Neutron Transport and Nuclear Burnup Analysis for the Laser Inertial Confinement Fusion-Fission Energy (LIFE) Engine

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Lawrence Livermore National Laboratory is currently developing a hybrid fusion-fission nuclear energy system, called LIFE, to generate power and burn nuclear waste. We utilize inertial confinement fusion to drive a subcritical fission blanket surrounding the fusion chamber. It is composed of TRISO-based fuel cooled by the molten salt flibe. Low-yield (37.5 MJ) targets and a repetition rate of 13.3 Hz produce a 500 MW fusion source that is coupled to the subcritical blanket, which provides an additional gain of 4-8, depending on the fuel.

In the present work, we describe the neutron transport and nuclear burnup analysis. We utilize standard analysis tools including, the Monte Carlo N-Particle (MCNP) transport code, ORIGEN2 and Monteburns to perform the nuclear design. These analyses focus primarily on a fuel composed of depleted uranium not requiring chemical reprocessing or enrichment. However, other fuels such as weapons grade plutonium and highly-enriched uranium are also under consideration. In addition, we have developed a methodology using ^{6}Li as a burnable poison to replace the tritium burned in the fusion targets and to maintain constant power over the lifetime of the engine. The results from depleted uranium analyses suggest up to 99% burnup of actinides is attainable while maintaining full power at 2GW for more than five decades.

I. INTRODUCTION

The Laser Inertial Confinement Fusion-Fission Engine (LIFE) is a new nuclear energy system being developed at the Lawrence Livermore National Laboratory.[1] Fusion-fission hybrid concepts have been considered in the past.[2-5] However, the near completion of the National Ignition Facility (NIF) has brought renewed interest in Inertial Confinement Fusion (ICF) as a potential source of neutrons to drive a multiplying fission blanket. 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 fissionable fuel. This geometry allows for a nearly 4π enclosure of the fusion neutron source by a fission blanket.

II. NUCLEAR DESIGN

Our vision includes the deployment of LIFE plants around the world as a viable, clean source of energy for the 21st century and beyond. With that in mind, LIFE is intended to fulfill multiple missions including nuclear waste incineration and energy production. As primary design criteria, six goals were initially set to govern the LIFE engine's nuclear design. These goals included requiring no fuel enrichment, requiring no fuel reprocessing at the end of a burnup cycle, minimizing proliferation concerns throughout operation, remaining subcritical at all times, being tritium self-sufficient and maximizing the balance of plant utilization.

Tritium self-sufficiency and balance of plant utilization are important when operating a LIFE engine in a mode devoted to producing electricity for the grid. They influence the economics of LIFE, and may be less important when fulfilling a waste incineration mission. Proliferation issues, however, are important for either mission.

II.A. LIFE System Options

LIFE is different from conventional nuclear reactors because no enrichment or reprocessing of the fuel is required. The fusion source converts and burns fertile fuel while remaining subcritical and minimizing proliferation issues. Multiple system design options are being explored to meet the aforementioned goals and optimize the engine's nuclear performance. For instance, early engine designs make use of NIF-like fusion target illumination geometry (NIF-like hot-spot), but future designs could employ low angle illumination geometry.[6] The nuclear fuel takes the form of TRISO[7] particles in pebbles, but molten salt options are also being explored.[8] The fuels include depleted uranium (DU), spent nuclear fuel (SNF), thorium and weapons-grade plutonium (Pu). For the purposes of this paper, we focus on 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.

TABLE I. LIFE TRISO Fuel Layers

Layer	Density [g/cm^3]	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 design is currently optimized to produce electrical power to the grid, although waste burning missions could also be fulfilled. Fig. 1 shows an overview of the central chamber. The engine consists of a central 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 results in 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.

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

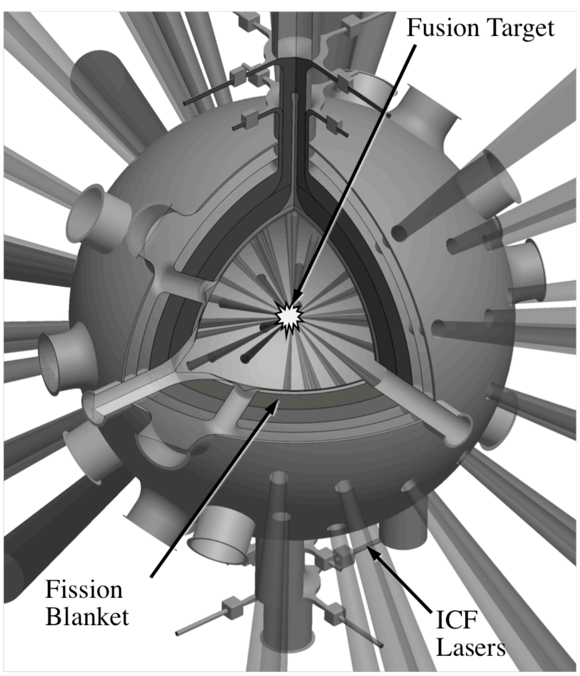

Fig. 1. Overview of LIFE engine design.

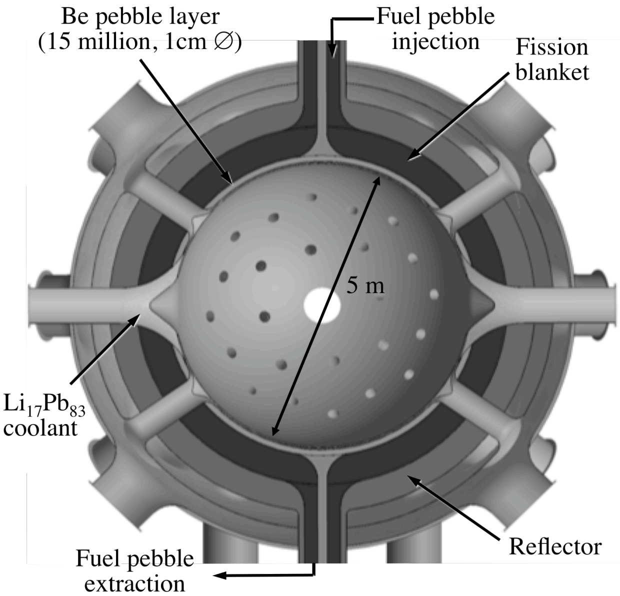

Fig. 2. Section View details of LIFE engine design.

$Li_{17}Pb_{83}$ 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,α)^{3}H). An injection plenum for the primary coolant surrounds the second wall. Flibe (2LiF + BeF_2) 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% packing fraction. The engine design allows for Be pebble extraction and inspection. Following the Be multiplier blanket is the fission fuel blanket containing 40 metric tonnes (MT) of DU fuel contained in TRISO particles within ~15 million 2-cm-diameter pebbles.

TABLE II. Key LIFE design parameters

Item	Value
Thermal Power (MWt)	2000
First wall coolant	$Li_{17}Pb_{83}$
Fusion yield (MWt)	500
Fission blanket DU mass (kg)	40,000
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)	86
Graphite reflector thickness (cm)	75

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]

III. METHODOLOGY

Our neutronics and burnup analyses encompass a variety of physics calculations, along with LIFE-specific control mechanisms. The engine is initially loaded with DU fuel and contains very little fissile material (0.26% ^{235}U by mass). After initial startup, 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 reaction

$$^{238}U(n,\gamma)^{239}U \xrightarrow[23\,\mathrm{min}]{\beta^-} {}^{239}Np \xrightarrow[2.3\,days]{\beta^-} {}^{239}Pu. \quad (1)$$

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 burns 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.

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 Fig. 3). However, this now under utilizes the fusion laser system and still produces many decades 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 Fig. 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 80-90% Fission per Initial Metal Atom (FIMA) at full power before the power drops due to exhaustion of stored tritium or depletion of the fertile and

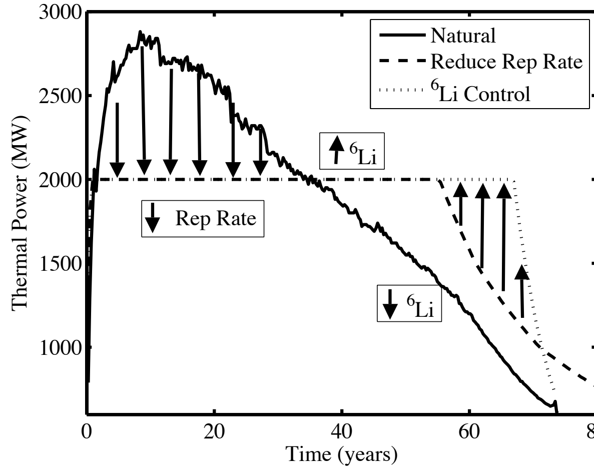

Fig. 3. LIFE engine natural operation, with laser rep rate control and with ^{6}Li control.

fissile materials. 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 paper, 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 Fig. 4.

A typical depletion 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

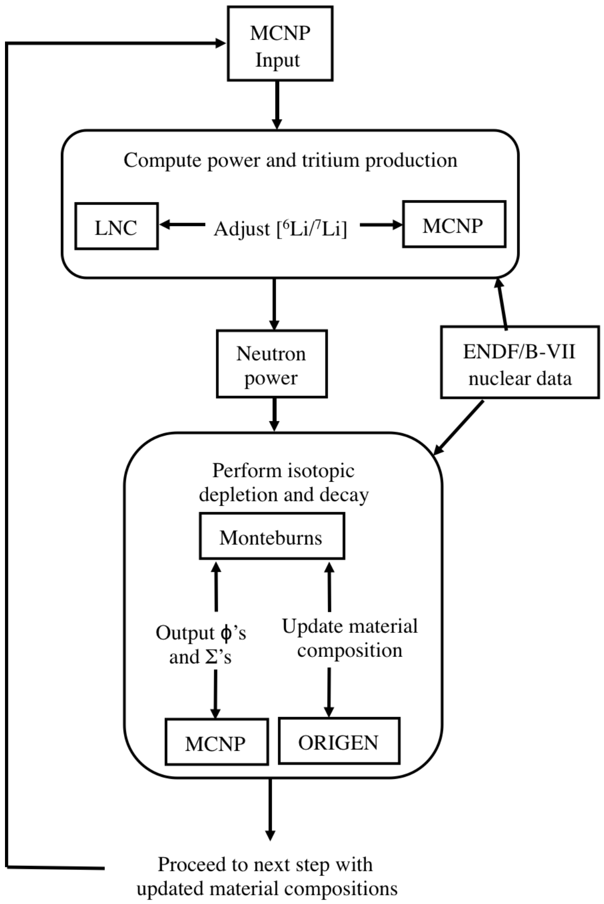

Fig. 4. Flow diagram of transport and burnup code suite.

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 validation efforts are underway.

IV. RESULTS AND DISCUSSION

IV.A DU Hot-Spot System Performance

A 2.5 m radius hot-spot ICF LIFE system is analyzed using the aforementioned codes and methods. Using 40 MT of DU in the fission blanket, we generate the thermal power history shown in Fig. 5. The power ramp-up phase takes approximately 1.2 years. Fissile production continues past this point, but the thermal power is controlled to remain at 2000 MW. The initial ramp up phase is followed by over 50 years of constant power with no enrichment or fuel reloading.

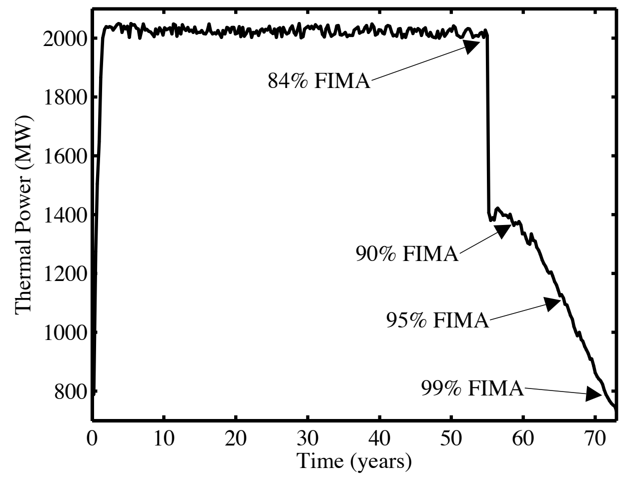

Fig. 5. LIFE 2000 MW DU engine power over time.

During this time, the TBR begins at 1.0, but rises up to a peak of 1.2, shown in Fig. 6. During the years that the TBR exceeds 1.0, tritium storage will be required. The TBR is allowed to fall over time so as to maintain the thermal power as the fissile production slows due to fertile depletion. Power is maintained constant until the stored tritium inventory is exhausted. At this point, the TBR is brought back to 1.0 by increasing the ^{6}Li enrichment to approximately 52% in the $Li_{17}Pb_{83}$ and 1.1% in the flibe. Doing so causes an immediate drop in system power from 2000 MW to approximately 1400 MW thermal as the ^{6}Li competes for thermal neutrons.

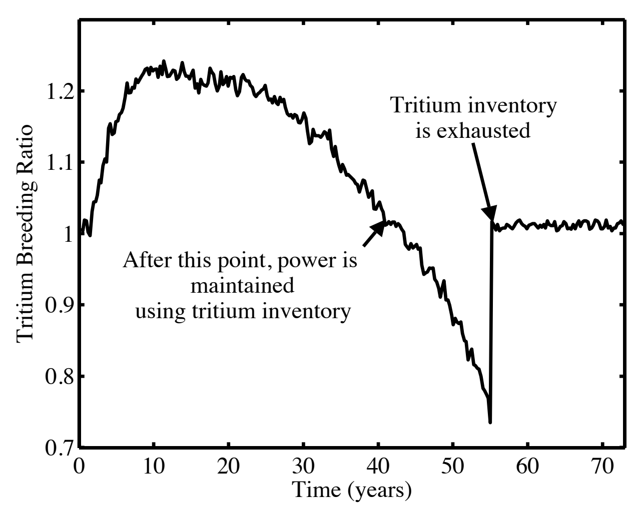

Fig. 6. LIFE 2000 MW DU engine TBR over time.

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.

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 time equal to zero and at time of peak Pu inventory is shown in Fig. 7. The neutron flux is normalized to the bin width illustrating the fact that significant flux exits throughout the whole spectrum from 14 MeV to thermal. Also, the flux varies in time due to the build up and burning of Pu and other minor actinides. The hardening spectrum in the fission blanket illustrates the fact that the fission blanket fuel composition evolves over time and care must be taken to ensure optimum fuel-to-moderator ratio over the course of burnup.

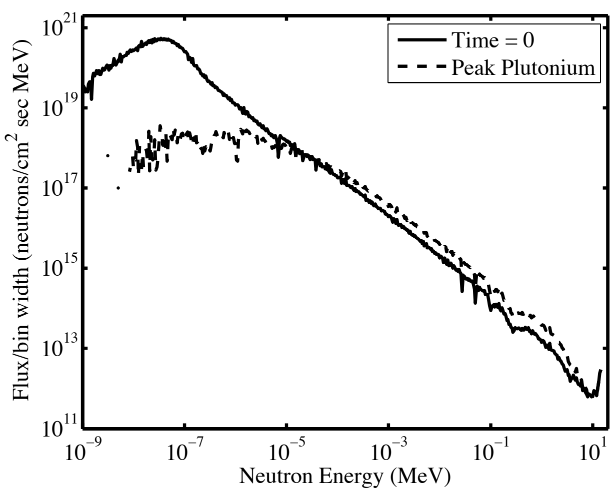

Fig. 7. LIFE fuel blanket neutron spectrum normalized to energy bin width.

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^{23} neutrons/cm^2, or 220 dpa in the fuel over its lifetime. The chamber will also require replacement every 5-7 years due to a 35 dpa/yr damage rate.

IV.B LIFE Actinide Inventory and Criticality

The LIFE engine is initially loaded with DU fuel and contains less than natural amounts of fissile material in

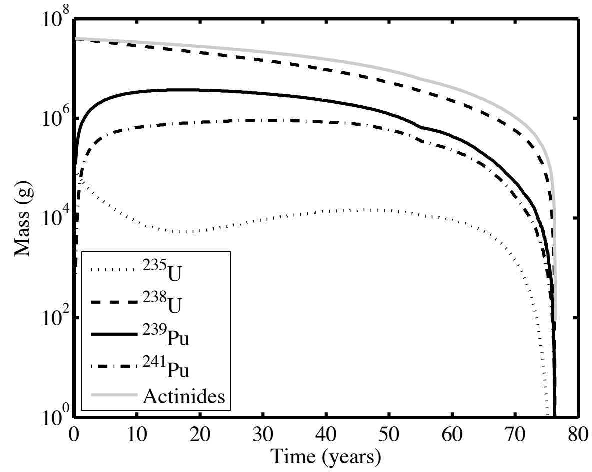

Fig. 8. Pu and actinide inventories throughout burnup

the form of ^{235}U. No Pu is loaded in the system. However, when the fusion source begins generating neutrons, they are absorbed in the blanket, thereby producing fissile material. The time histories of some important fissile isotopes during burnup are shown in Fig. 8. Early in time, ^{239}Pu, ^{241}Pu and other actinide masses grow quickly. Equilibrium between fission and production is reached at approximately 10 years into the burn. The ^{239}Pu reaches a peak of 3.7 MT, distributed across 15 million fuel pebbles giving 0.245 grams of ^{239}Pu per pebble. Although the fissile content increases significantly, the system stays well below k_{eff} = 1.0 at all times during operation.

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.

Fig. 9 shows the system k_{eff} over time. As expected, k_{eff} reaches a maximum at the time of peak ^{239}Pu inventory in the system. The LIFE engine remains subcritical throughout the burnup with a peak k_{eff} of ~0.7 at approximately 17 years. As the fissile production and destruction equilibrate, the system burns down and becomes more subcritical. Future work will include detailed criticality safety analysis and model refinement.

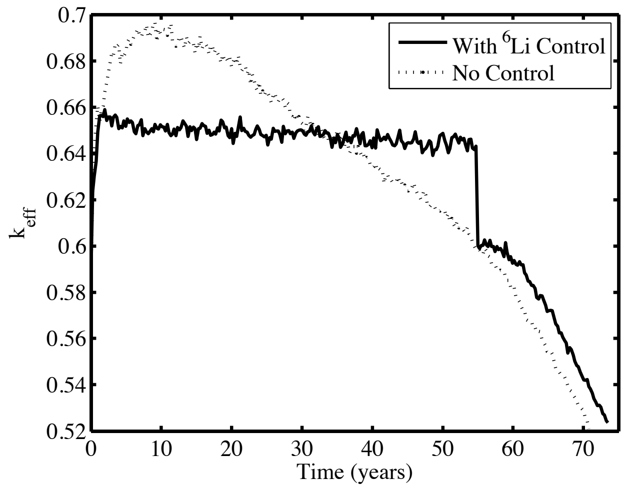

Fig. 9. k_{eff} of LIFE engine over burnup cycle

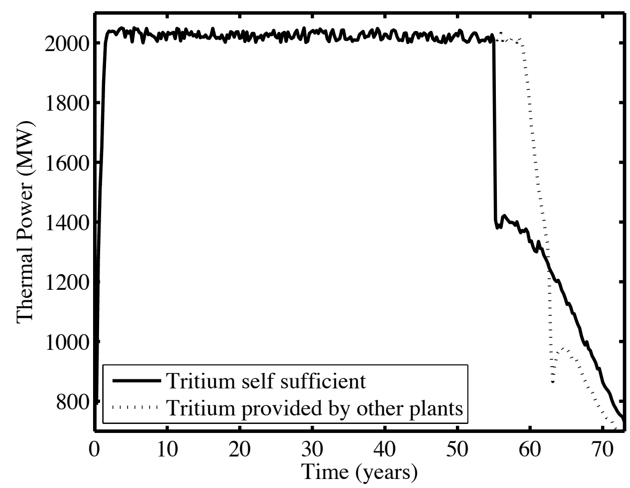

Fig. 10. LIFE burn curve with and without tritium support

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.

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 high-performance computing simulations using detailed geometries of TRISO particles inside each pebble. These large-scale transport calculations will be performed with both MCNP and the LLNL transport code Mercury.[17] New simulations will include the upgrade of current transport capabilities and the potential development of a new high-performance burnup package.

V.A ALTERNATIVE DESIGNS

There are many options that may improve system performance, including Tritium sharing and fuel-to-moderator control.

V.A.1. Tritium Sharing

It is possible to envision fleets of LIFE plants either sited at the same location or near one another. Since a LIFE plant produces excess tritium early in the fuel cycle, it must be stored for later use. Given its relatively short half-life of 12.3 years, a significant quantity of tritium is lost to decay. By sharing tritium between plants, lower concentrations of ^{6}Li can be used and higher thermal power can be generated for a longer time. Fig. 10 shows the potential improvement in a LIFE burn curve if tritium were provided when a plant exhausted its own supply. We estimate 50-60 kg of tritium must be supplied to the plant to extend the full power phase from 84% to 90% FIMA. More detailed studies of this concept are left as future work.

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 fissile ^{239}Pu. As the Pu concentration in the fuel increases, the spectrum becomes harder and fewer 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 more thermal neutrons. 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.

VI. CONCLUSIONS

LIFE offers a logical step to bridge the gap between fission and fusion power plants. We have shown details of a possible LIFE engine design based on a solid fuel form, using DU as the fertile fuel. This design produces 2000 MW of power for over 50 years using a fuel loading of 40 MT. Fuel enrichment and reprocessing are not required. Early results show promise for this system with limitations being driven by self-sufficient tritium production. Alternative designs are also being explored because of the challenge of fuel survivability, yet ongoing research is addressing fuel and structural material survival within the LIFE engine.

This current work is intended to develop an initial concept for the LIFE 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. Likewise, phasing LIFE plants in time and sharing tritium is an obvious alternative. Although further optimization is planned, the current LIFE engine meets all of our initial design goals.

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