/t.

Generally, the core fuel loading at beginning of cycle (BOC) is designed such that the effective multiplication factor (k_{eff}) of the core reaches 1.00 when the core average burnup is identical to the critical burnup (in other words, when core reaches the end of cycle). In order to represent the whole-core state adequately with an assembly-level calculation, the effect of neutron leakage through the core boundary must be accounted for in the assembly k_{inf} value. The FY 2005 study [1] indicated that the LRM gives a good estimate of the LS-VHTR reactivity letdown when an appropriate core leakage approximation is utilized. That study indicated that the LS-VHTR neutron leakage is a reactivity penalty of ~ 1 to 2% Δk. Thus, the fuel cycle length and discharge burnup were evaluated using the WIMS9 lattice code and a 1.5% neutron leakage approximation; the assembly k_{inf} must be 1.015 at the critical burnup point.

3.2 Deterministic Lattice Codes and Models

The WIMS9 code provides an extensive software package for neutronics calculations. [5] Methods for the neutron flux solution in WIMS9 include collision probability (1-D or 2-D), method of characteristics, Sn method (1-D or 2-D), diffusion theory, and hybrid methods. The code also provides an integrated Monte Carlo method (MONK) for the purpose of internal validation. WIMS9 is supplied with 69- and 172-group libraries based on the validated JEF2.2 nuclear data. It is noted that the WIMS9 code has the PROCOL module that provides a capability for calculating the collision probabilities of particulate fuel in cylindrical geometry that could be used in flux solvers to model the double heterogeneity effect of that fuel form.

The WIMS9 code, however, does not provide a direct treatment of the particulate-fuel double heterogeneity at the assembly level. A two-step scheme is therefore utilized in the WIMS9 calculation. In the first step, the PROCOL module is used for detailed treatment of the double heterogeneity at the pin-cell level; other items, such as Doppler and resonance treatments are considered. A super-cell calculation is performed at this stage. The result of this calculation is homogenized fuel pin-cell cross sections. These cross sections are then used in the second step, which embodies the full-assembly calculation. Besides the homogenized geometry of the fuel pin-cell, the detailed geometries of the other cells are retained in the assembly calculation.

As noted above, the WIMS9 code has many modules that could be used for calculating the spatial lattice solution for the LS-VHTR stringer assembly design. These include both the more accurate and efficient CACTUS method of characteristics (MOC) solution approach and the sufficiently accurate PIJ collision probability approach (which does not support hexagonal boundary). Unfortunately, the CACTUS approach only supports Cartesian XYZ and hexagonal lattices. To use the CACTUS module for this work a model employing a hexagonal arrangement of pins (versus the circular arrangement) that is representative of the stringer assembly was first developed. The schematic representation of this model is presented in Figure 3 (for the two-step approach).

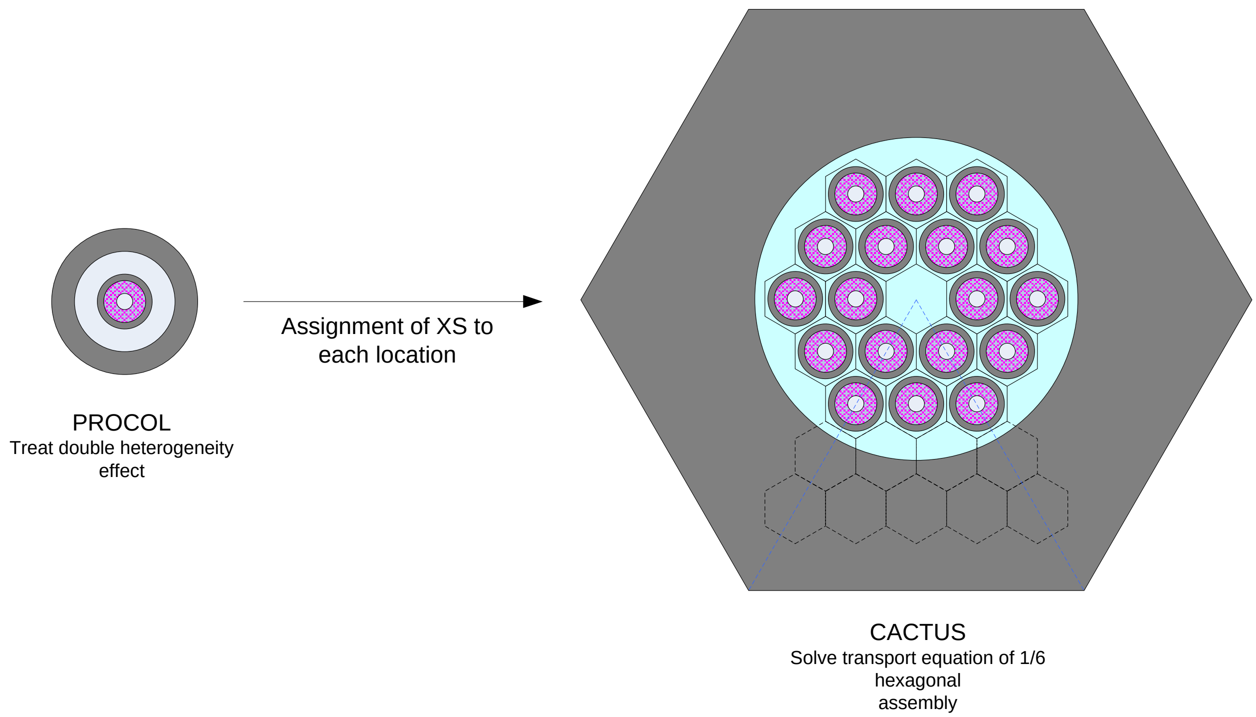

Figure 3. Schematic of CACTUS Geometry Model.

3.3 Lattice Code Verification by Comparison to Monte Carlo Results

The FY 2005 study demonstrated that the WIMS9 code is capable of calculating lattice parameters of interest very accurately compared to Monte Carlo reference solutions for the LS-VHTR. [1] Since the LS-VHTR stringer fuel assemblies are quite different from the block-type assemblies, further verification of the performance of the lattice code has been performed.

To show how well the CACTUS model is representative of the LS-VHTR stringer assembly, MCNP calculations were done with the circular and hexagonal pin arrangement models and their results were compared to the WIMS9 CACTUS results using the hexagonal pin arrangement model.

The MCNP4C calculations for the fuel assembly were performed using the ENDF/B-VI nuclear data library distributed with the code. The calculations were for the cold state (294 K) and have been performed without $S(\alpha,\beta)$ data for the light nuclides in the liquid-salt coolant because the data do not exist currently in both the MCNP4C and WIMS9. A lithium enrichment value of 99.995% was used. Figures 4 and 5 show the details of the MCNP models. The lattice arrangement in the fuel compact has been explicitly modeled as shown in Figure 4. Figure 5 also shows the details of each of the CFP in the graphite matrix. The WIMS9 code also has a model for treating the physics effects of the CFPs in the graphite matrix as described above.

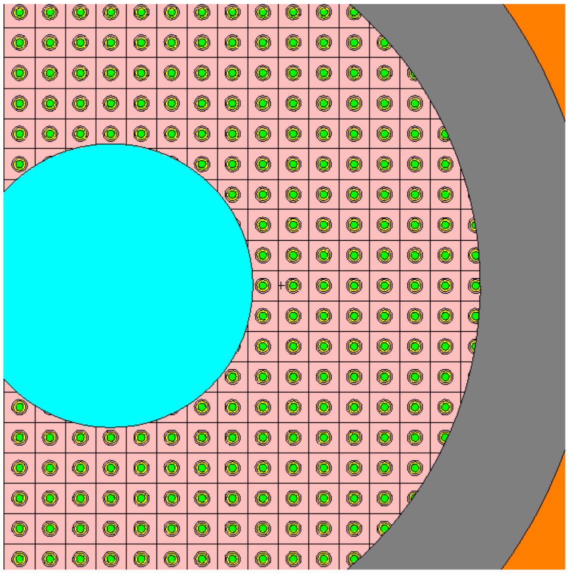

Figure 4. Enlarged View of Annular Fuel Compact.

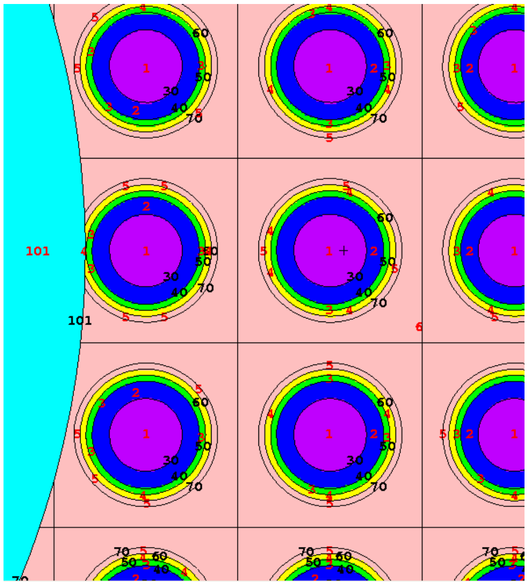

Figure 5. Representation of TRISO Particles in Fuel.

The k-infinity (assembly multiplication factor) results for the cold initial state are summarized in Table 2. Cases were done for both the 18-pin and 36-pin assembly designs and for packing fractions of 25, 30, and 35%.

Table 2. Comparison of k-infinity Values for Fuel Element at Cold State.

18-pin Assembly				
	Packing Fraction, %	25	30	35
MCNP	Circular stringer	1.6437	1.6622	1.6722
	Hexagonal stringer	1.6385	1.6572	1.6672
WIMS9 hexagonal		1.6592	1.6739	1.6821
36-pin Assembly				
	Packing Fraction, %	25	30	35
MCNP	Circular stringer	1.6204	1.6169	1.6088
	Hexagonal stringer	1.6160	1.6127	1.6067
WIMS9 hexagonal		1.6248	1.6160	1.6049

The results show that the impact of the circular fuel pin arrangement versus a hexagonal layout is at most ~0.2% for a single assembly model in MCNP. This indicates that the hexagonal arrangement model could be used in the WIMS9 code to represent the circular pin arrangement.

It is also observed that the agreement between the WIMS9 and MCNP results is quite good for the hexagonal arrangement of fuel pins, with a largest difference of ~800 pcm for the case with 18 pins and a packing fraction of 25%; much lower differences are obtained for the 36-pin design. Components of these differences come from the different nuclear data files used in the calculations (e.g., JEF2.2 for WIMS9).

3.0 PERFORMANCE OF LS-VHTR STRINGER FUEL ASSEMBLY

Parametric studies for the LS-VHTR using a stringer fuel assembly have been performed to ascertain that the constraint on the fuel enrichment will be met for the target cycle length of 18 months and discharge burnup greater than 100 GWd/t, similar to the FY2005 LS-VHTR studies. [1] The linear reactivity model developed and discussed in Section 3.1 was used for the study. The performance characteristics of the LS-VHTR core with 1-batch and 2-batch fuel management have also been evaluated. The results are presented in the following sub-sections.

4.1 Sensitivity Study on Number of Pins

The cycle length and discharge burnup were evaluated as functions of uranium enrichment, packing fraction, and number of fuel pins. Initially, a fuel enrichment of 15% was assumed and the packing fraction was varied from 25% to 35%. The lower value of the packing fraction is based on that derived in FY 2005 for the LS-VHTR block design and our current estimation that the stringer fuel design would require a higher value. Similar judgment was used for setting the initial enrichment value.

Results for the assembly k-infinity as a function of burnup are presented in Figure 6 for both the 18-pin and 36-pin stringer assembly configurations. Results for the LS-VHTR block design obtained in FY 2005 are also included for comparison. It is observed that the beginning of life (BOL) k-infinity decreases with increase in the number of fuel pins in the stringer assembly. This is due to the decrease in the amount of neutron moderation arising from the larger stringer-hole diameter for the 36-pin configuration, which reduces the amount of graphite moderator by almost 30%.

An interesting effect of using the stringer fuel assembly can be observed in Figure 6. Although the BOL k-infinity is much higher for the stringer assemblies (compared to the block design), the stringer assembly k-infinity values are lower than that of the block assembly later in life. This is due to the reduced fuel loading per assembly in the stringer designs. The 36-pin, 15%-enriched, and 25%-packing fraction stringer assembly contains 672 g of ^{235}U per assembly, compared to an average of ~900-1200 g for the block design. The 18-pin configuration has a ^{235}U loading of 336 g per assembly, much lower than for the block design.

The results have also been summarized as a function of cycle length and are shown in Figure 7. Though the 18-pin configuration has a larger amount of moderator and its BOL k-infinity is higher, its reactivity however burns out more quickly than the other cases. The reactivity of the 36-pin configuration trends similarly as the block design, but burns out more quickly because it has a lower fissile mass.

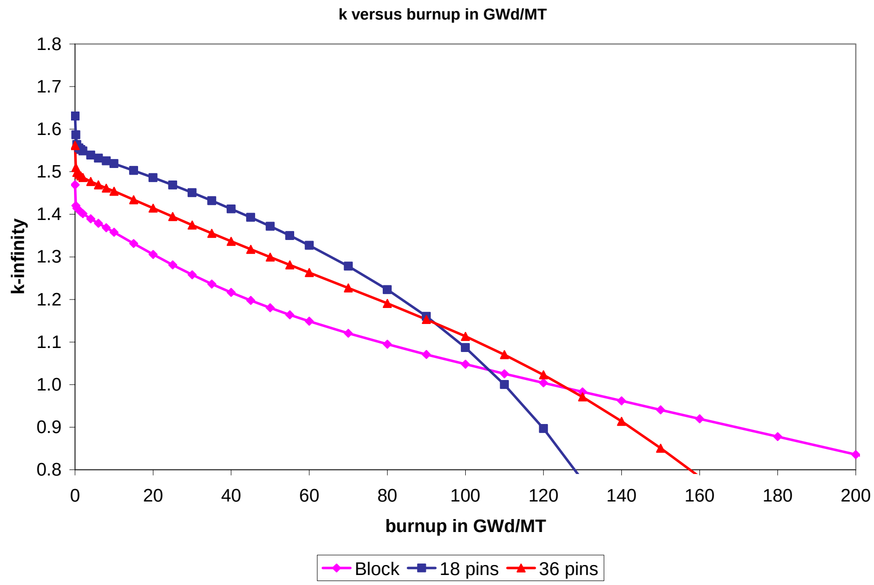

Figure 6. Comparison of k-infinity Versus Burnup for 25% Enrichment.

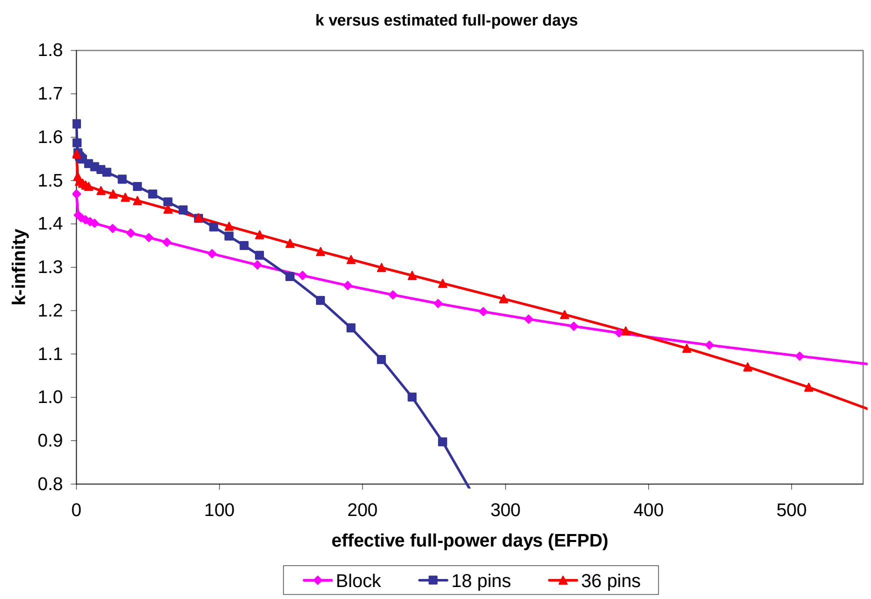

Figure 7. Comparison of k-infinity Versus Cycle Length for 25% Enrichment.

The results in Figures 6 and 7 indicate that the stringer fuel assembly would achieve a discharge burnup greater than 100 GWd/t with an enrichment of 25%, even with a 1-batch fuel management. Contrarily, the cycle length requirement cannot be met with this enrichment.

4.2 Sensitivity Study on Fuel-to-Moderator Ratio

The fuel-to-moderator number density ratio (N_U/N_C) is a key physics parameter in the study of graphite moderated systems. Figure 8 shows the effect of the N_U/N_C ratio on the BOL k-infinity trend. Results are presented for both the 18-pin and 36-pin configurations and for enrichments of 15% and 19.7%. Additional calculations were performed for the reference 15% enrichment cases to show trends; results for 10% packing fraction was included for the 36-pin configuration, while that for 50% packing fraction was included for the 18-pin configuration.

There appears to be an optimum N_U/N_C for the BOL k-infinity. This optimum is indistinguishable for the 18-pin configuration in the range evaluated. The optimum BOL k-infinity value is obtained with a packing fraction between 30 and 35% (N_U/N_C around 0.0015) for the 36-pin configuration. This packing fraction range seems appropriate also for the 18-pin configuration.

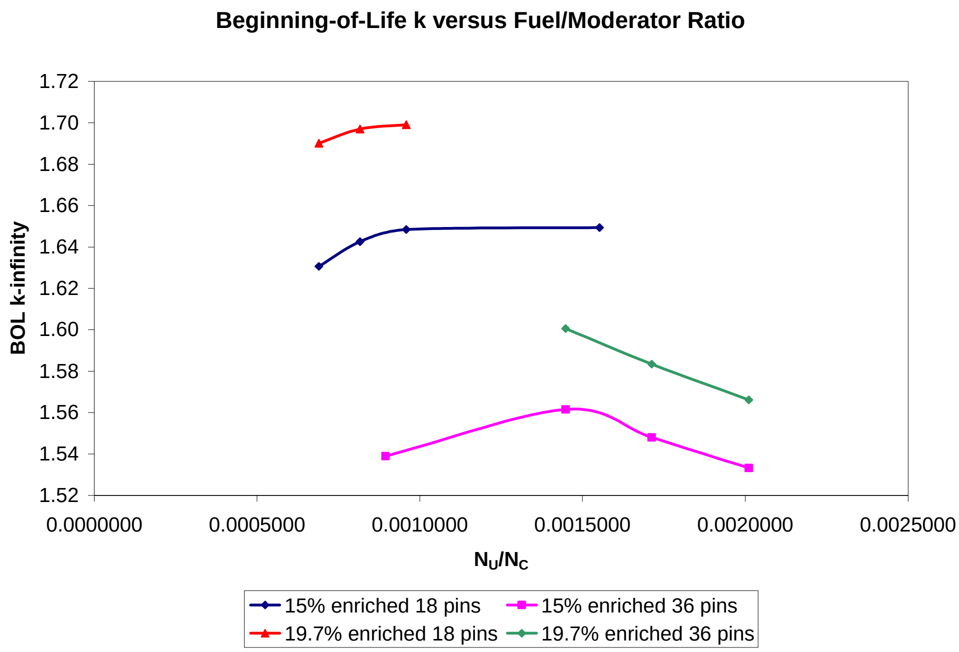

Figure 8. Trend of BOL k-infinity Versus Fuel-to-Moderator Ratio.

4.3 Impact of Fuel-to-Moderator Ratio on Cycle Length

As is quite well known, optimizing an assembly design for the BOL k-infinity does not necessarily imply optimization for the discharge burnup and cycle length. Consequently, due to the difficulty of meeting the cycle length requirement, its trend with the fuel-to-moderator ratio has been studied. Results are presented in Figure 9. Clearly, the optimum fuel-to-moderator ratio has not been reached for these stringer fuel assemblies, in terms of cycle length, which is quite dependent on the amount of uranium per assembly. A higher packing fraction could be desirable, but 35% was chosen as the upper limit for this study. In addition, the BOL eigenvalues are sufficiently high that the design goals can be satisfied with increased enrichment and packing fraction.

Within the constraint on the packing fraction (less than 35%), the results of Figures 8 and 9 indicate that a packing fraction in the range of 30 to 35% is a reasonable choice.

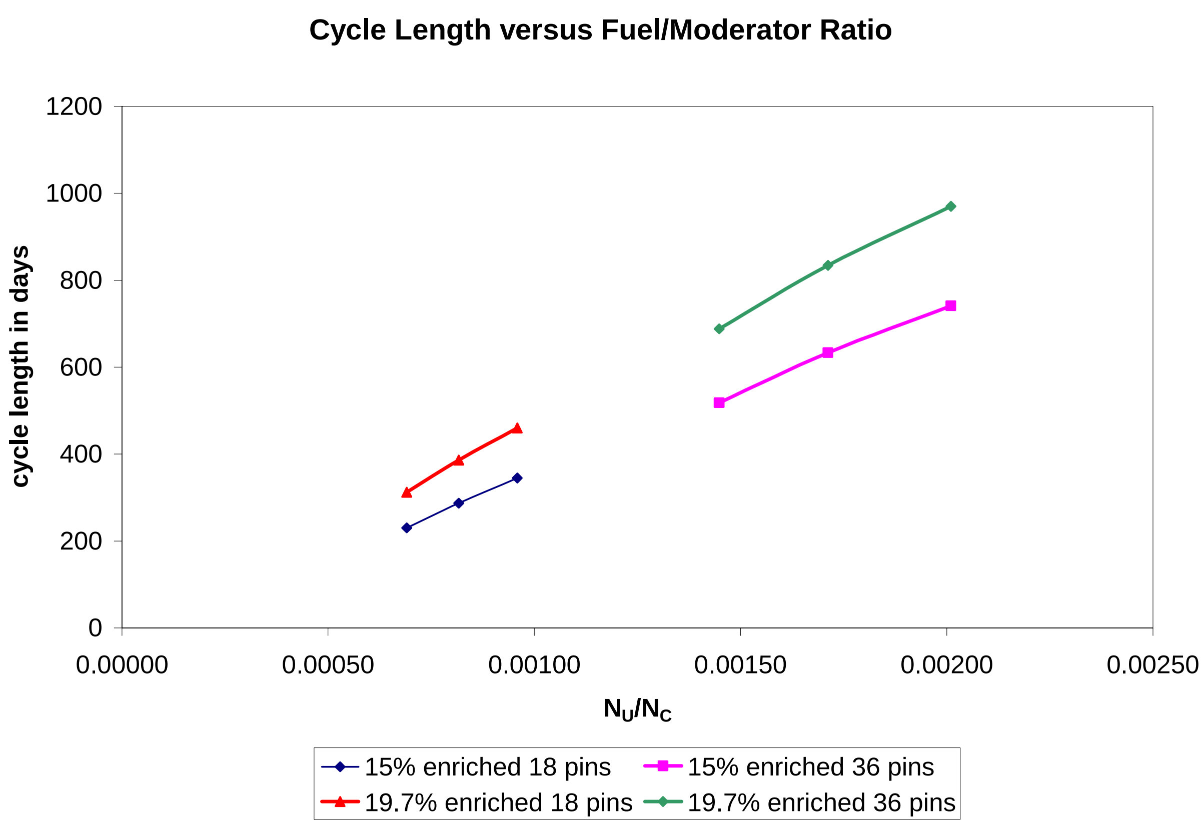

Figure 9. Cycle Length Versus Fuel-to-Moderator Ratio.

4.4 Flux Spectrum for LS-VHTR Fuel Assembly

A comparison of the BOL spectra for the block design and the 18- and 36-pin stringer assembly designs has been performed and is summarized in Figure 10. It is observed that while both the stringer-type assemblies have slightly softer spectra than the block design, the decreased moderation (and increased N_U/N_C ratio) in the 36-pin configuration gives a spectrum closer to that of the reference block-type fuel assembly. This finding is also consistent with the explanations presented above for the increased BOL and decreased EOL k-infinity values, and the beneficial impact of increased number of pins on the core cycle length and discharge burnup.

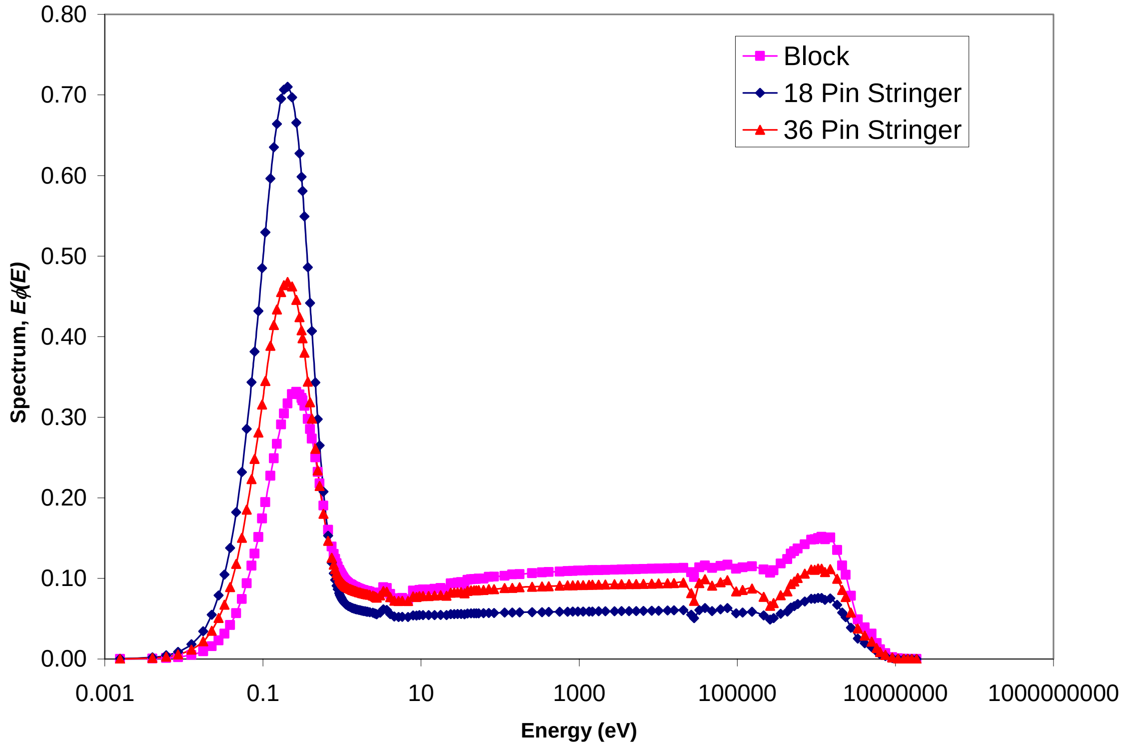

Figure 10. Variation of Neutron Spectrum with Assembly Design.

4.5 Sensitivity Study of Pin Pitch

Sensitivity analysis for the fuel pin spacing was performed using the CACTUS model shown in Figure 3. With this model it is possible to change the fuel pin spacing by changing the fuel pin pitch. The sensitivity analysis showed a 1.2% decrease in k-infinity for a 36-pin stringer assembly with a 4.0 cm pin pitch versus a 3.75 cm pin pitch (15% enrichment and

25% packing fraction were used). Increasing the fuel pin pitch, therefore, does not yield any benefit. However, the fuel pin pitch could be reduced a small amount from 3.75 cm, but the slight benefit of doing so could have consequences mechanically at high burnup; studies of the fuel pin swelling and expansion were not undertaken as part of this study, but with a 3.75 cm pitch there is only 0.35 cm space between the fuel pins and between the outer ring of fuel pins and the 13.3 cm radius stringer hole wall.

4.6 Sensitivity Study of Fuel Stringer Diameter

Changing the size of the fuel stringer hole had a significant impact on k-infinity values, as a small change significantly impacts the fuel/moderator ratio. For example, the difference in k-infinity for a 13.3 cm radius stringer hole and a 14 cm radius hole represents an overall change of less than 11%, in coolant area, which works out to a decrease of just over 5% of the amount of graphite per assembly. This change however reduces the k-infinity by 2-3%. Therefore, a 26.6 cm diameter hole was chosen to increase k-infinity by 2-3% and extend the cycle length.

4.7 Performance Results for 1- and 2-Batch Cores

Using the linear reactivity model, the performance characteristics for the LS-VHTR cores utilizing the stringer fuel assembly design and 1-batch or 2-batch fuel management have been determined. The results are summarized in Table 3. Two fuel enrichments were used for generating the results; the initial reference value (15%) and the limiting value (~20%).

The results show that the discharge burnup and core cycle length requirements cannot both be met simultaneously with an 18-pin stringer assembly design. Much higher packing fraction and enrichment than considered in this study would be required to meet the cycle length requirement.

Within the 20% constraint on the fuel enrichment, the discharge burnup and cycle length can both be met using the 36-pin stringer fuel assembly design. The results indicate that with a packing fraction of 30%, the discharge burnup and cycle length target values of >100 GWd/t and 18 months, respectively, can be obtained with an enrichment of 15%. For a 2-batch fuel management, an enrichment of 19.7% and a packing fraction greater than 25% can be used to meet both requirements.

Table 3. Cycle Length and Discharge Burnup (LRM with 1.5% Leakage Approximation).

18 pins, 15% Enriched				
Packing Fraction (%)	1-Batch		2-Batch	
	Discharge Burnup (GWd/t)	Cycle Length (Days)	Discharge Burnup (GWd/t)	Cycle Length (Days)
25	108	230	144	153
30	112	287	149	191
35	116	345	154	230
18 pins, 19.7% Enriched				
Packing Fraction (%)	1-Batch		2-Batch	
	Discharge Burnup (GWd/t)	Cycle Length (Days)	Discharge Burnup (GWd/t)	Cycle Length (Days)
25	146	312	195	208
30	151	386	201	257
35	154	460	205	307
36 pins, 15% Enriched				
Packing Fraction (%)	1-Batch		2-Batch	
	Discharge Burnup (GWd/t)	Cycle Length (Days)	Discharge Burnup (GWd/t)	Cycle Length (Days)
25	121	518	162	345
30	124	633	165	422
35	124	741	165	494
36 pins, 19.7% Enriched				
Packing Fraction (%)	1-Batch		2-Batch	
	Discharge Burnup (GWd/t)	Cycle Length (Days)	Discharge Burnup (GWd/t)	Cycle Length (Days)
25	161	688	215	459
30	163	834	217	556
35	162	970	217	647

5.0 CONCLUSIONS

Neutronic evaluations of the 18-pin and 36-pin LS-VHTR stringer fuel assemblies have been performed using the deterministic lattice code WIMS9 and the linear reactivity model. Calculations were done to evaluate the core cycle length and fuel discharge burnup and to determine the optimum uranium enrichment and packing fractions. The accuracy of the WIMS9 code for this evaluation was confirmed by comparing the code results to those obtained using the Monte Carlo code, MCNP4C.

The cycle length and discharge burnup were evaluated as a function of uranium enrichment, packing fraction, and the number of fuel pins per assembly. The fuel-to-moderator number density factor was used as a parameter for quantifying the results. From this sensitivity study, it was found that the optimum packing fraction to maximize the beginning of life k-infinity is greater than 30% for the 18-pin stringer fuel assembly design and greater than 25% for the 36-pin design. Additionally, the optimum fuel stringer hole diameter was determined to be 26.6 cm for the 36-pin fuel stringer.

The required uranium enrichment to obtain the target core cycle length (18 months) and fuel discharge burnup (> 100 GWd/t) were determined from parametric studies. It was found that the 18-pin configuration would not meet the combined demands on the cycle length and discharge burnup, even with an enrichment of about 20% and a 35% packing fraction. Using the 36-pin configuration and a 1-batch fuel management scheme, both core cycle length and fuel discharge burnup requirements can be met utilizing an enrichment of 15% and a packing fraction of 30%. For a 2-batch fuel management, these requirements can be met using an enrichment of ~20% and a packing fraction of 30%.

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