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Nuclear Design of Fissile Pu and HEU LIFE Engine - NA22

K.J. Kramer, J.F. Latkowski, R.P. Abbott

September 8, 2009

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Topical Assessment Report for LIFE – NA22

Nuclear Design of Fissile Pu and HEU LIFE Engine

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With contributions from the
Neutronics and Mechanical Design Teams

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I. INTRODUCTION

The Laser Inertial Confinement Fusion Energy (LIFE) engine is a new energy system being developed at the Lawrence Livermore National Laboratory.[1] Fusion-fission hybrid concepts have been considered in the past by a variety of researchers.[2-5] However, the LIFE concept seeks to utilize the hybrid application in ways not previously envisioned.

Past studies have focused on using fusion neutrons to breed fissile material for subsequent use in fission reactors. LIFE, by comparison, aims to provide a once-through, self-contained, closed fuel cycle without fuel enrichment or reprocessing. In the LIFE concept, a point source of fusion neutrons drives the fission blanket, eliminating the need for a critical assembly to sustain the fission chain reaction. Typically, in a single LIFE engine a 15–20 MW laser drives as little as 300 to 500 MW of fusion power, and generates 2000 to 5000 MW of thermal power (MW_{th}) in steady state for periods of years to decades, depending on the nuclear fuel and engine configuration. Various LIFE engines capable of burning any fertile or fissile nuclear material, including un-enriched natural or depleted uranium (DU) and SNF are possible. A LIFE engine can extract virtually all of the energy content of its nuclear fuel resulting in greatly enhanced energy generation per unit mass. The external source of neutrons also allows the LIFE engine to burn the initial fertile or fissile fuel to 99% FIMA (Fission of Initial Metal Atoms) without refueling or reprocessing, allowing for nuclear waste forms with significantly reduced concentrations of long-lived actinides per GWe-yr of electric energy produced. In short, LIFE provides an option for a once-through, closed nuclear fuel cycle that starts with a 15-20 MW laser system to produce 375-500 MW of fusion power and uses a subcritical fission blanket to multiply this to 2000–5000 MWth.

This report focuses on a LIFE design specifically targeted at burning of excess weapons grade material, either Pu (wgPu) or highly enriched uranium (HEU). The operational characteristics of the LIFE engine using these fuels are somewhat unique relative to fertile systems because the system “turns on” at full power. In the following sections, we describe the nuclear design, methodology, required fidelity, and analysis results relevant to a wgPu or HEU LIFE engine.

II. NUCLEAR DESIGN

The ICF fusion yield resembles a point neutron source and allows for a compact, spherically-shaped chamber containing multiple layers of coolant, multiplier, moderator and fissile fuel. This geometry allows for a nearly complete enclosure of the fusion neutron source by a fission blanket with the neutron leakage paths being the beam ports through which the lasers must enter. This feature allows for unique and compelling design studies centered on the fact that a strong independent source of 14.1 MeV neutrons (fusion target) can be used to irradiate the target nuclei at a very high rate. The LIFE concept relies on the fact that the system need not be critical to accomplish this.

II.A. LIFE System Options

LIFE is different from conventional nuclear reactors because no enrichment or reprocessing of the fuel is required. In a typical LIFE design, the fusion source converts and burns fertile fuel while remaining subcritical. The solid nuclear fuel version takes the form of TRISO[7] particles randomly packed in graphite pebbles. The fuels can include depleted uranium (DU), spent nuclear fuel (SNF), thorium, weapons-grade plutonium (Pu) and highly enriched uranium (HEU). For the purposes of this report, the wgPu/HEU design utilizes a NIF-like hot-spot illumination geometry using a 300μm radius TRISO-based uranium oxycarbide (UCO) fuel kernel, surrounded by additional porous and structural carbon-based layers, identified in Table 1. Further details of the TRISO design and performance can be found in the fuels report.

Table 1 - LIFE TRISO Fuel Layers

Layer	*Density [g/cm³]*	*Outer radius [μm]*
kernel (UCO)	10.5	300
buffer layer (C)	1.10	402
high-density PyC	1.95	407
SiC	3.20	497
Pebble matrix (C)	1.70	n/a

II.A.1. NIF-Like Hot Spot Geometry

The LIFE engine is currently designed to incinerate wgPu or HEU contained in TRISO fuel particles and produce electrical power to the grid. Fig. 1 shows an overview of the central chamber. The engine consists of a fusion target chamber of 2.5m radius, surrounded by multiplying/moderating media and a fission blanket. The ICF fusion target produces 37.5 MJ at ~13.3 Hz from D(T,n)α reactions resulting in 500 MW of fusion. This yields nearly 400 MW (1.8×10^{20} n/s at 14 MeV) of neutrons. The remaining fusion power is emitted as ions and x-rays. The first wall is composed of ODS ferritc steel and is protected with 250-500 μm of tungsten.

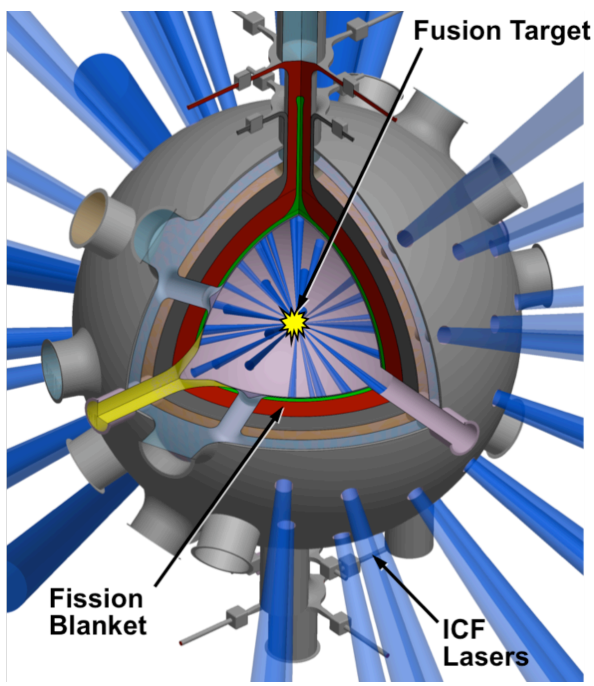

Figure 1 - Overview of LIFE engine Design

Fusion neutrons stream outwards through the first wall and enter multiple blanket layers, shown in Fig. 2. Details of the design are given in Table 2. A dedicated $Li_{17}Pb_{83}$ coolant initially at natural ^{6}Li enrichment surrounds the first wall. This coolant was chosen because of its favorable thermal properties, which are essential to cooling the first wall. The $Li_{17}Pb_{83}$ also provides neutron multiplication (via Pb(n,xn)) and tritium production (via $^{6}Li(n,\alpha)^{3}H$). An injection plenum for the primary coolant, flibe (2LiF + BeF_2), surrounds the second wall. Flibe is used throughout the whole engine due to its excellent tritium production, neutron moderation and multiplication properties. The flibe flows radially outwards from the injection plenum to the multiplier region, which contains 1 cm Be pebbles with a 60% random packing fraction. The engine design allows for annual Be pebble extraction and inspection. Following the Be multiplier blanket is the fission fuel blanket containing ~7 metric tonnes (MT) of wgPu or HEU fuel contained in TRISO particles within ~13 million 2-cm-diameter pebbles. As discussed later in this report, the fissile fuel pebbles are poisoned via ^{6}Li in the graphite matrix to prevent criticality excursions during startup.

A 60/40 volume percent graphite and flibe reflector surrounds the entire fission blanket. The graphite also takes the form of pebbles allowing for periodic replacement as needed. The flibe is then extracted from a plenum outside the reflector blanket and sent to thermal hydraulics systems for power conversion.[9]

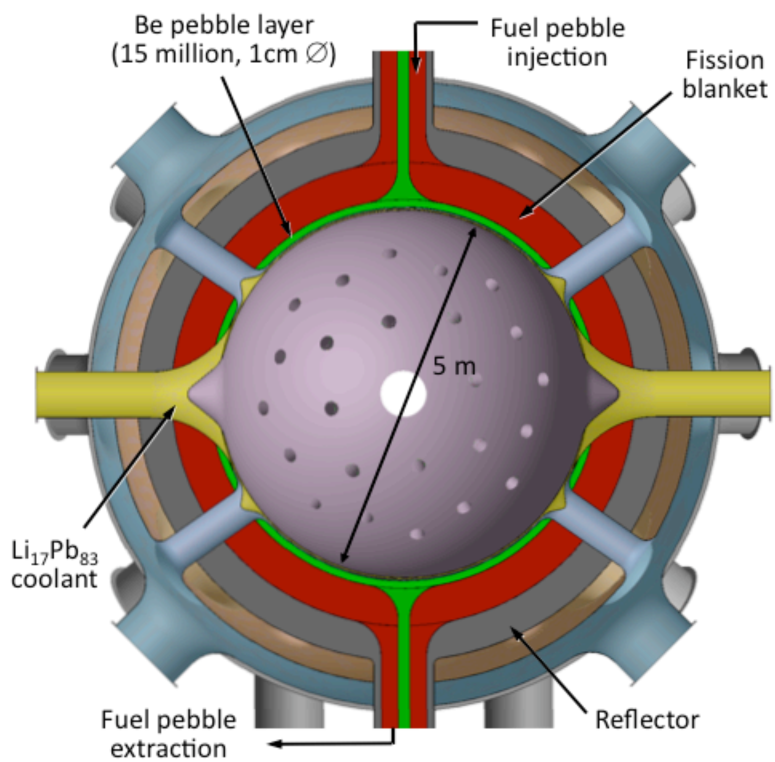

Figure 2 - Section View details of LIFE engine design (update figure)

Table 2 - Key LIFE Design Parameters

Item	Value
Thermal Power (MWth)	3800
First wall coolant	$Li_{17}Pb_{83}$
Fusion yield (MWth)	500
Pu/HEU blanket mass (kg)	7,000
Burnable poison added to pebble	^{6}Li or ^{10}B
Primary coolant	flibe
First wall inner radius (m)	2.5
TRISO packing fraction (%)	30
Pebble packing fraction (%)	60
Be multiplier thickness (cm)	16
Fission blanket thickness (cm)	76
Graphite reflector thickness (cm)	75

III. METHODOLOGY

The neutronics and burnup analyses encompass a variety of physics calculations, along with LIFE-specific control mechanisms. The engine is initially loaded with fissile fuel. The LIFE fissile fuel burner acts very similar to a fertile DU/SNF burner, with the exception of the initial startup period. In the case of a fertile fuel burner, the thermal power begins to naturally rise, shown in Fig. 3, as fissile Pu builds up in the fission blanket primarily from the ^{238}U capture reactions, as well as other reaction chains.

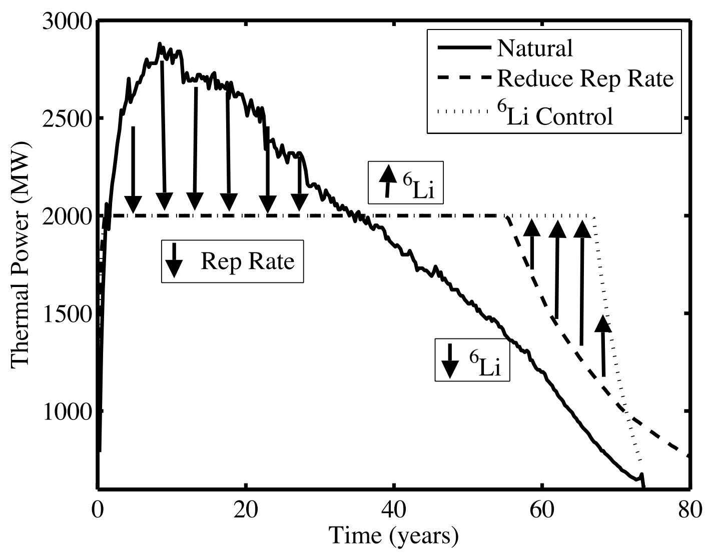

Figure 3 - LIFE engine burning fertile fuel under natural operation, with laser rep-rate control and with ^{6}Li control.

Without any control, the thermal power would continue to rise until the Pu fission and breeding rates equilibrate after about 12 years (solid curve Fig. 3). Following peak Pu inventory, the system exhausts the remaining Pu over 4-5 decades. The decrease in fissile inventory causes a corresponding reduction in thermal power. This power production curve is unattractive primarily because the plant must be designed to operate at a peak power of ~2800 MW, but is only utilized at that power for a short time. Thus, the balance of plant utilization is poor. The fissile wgPu/HEU system operates in the exact same manner, with the exception of the breed up phase. Since the highest fissile content and most critical configuration is at the time of startup, the system starts up at full power followed by a continuously decreasing thermal power as the fissile fuel is exhausted.

To improve this unattractive power curve, we can reduce the fusion rep rate to maintain a flat power curve over much of the system life (dashed curve Figure 3). However, this now under utilizes the fusion laser system and still produces many years at the end of operation where the power is below the operating maximum, resulting in an improved but still inadequate balance of plant utilization. This tail of the curve is due to the fact that neutrons normally used for fission must be used to produce tritium such that the system is self-sufficient.

As an alternative, we have developed a control scheme using a time varying $^{6}Li/^{7}Li$ concentration in the flibe and $Li_{17}Pb_{83}$ (dotted curve Figure 3). By adjusting the ^{6}Li enrichment over time, we can maintain a nearly constant system power of 2000 MWth for ~12 years longer than simply reducing the fusion power via rep rate reduction. When the ^{6}Li concentration is high, excess tritium is produced and thermal power is suppressed. This tritium is stored and used later, thereby increasing the thermal power later in time. This technique allows the LIFE engine to reach >80% FIMA at full power before the power drops due to exhaustion of stored tritium or sufficient depletion of the fissile materials to sustain the desired thermal power. Once this occurs, a power ramp-down and incineration period begins. At this point, the system can either be shutdown, refueled or allowed to incinerate the remaining actinides in the fuel, albeit with a continuously decreasing thermal output. For the purposes of this report, we discuss the last option.

III.A. Transport and Burnup Simulation Tools

The neutron and photon transport calculations were performed using the three-dimensional Monte Carlo transport code MCNP5 (Ref. 10). Burnup calculations were performed using Monteburns 2.0 (Ref. 11), which in turn utilizes ORIGEN2 (Ref. 12) for the nuclide evolution. Improvements to Monteburns, as well as custom code development, were required to perform the burnup calculations for LIFE. We developed a C++ code named the LIFE Nuclear Control (LNC)[13] code to function as the main controlling code for LIFE depletion and transport calculations. A flow diagram of our neutronics code suite is shown in Figure 4.

A typical calculation begins with a three-dimensional MCNP model of a LIFE engine. The nuclear data used is ENDF/B-VII[14] Doppler broadened to 600°C, although additional temperatures have been studied. We perform an initial transport calculation to determine the current system thermal power and tritium breeding ratio (TBR). Next, the LNC code iteratively searches for a ^{6}Li enrichment in the coolant(s) to maintain either the power and/or TBR in user-defined ranges. The $^{6}Li/^{7}Li$ ratio is adjusted while maintaining proper stoichiometry. Once an acceptable enrichment is found, the updated material definitions and cell densities are written to a final MCNP input deck for the given time step. A transport calculation is then performed. Upon completion, the total neutron energy deposition is extracted, summed and used to update a Monteburns input file. This neutron power is used by Monteburns to properly normalize the neutron flux for depletion. Monteburns then performs a series of transport (MCNP) and depletion (ORIGEN2) calculations where it acts as a client for the two separate codes. MCNP calculates the group collapsed fluxes and cross-sections, which are then used by ORIGEN2 to perform the isotopic evolution. The updated material compositions are then passed from ORIGEN2 back to MCNP for an additional transport calculation based on the number of desired predictor-corrector steps. Upon completion of the Monteburns calculation, a new MCNP deck is written by the LNC code for the next step in the depletion sequence. Modern software quality assurance practices are in place and continuing verification and validation efforts are underway.

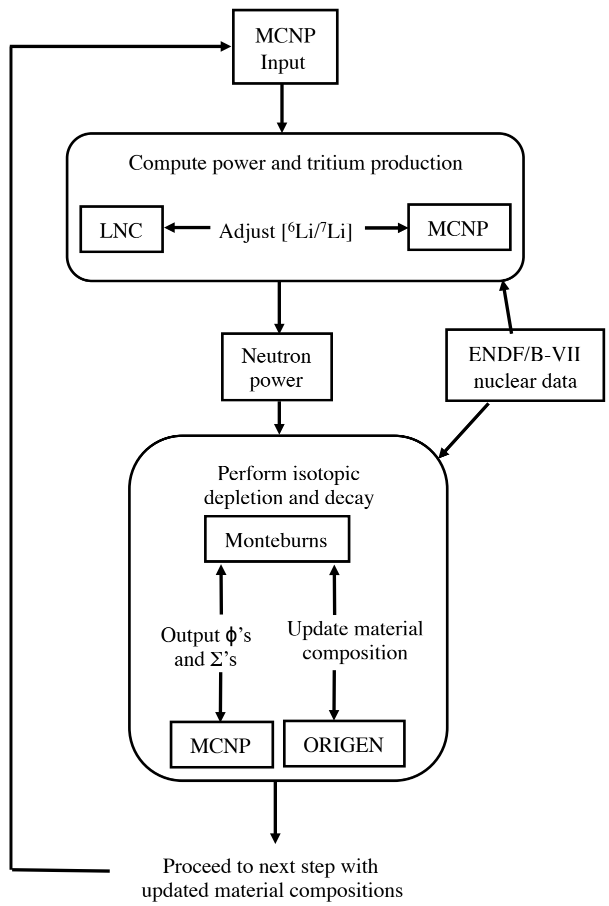

Figure 4 - Flow diagram of transport and burnup sequence used for fissile burnup calculations

IV. RESULTS AND DISCUSSION

Based on the aforementioned design constraints and codes, a suite LIFE fissile burner system options were explored and are described in the following sections.

IV.A Model Fidelity

Early in this study, the level of fidelity required for accurate results needed to be determined. Namely, simulating a fully detailed 3D heterogeneous model has proven too costly for day-to-day design parameter and sensitivity studies. The computational cost of modeling a fully detailed LIFE engine down to the TRISO particle layers typically requires almost an order of magnitude more cpu cycles than running with homogenized equivalents and is thus reserved for special cases of interest.

Homogenization is the process of smearing or blending material definitions for discrete components together. This technique relies upon the fact that neutron transport through a material depends solely on the mean free path of the particle before an interaction and is a function of the material composition alone. In most cases, the edges moving from one material to another are sufficiently blurred relative to the mean free path that homogenization can be used.

In simulating the LIFE engine, multiple models were developed ranging from fully homogenized to fully detailed. A cut away of a fully homogenized model is shown in Figure 5. Discrete walls made of ODS ferritic steel as well as beam ports that serve to allow the lasers in to the chamber are explicitly modeled. The fuel, beryllium and graphite pebbles, however, are completely homogenized with the coolant in each respective region of the blanket. This process does introduce bias in the results and thus are generally only used for scoping studies.

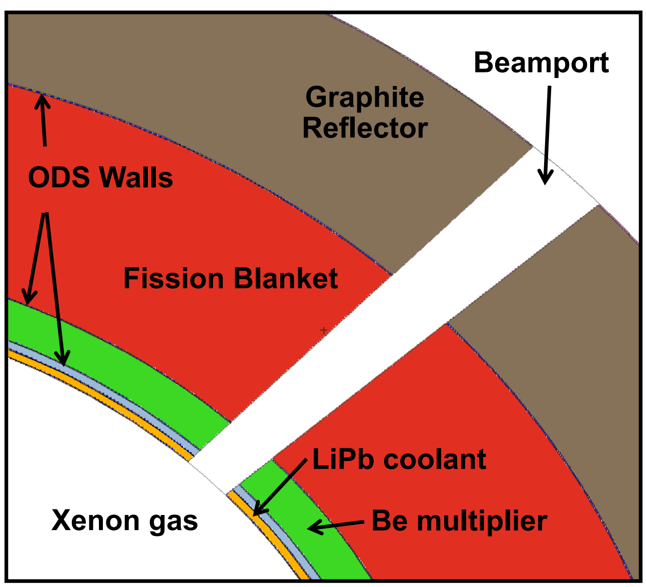

Figure 5 – Section of transport model showing details of wall and beam port geometry

Detailed analyses were also performed using fully heterogeneous geometry for the fuel as well as the Be and graphite pebbles. Figure 6 shows an example of a typical detailed calculation utilizing full geometric detail down to the fuel kernel. We should note that to achieve the desired packing fraction of the fuel in the pebble and pebbles in the coolant, partial pebbles and fuel kernels are allowed. The effect of this approximation must still be quantified, but is expected to be of little significance. Likewise, the pebbles and TRISO particles are arranged in a uniform BCC lattice. Transport calculations using fully random pebble and fuel particle orientations like that shown in Figure 7 differed by insignificant amounts. Normal system simulations include full detailed geometry for the fuel, Be and graphite pebbles, but neglect the random orientation.

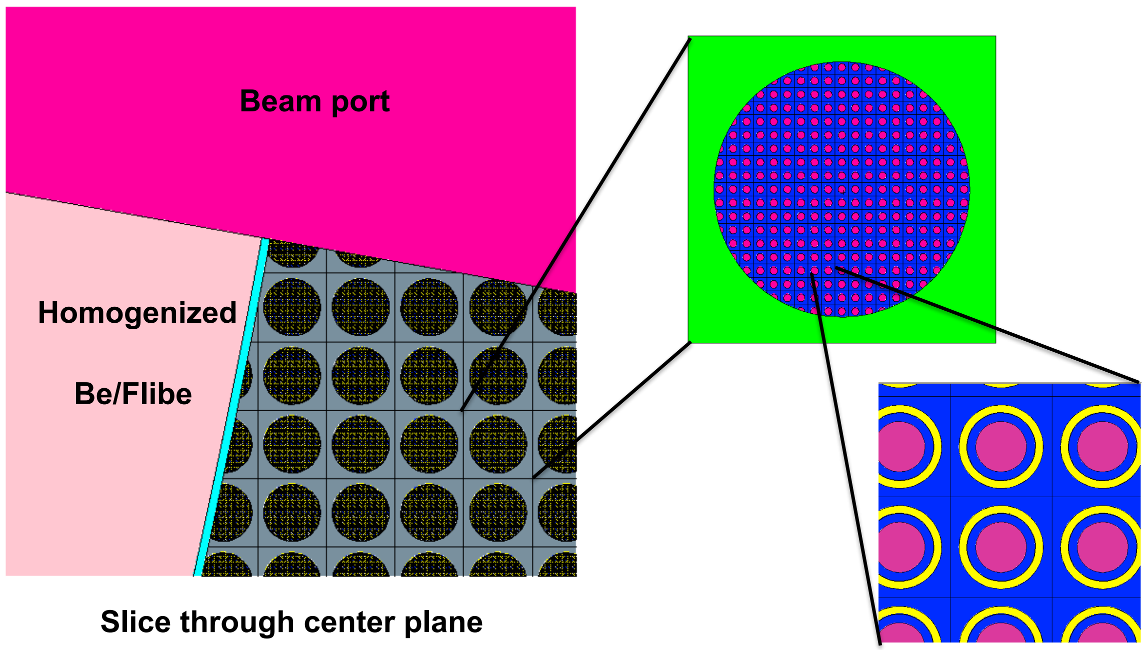

Figure 6 – BCC lattice of fissile pebbles containing fully detailed TRISO particles with a center pebble contacted by each octant of adjoining pebbles

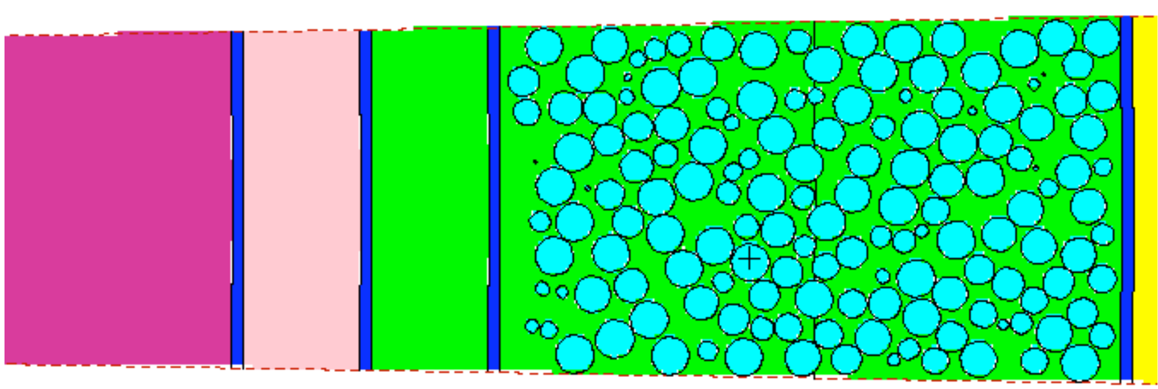

Figure 7 – 2-degree wedge slice from LIFE engine showing random Be pebble packing

IV.A Design Basis Event Calculations

The fissile LIFE engine contains 6-7 MT of highly enriched fissile material and care must be taken to ensure the system stays subcritical under loss of coolant accidents (LOCA). With this in mind, the approach taken when designing engine components assumed a LOCA event. By designing the system starting from a LOCA configuration, we can capture a possible worst-case scenario and ensure that it cannot lead to a criticality excursion. We accomplish this by first calculating the k_{inf} for a unit cell of close packed pebbles without coolant around it with perfectly reflecting boundary conditions. The unit cell for this calculation is a BCC lattice with all pebbles touching each other, shown in Figure 8. This approximates a full random packing of a group of pebbles with the coolant removed. The TRISO particles are modeled in full detail with the only approximation being that the plane of the pebble cuts the kernels. In reality, the kernels would not be cut, but this approximation has been shown to be sufficient for most pebble bed simulations.

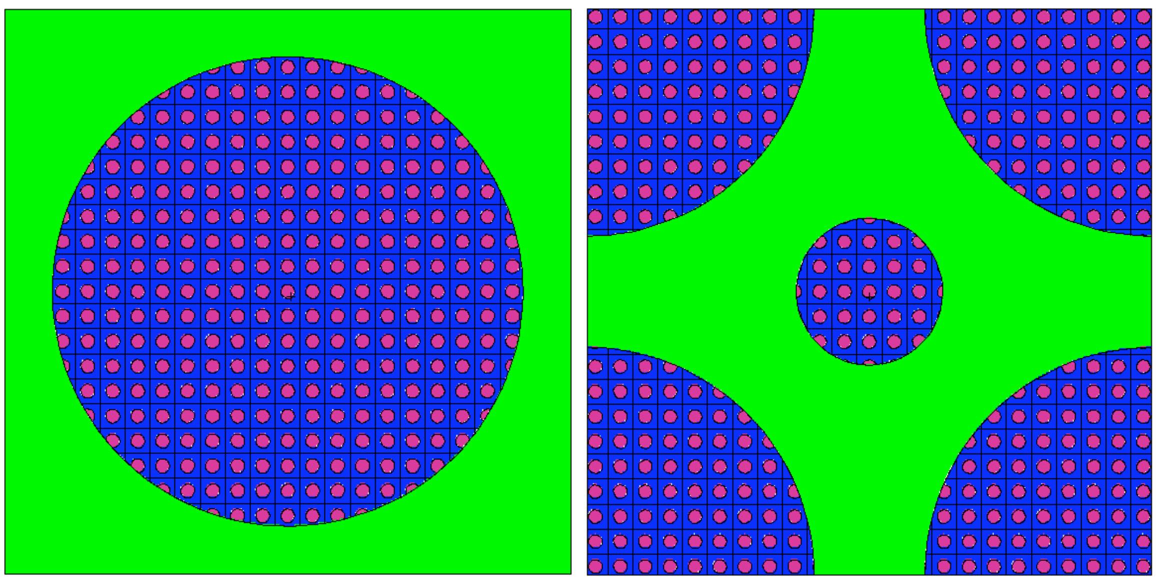

Figure 8 – BCC lattice of fissile pebbles containing fully detailed TRISO particles with a center pebble contacted by each octant of adjoining pebbles

Using the above geometry and reflecting boundary conditions, the maximum criticality that the system can achieve under these LOCA conditions is controlled to be subcritical by blending in burnable poison in the form of ^{6}Li or ^{10}B into the pebble graphite matrix. Depending on the TRISO packing fraction and poison chosen, this poison amount is generally maintained between 5%-10% by volume to keep the system deeply subcritical (k_{inf} < 0.95) under LOCA.

As with other subcritical systems, LIFE is expected to have a very different response to typical reactor kinetic feedback mechanisms. Feedback important to critical systems has been shown to be less important to deeply subcritical systems like LIFE.[15] In addition, our preliminary studies of temperature feedback and coolant voids have shown little impact on LIFE performance.

IV.A Fissile Hot-Spot System Performance

Using a nominal ~7 MT of wgPu or HEU in the fission blanket, we generate the thermal power history shown in Figure 9. As stated earlier, the thermal power begins immediately at full power because startup is when the system has the highest fissile content and is in the most critical configuration, even though it is still deeply subcritical. Fissile consumption continues past this point and the thermal power is controlled to remain at a constant 3800 MW. It takes approximately 9 years to completely incinerate the heavy metal content to 99% FIMA.

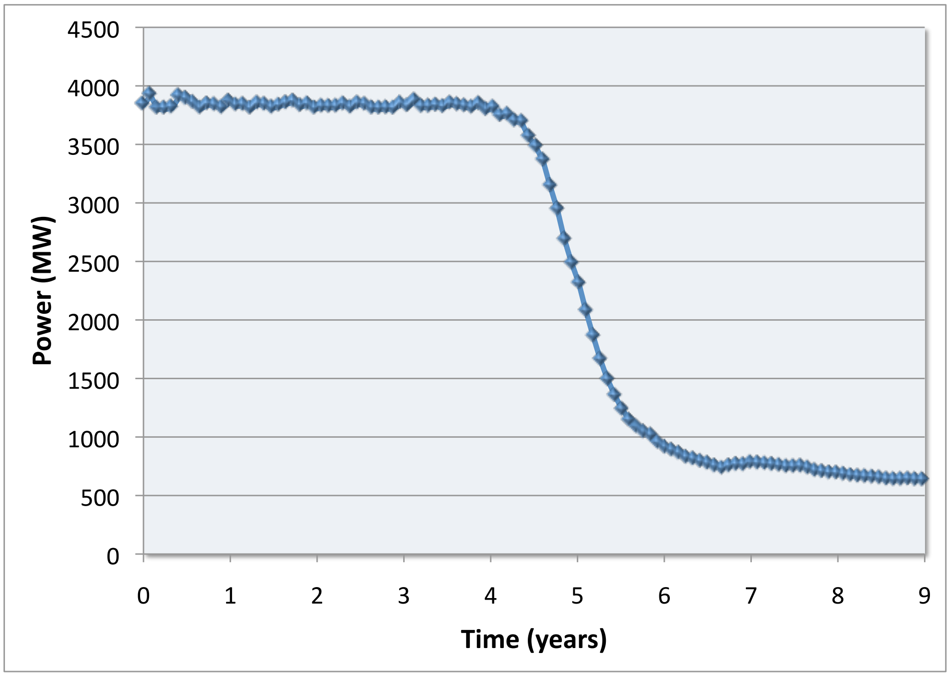

Figure 9 - 3800 MWth LIFE engine power over time

Throughout the burnup, the TBR begins at ~2.0, shown in Figure 10. During the years that the TBR exceeds 1.0, tritium is stored. The TBR is allowed to fall over time so as to maintain the thermal power as the fission slows due to depletion, similar to a nuclear reactor. Power is typically maintained constant until the stored tritium inventory is exhausted or the remaining fissile material is too low to sustain the thermal power. At this point, the TBR is brought back to 1.0 by increasing the ^{6}Li enrichment in the $Li_{17}Pb_{83}$ and flibe. The remaining time is used to incinerate the residual actinides to reach the desired FIMA burnup. Since the fission blanket is composed of solid pebbles that must be periodically inspected for damage, we can envision a system where fully burned pebbles are removed during inspection and replaced with fresh fuel. This would potentially eliminate the ramp down in power.

Tritium production for LIFE is analogous to control rod insertion and removal for a conventional nuclear reactor with two key differences. First, the ^{6}Li control mechanism provides a useful reaction product (tritium) as opposed to simply acting as a parasitic neutron absorber. Second, the control system is completely independent of the safety system. Criticality safety is beyond the scope of this document, but two points should be mentioned. First, the fission blanket is maintained subcritical at all times during operation. Even without controlling the system power, the LIFE engine cannot become critical under normal operation. Second, the lasers can be instantly shut off thereby providing an extremely fast (< .08 sec) way to shut down the LIFE engine.

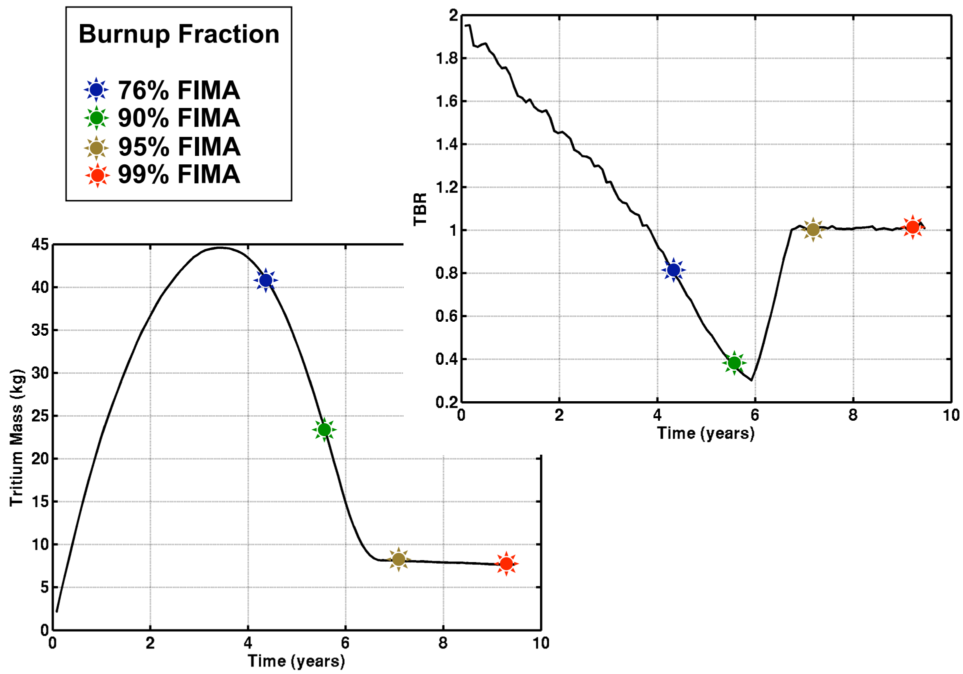

Figure 10 - Tritium inventory generated over time

Various parameter studies where performed to arrive at the aforementioned design point. Parameters including TRISO and pebble packing fraction, coolant choice, moderator choice, chamber radius, blanket thicknesses and system powers were explored. The most significant variables were found to be those that impacted the fuel-to-moderator ratio (F/M). Changing of the F/M ratio results in a spectrum shift to alter the way the engine operates. Softer neutron spectra result in more tritium production and other parasitic capture reactions. Harder spectra can increase the fission rate for a period of time, but result in lower fuel utilization. Figure 11 illustrates this fact by showing the effects of varying the TRISO packing fraction in the pebble from low packing (low F/M) to high packing (high F/M). The result is that a 20%-30% packing fraction appears to be a near optimum to sustain power for the longest period of time while reaching the highest burnup at that power. This is just one example of the hundreds of parameter studies performed to arrive at the current configuration.

It is important to note that, unlike typical fertile designs, the drop in power is not a result of the system exhausting the tritium supply. Alternatively, burnup of the fissile material has progressed far enough that the maximum sustainable thermal power is no longer maintainable. I.E. the engine burned >90% of the Pu/HEU and most of what remains is fission products. This characteristic is advantageous to improving the design. Namely, the system does not need to produce as much tritium as currently designed. This feature opens up the possibility of significantly different approaches. For example, it may be possible to completely remove the Be pebble layer due to the abundant tritium production, or use the excess tritium to supply other LIFE engines. Alternative concepts are being explored to determine what alterations to our baseline design are possible.

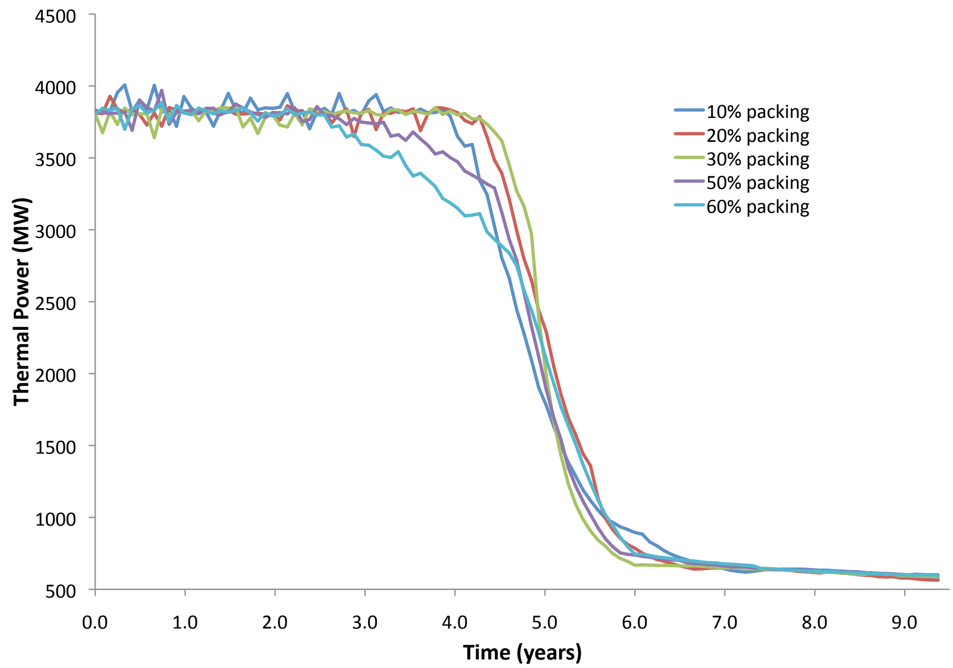

Figure 11 – Varying TRISO packing fraction from 10% to 60% and resulting burn curves show a near optimum at 30% packing fraction.

IV.A.1. Fuel Blanket Neutron Spectrum

The neutron flux throughout the LIFE engine is high relative to most nuclear systems. The flux spectrum at the beginning and end of life is shown in Figure 12. It shows that significant flux exists throughout the whole spectrum from 14 MeV to thermal. Also, the flux varies in time due to the build up of fission products and burning of Pu, and other minor actinides. The hardening spectrum in the fission blanket illustrates the fact that the fuel composition evolves over time and care must be taken to ensure optimum fuel-to-moderator ratio over the course of burnup.

These high fluxes over decades of operation also present a significant challenge to fuel and structural wall survival and is an active area of research. The total neutron fluence in the fuel region has been calculated to be ~10^{22} neutrons/cm^2, causing ~31 dpa in the carbon over its lifetime. The chamber first wall is damaged at a rate (35 dpa/yr) that will require replacement every 5-7 years. For a much more detailed description, please see the accompanying LLNL fuels report.

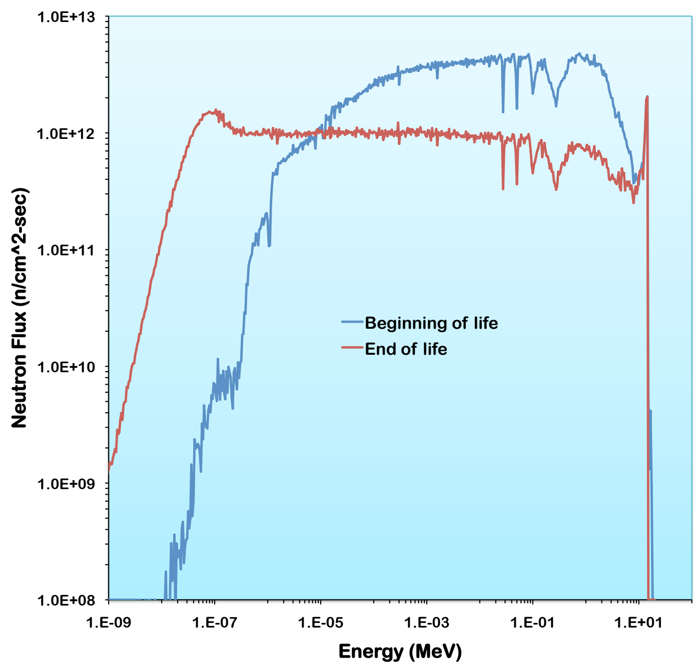

Figure 12 - LIFE fuel blanket neutron spectrum at beginning and end of burn showing large changes in the spectrum as fission products build up in fuel blanket

V. FUTURE WORK

Our results thus far are very encouraging. However, additional effort is required to improve the simulation tools and analyses. Verification and validation efforts have begun and will be expanded. Likewise, our MCNP neutron transport models will be upgraded to incorporate improved techniques for modeling triply heterogeneous TRISO-based pebble bed systems like reactivity-equivalent physical transformation method.[16] We also intend to conduct additional high-performance computing simulations using detailed geometries of TRISO particles inside each pebble to explore alternative design spaces.

V.A ALTERNATIVE DESIGNS

There are many options that may improve system performance, including tritium sharing, segmenting the blankets, variable fuel-to-moderator control, removing Be pebbles and other options. Two alternatives that show much promise to improve the fissile system performance include segmented blankets and variable fuel-to-moderator control.

V.A.1. Segmented blanket design

Besides sharing tritium across plants, fuel-shuffling routines offer a way to extend the system thermal power, while completely incinerating the remaining actinides. Any fuel shuffling routine relies on the movement of fuel from a low flux region to a high flux region or vice versa, depending on the scheme and burnup. The design of the LIFE engine lends itself to shuffling of different radial layers because of a high flux gradient from the innermost portion of the blanket to the outer layers. Figure 13 shows a central promotion scheme for different blanket layers. Using this scheme, layer 1 is subjected to the highest neutron flux and thus burns faster. In fact, it can reach 99% FIMA while the outer layers are only at 10-20% FIMA. This shuffling scheme simply promotes each outer layer forward such that layer 4 takes the place of layer 3, 3 moves 2 and 2 moves to 1. Fresh fuel is loaded into the space previously occupied by layer 4 and layer 1 is discarded to waste. Although not optimized, this fuel-shuffling scheme shows great promise to improve the burn curve from that shown in Figure 9 to that illustrated in Figure 14.

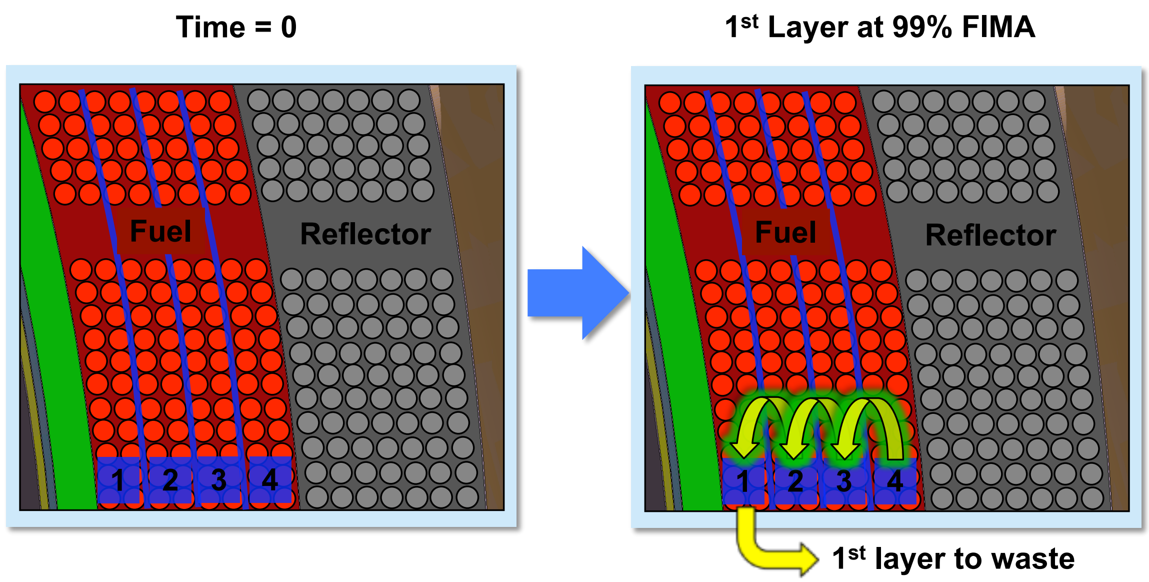

Figure 13 - Segmented blanket design showing central promotion scheme of fuel

This simple shuffling scheme is quite promising because the scheme is relatively simple in concept and results suggest we can achieve high burnup of the fissile fuel while maintaining continuous power. Although we illustrate the concept with only 4 layers, the actual number of layers and optimum shuffling scheme has yet to be determined and must be studied further.

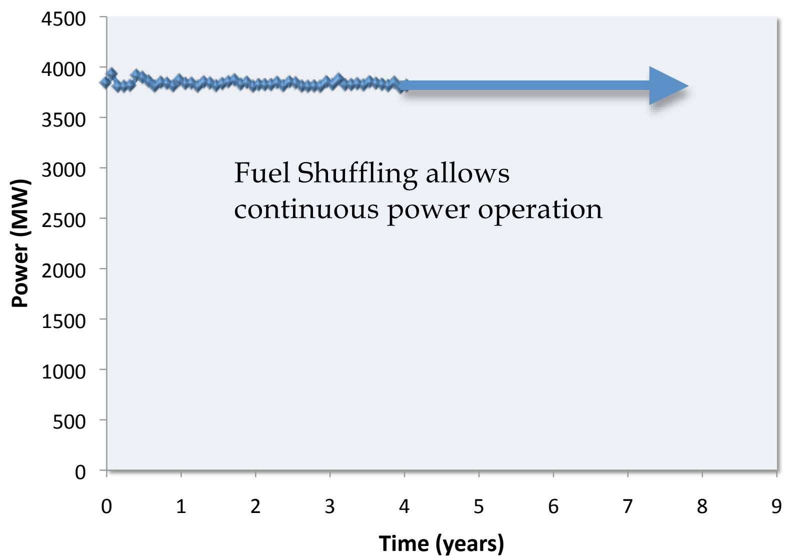

Figure 14 - Thermal power when utilizing central promotion fuel shuffling routine

V.A.2. Variable Fuel-to-Moderator Ratio

As shown earlier, the neutron flux spectrum changes considerably over time. This results from the buildup of fission products and burning fissile materials like ^{239}Pu. As the Pu concentration in the fuel decreases, the spectrum becomes softer and more thermal neutrons are available for tritium production. By changing the graphite content in the fuel region over time, one could better control the fuel-to-moderator ratio to a relatively constant, optimized level that results in better fast and thermal neutron economy. Since additional thermal neutrons provide better tritium production, increasing the carbon content in the fuel region at time at peak Pu would soften the spectrum and produce more tritium, thus sustaining higher burnup for a longer time. To model this, modification of our simulation tools is required and is planned for future analyses.

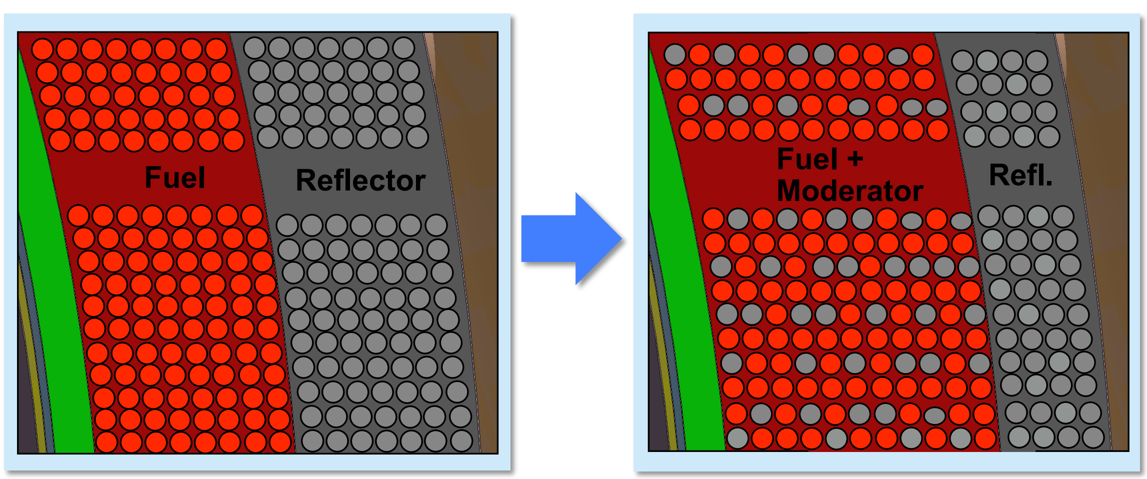

Figure 15 - A possible way to improve fissile burner performance by shifting the neutron energy spectrum via variable fuel-to-moderator control

VI. CONCLUSIONS

LIFE offers a logical step to bridge the gap between fission and fusion power plants and offers a novel way to destroy excess wgPu or HEU. We have shown details of a possible LIFE engine design based on a solid fuel form, using fissile wgPu. This design produces 3800 MW_{th} of power for 5 years using a fuel loading of 7 MT. Fuel reprocessing is not required, although it would need to be fabricated into TRISO particles. Early results show promise for this system with limitations imposed by requiring only a single fuel loading. Ongoing research is addressing fuel and structural material survival within the LIFE engine, and alternative designs are also being explored because of the challenge of fuel survivability.

This current work is intended to further develop the initial concept for the LIFE wgPu/HEU engine. Our nuclear burnup and transport calculations are performed with standard tools and practices. We have shown through detailed Monte Carlo-based analysis how the current engine concept could operate and we have offered options for performance improvement. Some performance improvements will occur naturally as the LIFE concept is further developed. For instance, fresh fuel loading is current practice in the fission reactor community and the pebble-based design lends itself to online refueling. Although further optimization is planned, the current LIFE engine meets all of our initial design goals.

ACKNOWLEDGMENTS

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