LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-JRNL-414824

Parameter Study of the LIFE Engine Nuclear Design

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

July 17, 2009

Energy Conversion and Management

Elsevier Editorial System(tm) for Energy Conversion and Management
Manuscript Draft

Manuscript Number: ECM-D-09-00636R1

Title: Parameter Study of the LIFE Engine Nuclear Design

Article Type: Special Issue: ICENES 2009

Keywords: LIFE; fusion-fission; hybrid; nuclear; inertial; fusion

Corresponding Author: Mr. Kevin J Kramer,

Corresponding Author's Institution: Lawrence Livermore National Laboratory

First Author: Kevin J Kramer

Order of Authors: Kevin J Kramer; Wayne R Meier; Jeffery F Latkowski; Ryan P Abbott

Manuscript Region of Origin: UNITED STATES

Energy Conversion and Management
Submission Checklist

Please save a copy of this form to your computer, complete and upload as 'Checklist for New Submissions'.

Your manuscript will be considered incomplete unless all the below requirements have been met. Please initial each step to confirm.

(1) I _Kevin Kramer__{enter name} confirm that the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, without the written consent of the Publisher.

Authors found to be deliberately contravening the submission guidelines on originality and exclusivity shall not be considered for future publication in this journal.

(2) The source document is editable, i.e. Word, WordPerfect or Latex
_KJK__ {enter initials}

(3) The source document is double-spaced
__KJK_ {enter initials}

(4) The source document has been prepared prepared in 12 or 10 point font size, preferably 12 points
__KJK_ {enter initials}

(5) The source document is in one column per page
__KJK_ {enter initials}

(6) The figures and tables have been supplied: either integrated with the text file or as separate files.
__KJK_ {enter initials}

Parameter Study of the LIFE Engine Nuclear Design

K.J. Kramer[a,b,**], W.R. Meier[a,*], J.F Latkowski[a], R.P Abbott[a]

[a] *Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, USA*
[b] *University of California, Berkeley, CA 94720, USA*

Abstract

LLNL is developing the nuclear fusion based Laser Inertial Fusion Energy (LIFE) power plant concept. The baseline design uses a depleted uranium (DU) fission fuel blanket with a flowing molten salt coolant (flibe) that also breeds the tritium needed to sustain the fusion energy source. Indirect drive targets, similar to those that will be demonstrated on the National Ignition Facility (NIF), are ignited at ∼13 Hz providing a 500 MW fusion source. The DU is in the form of a uranium oxycarbide kernel in modified TRISO-like fuel particles distributed in a carbon matrix forming 2-cm-diameter pebbles. The thermal power is held at 2000 MW by continuously varying the ^{6}Li enrichment in the coolants. There are many options to be considered in the engine design including target yield, U-to-C ratio in the fuel, fission blanket thickness, etc. Here we report results of design variations and compare them in terms of various figures of merit such as time to reach a desired burnup, full-power years of operation, time and maximum burnup at power ramp down and the overall balance of plant utilization.

Keywords: LIFE, fusion-fission, hybrid, nuclear, inertial, fusion

1. Introduction

Recent projections by the Energy Information Agency and current Intergovernmental Panel on Climate Change show that worldwide electric power demand is expected to double from its current level to 4 TWe by 2030 [1, 2]. It is also expected that the bulk of the electricity production will continue to be provided by fossil fuels including coal and natural gas for the next 30 to 50 years. Coal-fired power plants currently supply 41% of the world's electricity and will likely grow

*Corresponding author
**Principal corresponding author
Email addresses: kramer12@llnl.gov (K.J. Kramer), meier5@llnl.gov (W.R. Meier)

to 45% by 2030 [1]. New carbon-neutral technologies and alternative sources of energy will be required as early as possible in the 21^{st} century to meet the increasing world energy demand and stabilize the concentration of CO_2 in the atmosphere. Since the 1960's, nuclear energy has been a key component of the world's energy production and currently accounts for about ∼16% of worldwide electricity production [3]. However, several factors make its long-term sustainability and growth difficult. Concerns associated with the risk of proliferation, the generation of radioactive, long-lived nuclear waste and a reliance on a once-through, open nuclear fuel cycle are just a few issues hampering its expansion. In the United States alone, it is estimated that we currently have enough Spent Nuclear Fuel (SNF) to fill the Yucca Mountain geological waste repository to its legislated limit of 70,000 MT.

Fusion continues to be an attractive option for the future, and two distinct approaches to fusion power plants are being developed worldwide. Magnetic fusion energy (MFE) uses strong magnetic fields to confine a low-density deuterium and tritium (DT) plasma for a long enough time to achieve sustainable conditions required to generate energy. Alternatively, Inertial Confinement Fusion (ICF) uses lasers, heavy ion beams, or pulsed power systems to compress a capsule containing a mixture of DT ice and gas. The DT fusion reactions yield both alpha particles and 14.1-MeV neutrons, generating significant energy gain [4]. The National Ignition Facility (NIF) is expected to demonstrate the capability of lasers to create the conditions required for ICF ignition [5]. The National Ignition Campaign (NIC), beginning in 2009, seeks to achieve ignition and modest target gain (∼10), leading to 10-15 MJ yields in 2010/2011. The first planned experiments to demonstrate ignition and gain will use an indirect drive configuration utilizing a central hot spot ignition (HSI) target with 350 nm laser light [6, 7]. The NIF ignition experiments with HSI targets are expected to be successful and the resulting demonstration of ignition and net energy gain will likely be a transforming event for inertial fusion. This will potentially focus the world's attention on the possibility of ICF as a energy production technology. Even so, target gains of ∼100 would be required for efficient, cost effective power generation with HSI targets. Likewise, larger laser energies (∼2.5 MJ) and corresponding fusion yields (150-200 MJ) are needed for pure inertial fusion energy (IFE) systems and require additional development.

To mitigate the challenges of nuclear fission energy and advance the time scale of useful fusion sources, LLNL is developing a novel once-through, self-contained, closed nuclear fuel cycle in collaboration with several university, laboratory, and industrial partners [8, 9, 10, 11]. Our approach makes use of a fusion driven fission engine that combines the best aspects of nuclear fusion and fission, termed Laser Inertial Fusion Energy (LIFE), and consists of an ICF neutron source (typically $1 - 2 \times 10^{20}$ n/sec) surrounded by a spherical subcritical fission blanket. Fusion-fission hybrid concepts have been studied in the past with encouraging results [12, 13, 14]. Andrei Sakharov originally discussed the concept of fusion driven fission systems in the 1950's [15]. Later, Hans Bethe and Nikolai Basov expanded on his ideas in the 1970's and 1980's, as did many other groups around the world [14, 16, 17, 18]. Although the focus of many of these studies was on the use of fusion neutrons to generate fuel for fast nuclear reactors, Basov as well as Maniscalco also discussed the possibility of using laser-driven fusion targets to drive a fission blanket for generating commercial power. Many proposals have been also made to use accelerators to generate neutrons to transmute nuclear waste and generate electricity [19]. Unfortunately, fusion driven fission systems never moved beyond the discussion stage mainly because fusion ignition was judged to be several decades away, and powerful high-average-power lasers and other required technologies did not exist. Similarly, accelerator-based schemes never advanced past the conceptual study phase. This was in part because a complete nuclear fuel cycle, including U enrichment and nuclear waste reprocessing, was still required to economically generate electricity. As a result, the efficiency and cost of those systems proved to be prohibitive relative to the benefit of transmuting nuclear waste.

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, the point source of fusion neutrons drives the fission blanket, obviating the need for a critical assembly to sustain the fission chain reaction. If very high burnup fission fuels can be developed, a LIFE engine will be able to generate 2000-5000 megawatts 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. The energy and materials flow for LIFE engine is shown schematically in Figure 1. As shown, a variety of different system configurations are possible, depending on the mission. LIFE provides an option for a once-through, closed nuclear fuel cycle that starts with a 15-20 MW laser system to produce 350-500 MW of fusion power and uses a subcritical fission blanket to multiply this to 2000–5000 MW_{th}. A LIFE engine can extract virtually all of the fission 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 per Initial Metal Atoms) without refueling or reprocessing, thus allowing for nuclear waste forms with significantly reduced concentrations of long-lived actinides per GWe-yr of electric energy produced.

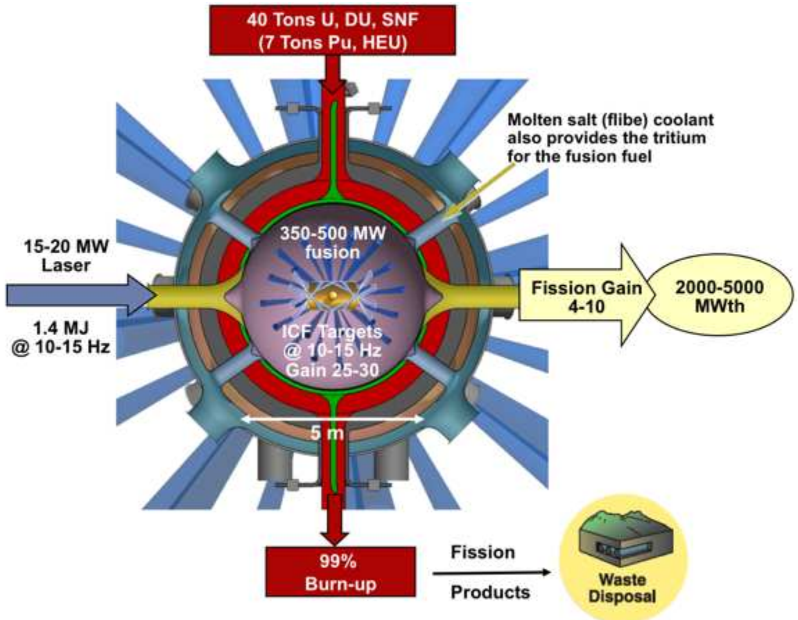

Figure 1: The energy and materials flow for the NIF-based laser illumination LIFE engine

With the completion of the National Ignition Facility, there is a renewed interest in ICF as a potential source of neutrons to drive a multiplying fission blanket. This deeply subcritical design ($k_{eff} < 0.9$) shares some features of other fusion-fission hybrids, but has unique and compelling objectives not previously emphasized. If successful, LIFE will eliminate the need for fuel enrichment and reprocessing, thus reducing proliferation concerns by reducing the mass per unit energy produced (kg/GWe-yr) of waste that must be disposed of in deep geologic repositories. Because of all of these advantages, LIFE engines offer a pathway toward sustainable and safe nuclear power that significantly mitigates nuclear proliferation concerns and minimizes nuclear waste. Advances at the NIF and other ICF facilities around the world are putting scientists and engineers closer to demonstrating the physics and key technologies required to make LIFE a reality. In fact, we believe that with an appropriate research, development and engineering program, LIFE engines could start providing electricity to U.S.

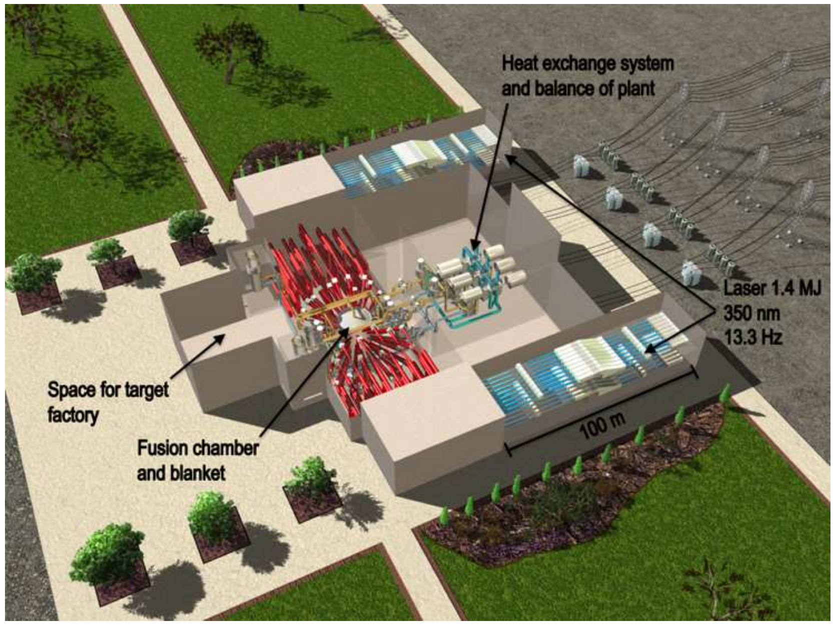

Figure 2: Conceptual design of a LIFE engine power plant based on 35 MJ yield targets expected from hot-spot ignition targets on NIF.

consumers relatively soon and could provide a very significant fraction of U.S. and international electricity demand by 2100.

In this paper we describe the LIFE engine with emphasis on parametric studies performed to learn how to best meet key design criteria. We begin with an overview of the baseline design and methodology, followed by fission blanket options and a limited parameter study.

2. System Description and Performance

The LIFE power plant (see Figure 2) discussed in this paper consists of a 10 to 15 Hz diode-pumped solid-state laser (DPSSL) with an estimated efficiency of 10-15%, a fusion target factory, a fusion target chamber surrounded by a subcritical fission blanket, and the thermal mechanical systems comprising the balance of the plant. The baseline LIFE system is designed to operate with fusion energy gains of 25–30 to provide 350–500 MW of fusion power, approximately 80% of which comes in the form of 14.1-MeV neutrons, with the rest of the energy in the form of x-rays and ions. This approach to fusion generates approximately 10^{19} 14.1-MeV neutrons per shot, or 10^{20} n/sec and is a logical extension of the single-shot NIF laser and NIF yields. When used to drive the sub-critical fission blanket, these fusion neutrons generate an additional fission energy gain of 4–10 to allow overall LIFE system energy gains of 100–300. The additional fission gain has important consequences for the overall LIFE system, as compared with a pure IFE option. Namely, a pure fusion system with a fusion gain of 25-30 would not be economically viable [9].

3. Baseline Design

Multiple system design options are currently being explored to optimize the engine's performance and meet the aforementioned goals. Current designs make use of NIF-like fusion target illumination geometry, but alternative fusion target designs employing low angle illumination geometry are being investigated [20]. We have focused on a nuclear fuel in the form of modified TRISO [21] particles randomly disbursed in graphite pebbles. Other fuel design options are also under development [22]. For the purposes of this paper, we focus on a LIFE chamber using a 300 μm radius TRISO-based uranium oxycarbide (UCO) fuel kernel surrounded by porous carbon buffer and SiC [10].

The presented LIFE engine is designed to deliver ∼2000 MW_{th}. Figure 3 shows an overview of the LIFE engine's central chamber. The engine consists of a 2.5 m radius fusion cavity surrounded by several neutron multiplying and moderating layers and a fission blanket. The ICF fusion targets produce 500 MW (37.5 MJ yield at ∼13.3 Hz) from D(T,n)α fusion reactions. This results in nearly 400 MW (1.8×10^{20} n/s at 14.1 MeV) of fusion neutrons. The remaining fusion power is emitted as ions and x-rays. The 2.5 m radius, ODS ferritic steel first wall is protected with approximately 250-500 μm of tungsten. A dedicated

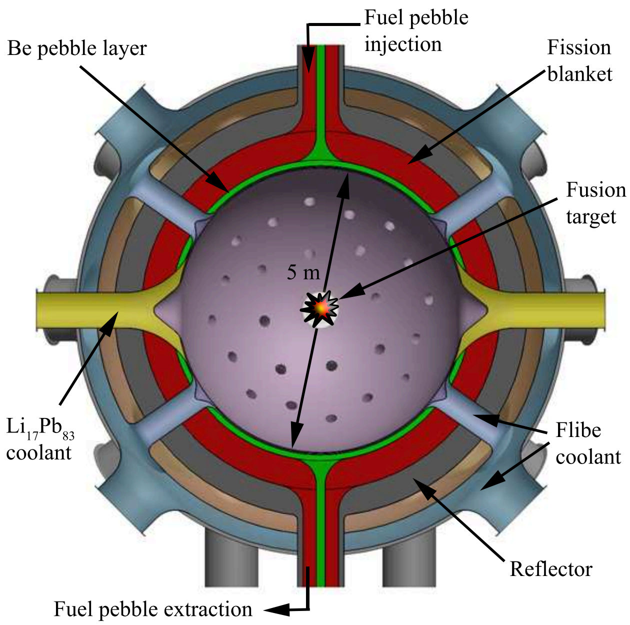

Figure 3: Section view details of LIFE engine

$Li_{17}Pb_{83}$ coolant, initially at natural ^{6}Li enrichment, cools and surrounds the first wall to provide neutron multiplication (via Pb(n,xn)) and tritium production (via ^{6}Li(n,α)T and ^{7}Li(n,nα´)T). Flibe (2LiF+BeF_2) is the primary system coolant, chosen for its tritium breeding, neutron muliplication and high volumetric heat capacity. It flows radially outwards from the injection plenum to the Be pebble multiplier, fuel and reflector regions. It should be noted that $Li_{17}Pb_{83}$ is chosen to cool the first wall because a high heat transfer rate is required to prevent the wall from failing due to the high thermal flux (∼1.5 MW/m^2) [8]. Following a Be multiplier blanket, the fission fuel blanket holds 40 metric tonnes (MT) of DU fuel contained in about 15 million, 2 cm diameter pebbles. A 60/40 volume percent graphite (pebble form) and flibe reflector surrounds the entire fission blanket. The flibe then flows from an extraction plenum outside the reflector blanket and to the thermal hydraulics systems for

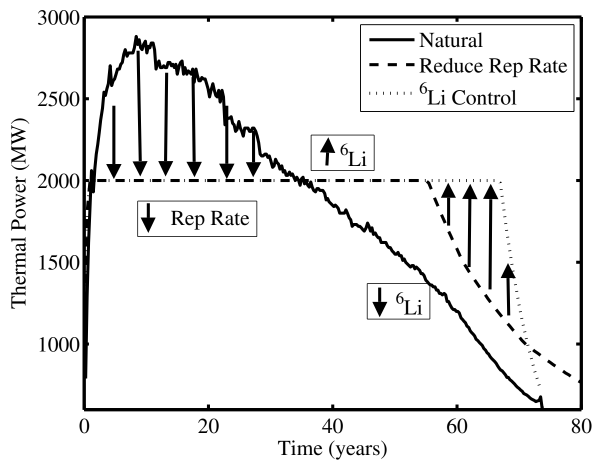

Figure 4: LIFE engine operation requiring only TBR > 1.0, with laser rep-rate control and with ^{6}Li control mechanism

power conversion [8].

The LIFE engine relies on the fact that neutrons, provided by the fusion source, can be used to produce fissile ^{239}Pu from fertile ^{238}U, as well as to produce tritium. Without control, the thermal power would continue to rise until the Pu production and fission rates equilibrate after about 12 years (solid curve Fig.4). Following peak Pu inventory, the system burns the remaining Pu over 4-5 decades with corresponding reduction in thermal power. This is unattractive primarily because of poor balance of plant (BOP) utilization defined as the ratio of the average to the peak thermal powers. To improve this, we can reduce the fusion pulse repetition rate (rep-rate) to flatten the power curve over much of the system life (dashed curve in Fig. 4), resulting in laser underutilization. As an alternative, we have employed a control scheme using a time varying ^{6}Li/^{7}Li concentration in the flibe and $Li_{17}Pb_{83}$ coolants resulting in the dotted curve in Fig. 4. By increasing the ^{6}Li concentration early in time, excess tritium is produced and the thermal power is suppressed. This tritium is stored for later use, thereby allowing for increased thermal power late in time at the expense of

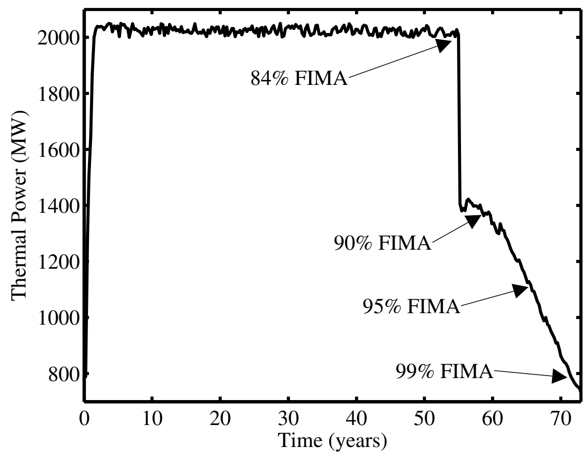

Figure 5: LIFE 2000 MW_{th} DU engine power vs. time

tritium production. By adjusting the ^{6}Li enrichment over time, we maintain a nearly constant thermal power of 2000 MW_{th} for almost 12 years longer than simply via laser rep-rate reduction. This technique allows the LIFE engine to reach 80-90% FIMA while at full power before the power falls due to either the exhaustion of stored tritium or depletion of the fertile and fissile materials. Once this occurs, a ramp-down and incineration period begins. At this time, the system can either be shut down, refueled, or allowed to incinerate the remaining actinides, albeit with a continuously decreasing thermal output. For the purposes of this paper we assume the latter.

The baseline system generates the thermal power history shown in Fig. 5. The power ramp-up phase takes less than one year. Fissile production continues past this point, but the thermal power is controlled, via coolant ^{6}Li enrichment, to remain at 2000 MW_{th} for over 50 years with no fuel enrichment or reloading. Constant power is effectively maintained until the stored tritium inventory is exhausted. At this point, the tritium breeding ratio (TBR) is brought back to $\sim$1.0 (from $\sim$ 0.7) by increasing the ^{6}Li enrichment in the coolants causing an immediate drop in system power from 2000 MW_{th} to approximately 1400 MW_{th}. The remaining time is used to incinerate the residual actinides to reach the desired burnup.

The LIFE engine is initially loaded with DU fuel (no Pu) and contains less than natural amounts of fissile material (0.26% ^{235}U by mass). After startup, the thermal power begins to naturally rise, shown in Fig. 5, due to build up of fissile ^{239}Pu in the fission blanket primarily resulting from ^{238}U capture. ^{239}Pu, ^{241}Pu and other actinide masses grow quickly from capture reactions. Equilibrium between fission and production is reached at approximately 17 years into the burn with a peak ^{239}Pu mass of 3.7 MT, which is distributed across ∼15 million fuel pebbles. The fission blanket is maintained subcritical at all times during operation. In addition, our preliminary studies of temperature feedback and coolant voids have shown little impact on LIFE performance.

4. Methodology and Simulation Tools

The neutron transport calculations were performed using the Monte Carlo transport code MCNP5 [23]. Burnup calculations were performed with Monteburns 2.0 [24], which in turn utilizes ORIGEN2 [25] for the nuclide evolution. Custom code development was needed to perform the LIFE burnup calculations. We developed a C++ code named LIFE Nuclear Control (LNC) to act as the main controlling code for LIFE depletion calculations (shown in Fig. 6) [26]. A typical depletion calculation begins with a three-dimensional MCNP5 model of a LIFE engine utilizing ENDF/B-VII nuclear data Doppler broadened to 600 °C, although additional temperatures have been studied [27]. An initial transport calculation is used to determine the current system thermal power and 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. Once an acceptable enrichment is found, the updated material definitions and cell densities

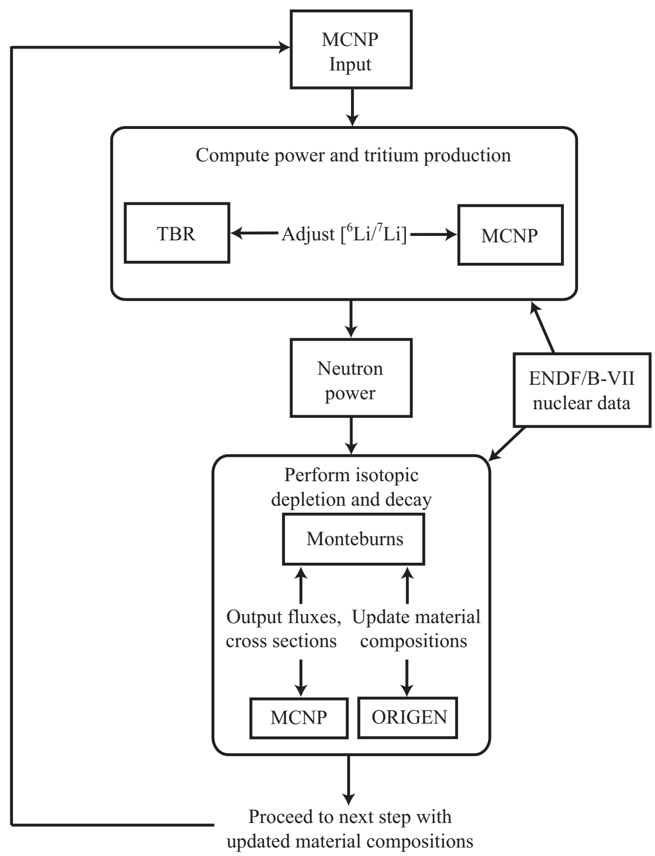

Figure 6: Flow diagram of burnup code suite

are calculated and written to a final MCNP5 input deck for the given time step. Upon completion of a final transport calculation, the total fission neutron power deposition is integrated and used to update Monteburns input. Monteburns is then called by LNC to perform a series of transport (MCNP5) and depletion (ORIGEN2) calculations. MCNP5 calculates the group collapsed fluxes and cross-sections, which are then used by ORIGEN2 to perform the isotopic evolution. The updated material compositions are passed from ORIGEN2 back to MCNP5 for a flux and cross section update based on the number of desired predictor-corrector steps. Upon completion, a new MCNP5 deck is written by the LNC code for the next step in the code sequence. Modern software quality assurance practices are used and validation efforts are underway.

5. Parametric Studies

To search for an optimum system design, we focused on a four metrics: the maximum time at full power, the burnup at the point that power drops, the time required to reach 99% FIMA and the BOP utilizaton. These metrics identify how well the fuel is being utilized to produce tritium and the desired thermal power. We limited the scope of this study to five key variables; the fuel mass, the first wall radius, fission blanket gain, fusion power to drive the blanket and the TRISO packing fraction.

Varying the fuel mass load serves to shorten or extend the burn curve, relative to the 40 MT baseline, as shown in Fig. 7. The fuel mass loading is varied from 10 MT to 50 MT and burnup is carried out until 99% FIMA is reached. Results indicate that if too little fuel mass is loaded, the system can achieve the desired 2000 MW_{th} for only a short time, as evidenced in the 10 MT fuel loading. At these low fuel loadings, the blanket neutron leakage becomes excessively high and limits the fission process. Alternatively, too much mass causes the fuel blanket to become very thick and the neutron flux is insufficient to effectively

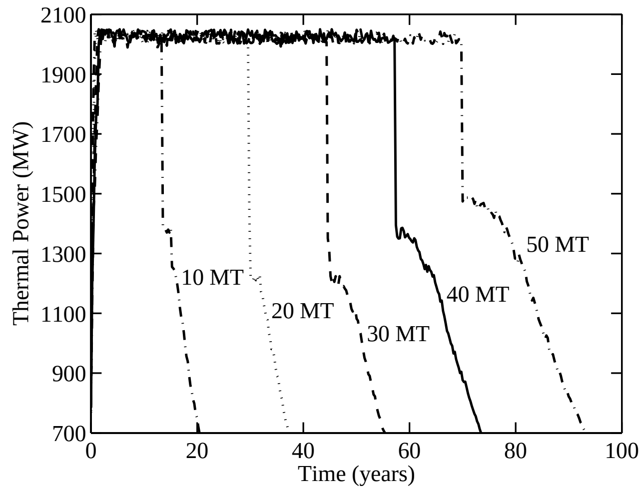

Figure 7: Effect of varying fuel mass load

burn the outer pebbles, as indicated by the 50 MT loading and longer tail of the burn curve. Based on the desire to maximize the ratio of time at full power to the time to reach 99% FIMA, Fig. 7 shows that a ∼30 MT fuel loading is near optimal for the current design because of the shortened "tail" of the curve (with 30% TRISO packing in the pebbles and 60% pebble packing). Increasing the fuel load results in longer times operating below full power (40-50 MT cases) to reach the same burnup.

Increasing the first wall radius is of interest because this reduces the fast flux on the first wall and increases its neutron damage lifetime. However, doing so also reduces the total flux in the fuel region and correspondingly reduces the time at full power. Figure 8 shows that multiple metrics are adversely affected by increasing the 1st wall radius. The total time it takes to reach 99% FIMA increases by about 3 years (or ∼2%), relative to the baseline 2.5 m case. In addition, the burnup at which the full power can no longer be maintained decreases. This implies that the engine must run for a longer fraction of its operational time below peak power. The BOP utilization is effectively reduced

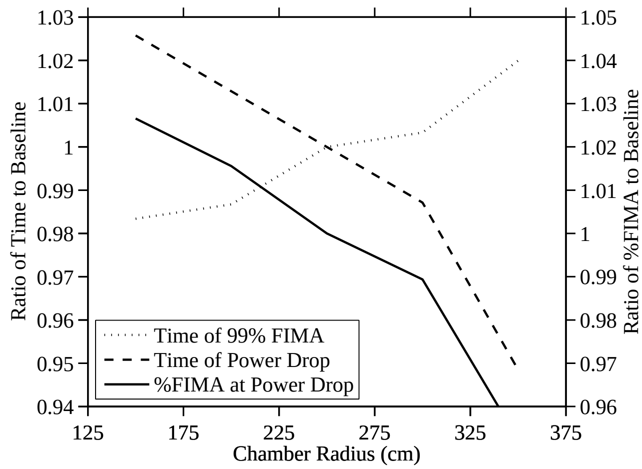

Figure 8: Effect of varying first wall radius

from 91.5% to 88% by increasing the radius, as shown in Fig. 9. Even though the damage rate (displacements per atom/yr) decreases dramatically from a 1.50 m radius chamber to 3.5 m, the BOP suffers with increasing radius. This, however, does not imply that the fuel or structural materials will survive the damage rates to such high burnup. Given a maximum of 150-300 dpa as an ODS structural steel limit and a 35 dpa/yr damage rate, the first wall would require replacement every 3-5 years. Likewise, our estimates of stress induced from fission gas pressure alone suggest that our modified TRISO design could survive. However, dpa damage rates could lead to earlier failure. A best estimate of structural carbon allowable damage is 25-50 dpa, but it is not clear that this carbon limit would apply to the TRISO fuel. If it does, the 4 dpa/yr in the fuel carbon materials would further reduce the allowable burnup. Ultimately, further work is required and the trade-offs will be studied in much more detail via a systems analysis code.

In an effort to increase the fission blanket energy gain, we can reduce the ^{6}Li enrichment throughout the coolants. However, increased blanket gain causes the system to drop from full power much earlier in time as shown in Fig 10.

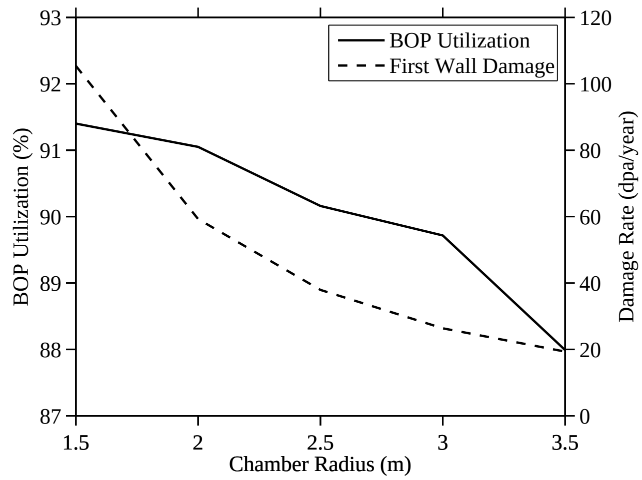

Figure 9: BOP utilization and damage rates as a function of first wall radius

The early drop in power is due to exhaustion of the tritium supply and yields a continuously decreasing thermal power in an effort to restore the TBR to 1.0. Interestingly, the time to reach 99% FIMA is relatively unaffected. This implies that increasing blanket gain not only reduces the time at peak power, but also requires much longer operation below peak power to reach a desired burnup. Hence, the optimum blanket gain balances the time at full power against electrical output.

The fusion power input strongly affects the system performance (Fig. 11). As one lowers the fusion power (for a fixed radius) in an effort to reduce first wall loading, the time required to reach 99% FIMA increases. Likewise, the burnup level when power can no longer be sustained is reduced for decreasing fusion power input. Effectively, a lower neutron source term causes a longer time to burn out the fuel, a lower tritium production rate and a lower peak thermal power that the system can be operated at.

Perhaps the most significant factor affecting the fuel blanket design is the fuel-to-moderator ratio (F/M), adjusted via the TRISO particle packing frac-

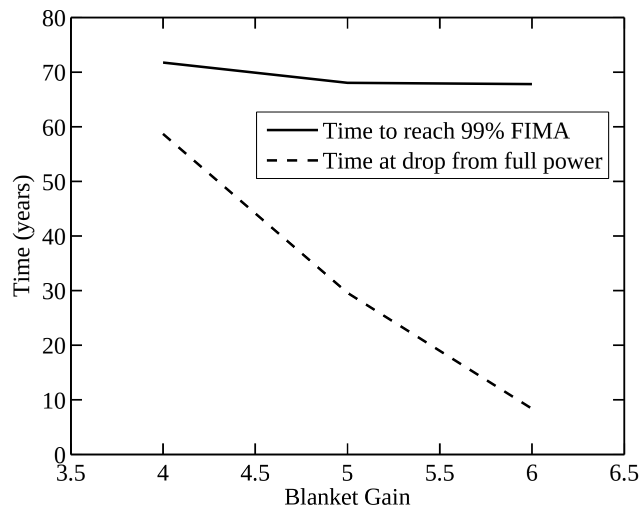

Figure 10: Relative performance as function of blanket gain for fixed fuel mass

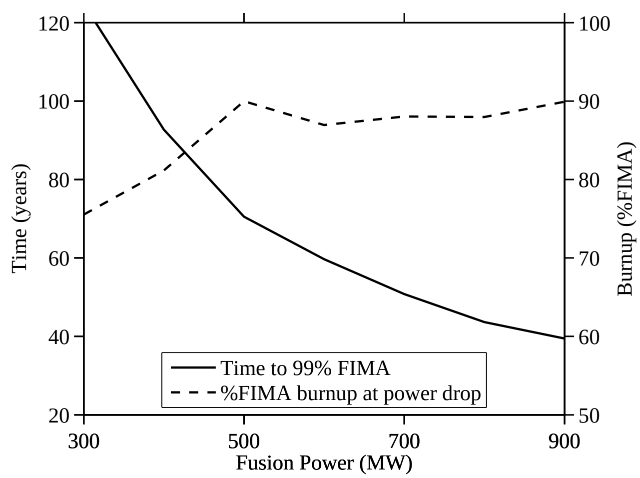

Figure 11: Burnup and time to reach 99% burnup as function of fusion power

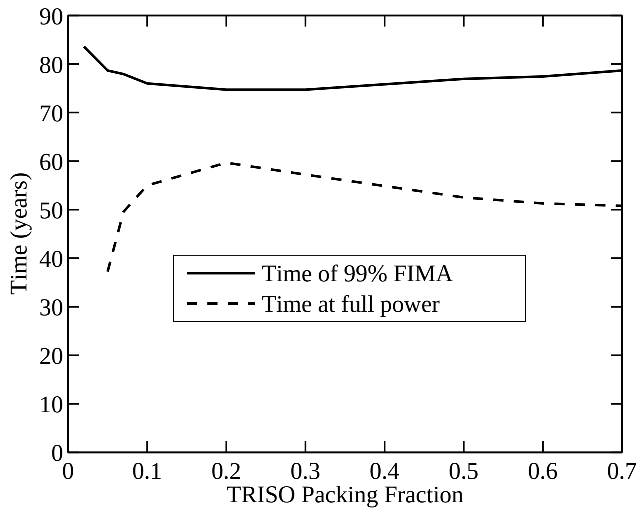

Figure 12: Effect of TRISO packing on burnup

tion in the pebble. Figure 12 shows the effect of varying the TRISO packing fraction from 5% to 70%. (Random TRISO packing beyond 63% is not physically realizable, but adding pure graphite pebbles to the fuel bed could simulate the F/M ratio.) We find that the actual optimum packing fraction is approximately 20% based on the desire to reach 99% FIMA in shortest amount of time while maintaining the maximum time at full power. Packing fractions below 5% never reach the desired full power due to a lack of fissile material buildup in the blanket.

Based on the results of our single parameter variation analyses, a more efficient neutronics design for a LIFE engine would operate with a blanket gain of 4, with approximately a ∼30 MT fuel load, driven by 500 MW fusion, with a TRISO particle packing fraction around 20%. Of course, these neutronics results still require integration into a full systems economic analysis.

6. Future Work

We continue to examine better fuel blanket configurations. The current study only examined the effects of a single parameter change at a time. Future work will include more detailed studies varying multiple parameters simultaneously, akin to N-factorial design methods [28]. We also continue to study more advanced fuel utilization strategies including multilayer segmenting of the blanket along with shuffling strategies. Likewise, all current results rely on the assumption of a tritium self-sufficiency requirement. However, if tritium were supplied externally (pure fusion plant, for instance), the parameter space that could be explored would vary significantly due to the reduced tritium requirements.

7. Conclusions

LIFE offers a logical next-step beyond NIF to bridge the gap between fission and fusion power plants by lowering the required fusion yields and maximizing energy production, while minimizing waste. 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_{th} of power for approximately 50 years using a fuel loading of ~40 MT. Fuel enrichment and reprocessing are not required. Parameter studies illustrating the effects of different fuel loads, blanket gains, first wall radius, fusion power and F/M ratio show potential improvements over the current design. Reducing the F/M ratio from the current baseline design of 30% to 20% and reducing the fuel loading from 40 MT to 30 MT will improve our characteristic burn curve and tritium production. Early results show promise for this system with limitations being driven by self-sufficient tritium production.

This current work is intended to develop a basis for the initial LIFE concept with nuclear burnup and transport calculations being performed using standard tools and practices. We have shown through Monte Carlo-based analysis how the current engine concept could operate and how performance is impacted by different parameters. Similarly, we have offered options for performance improvement and intend to further investigate online fuel reloading, tritium sharing between plants, and improved blanket designs.

8. Acknowledgements

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] Office of Integraged Analysis Energy Information Administration and U.S. Department of Energy Forecasting. EIA - international energy outlook 2009 with projections to 2030, 2007.

[2] E.H. SIMS, R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martinez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, and X. Zhang. Energy supply. in climate change 2007: Mitigation. contribution of the working group III of the forth assessment report of the intergovernmental panel on climate change. Cambridge University Press, 2007.

[3] International Energy Agency. Key world energy statistics, 2006.

[4] J.H. Nuckolls, L. Wood, A. Thiessen, and G.B. Zimmerman. Laser compression of mater to Super-High densities: Thermonuclear (CTR) applications. *Nature*, 239(139), 1972.

[5] J.T. Hunt, K.R. Manes, J.R. Murray, P.A. Renard, R.W. Sawicki, J.B. Trenholme, and W. Williams. Laser design basis for the national ignition facility.

[6] J.D. Lindl. The physics basis for ignition using indirect-drive targets on the national ignition facility. *Physics of Plasmas*, 11(2):339, 2004.

[7] J.D. Lindl. *Inertial Confinement Fusion*. Springer-Verlag, 1998.

[8] R.P. Abbott, M.A. Gerhard, K.J. Kramer, J.F. Latkowski, K.L. Morris, P.F. Peterson, and J.E. Seifried. Thermal and mechanical design aspects of the LIFE engine. *Fusion Science and Technology*, 56(2):618–624, August 2009.

[9] E.I. Moses, T. Diaz de la Rubia, J.F. Latkowski, J.C. Farmer, R.P. Abbott, K.J. Kramer, P.F. Peterson, H.F. Shaw, and R.F. Lehman II. A sustainable nuclear fuel cycle based on laser inertial fusion energy (LIFE). *Fusion Science and Technology*, 56(2):566–572, August 2009.

[10] K.J. Kramer, J.F. Latkowski, R.P. Abbott, J.K. Boyd, J.J. Powers, and J.E. Seifried. Neutron transport and nuclear burnup analysis for the laser inertial confinement Fusion-Fission energy (LIFE) engine. *Fusion Science and Technology*, 56(2):625–631, August 2009.

[11] W.R. Meier, Ryan P. Abbott, R. Beach, J. Caird, A. Erlandson, J. Farmer, W. Halsey, T. Ladran, J. Latkowski, A. MacIntyre, R. Miles, and E. Storm. Systems modeling for the laser Fusion-Fission energy (LIFE) power plant. *Fusion Science and Technology*, 56(2):647–651, August 2009.

[12] H. A. Feivenson, F. Von Hippel, and R.H. Williams. Fission power: An evolutionary strategy. *Science*, 203:330–337, 1979.

[13] R. Avery. Fusion-fission hybrid study, July 1978.

[14] H. A. Bethe. The fusion hybrid. *Physics Today*, pages 44–51, 1979.

[15] A. Sakharov. *Memoirs*. New York, 1990.

[16] N.G. Basov et al. Hybrid reactor based on laser thermonuclear fusion. *Soviet J. of Quant. Elec.*, 17:1324–32, 1987.

[17] M. Kotschenreuther et al. Fusion-Fission transmutation Scheme–Efficient destruction of nuclear waste. *Fusion Engineering Design*, 84:83–88, 2009.

[18] J.A. Maniscalco and L.F. Hansen. Status of laser driven fusion-fission energy systems, 1978.

[19] G. Michaels. Potential benefits of waste transmutation to the U.S. High-Level waste repository. In *AIP Conference Proceedings*, volume 8, 1995.

[20] M. Tabak, J. Hammer, M. E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Cambelle, M.D. Perry, and R.J. Mason. Ignition and high gain with ultrapowerful lasers. *Physics of Plasmas*, 1 (2)(5):1626–1634, 1994.

[21] W. J. Kovacs, K. Bongartz, and D. Goodin. TRISO-Coated HTGR fuel Pressure-Vessel performance models, October 1983.

[22] R.W. Moir, H.F. Shaw, A. Caro, L. Kaufman, J.F. Latkowski, J. Powers, and P.E.A. Turchi. MOLTEN SALT FUEL VERSION OF LASER INERTIAL FUSION FISSION ENERGY (LIFE). *Fusion Science and Technology*, 56(2):632–640, August 2009.

[23] Los Alamos National Laboratory. MCNP - a general monte carlo N-Particle transport code. *LA-UR-03-1987*, 2003.

[24] D.L. Poston and H.R. Truelle. Users manual, version 2.0 for MONTEBURNS version 1.0, 1999.

[25] A.G. Croff. ORIGEN2: a versatile computer code for calculating the nuclide compositions and characteristics of nuclear materials. *Nuclear Technology*, 62:335–352, September 1983.

[26] K.J. Kramer. Description and verification of LNC (LIFE nuclear control code) for use in LIFE calculations. Technical Report Internal Memo, Lawrence Livermore National Laboratory, September 2008.

[27] M.B. Chadwick, P. Oblozinsky, M. Herman, and et al. ENDF/B-VII.0: next generation evaluated nuclear data library for nuclear science and technology. *Nuclear Data Sheets*, 107:2931–3060, 2006.

[28] H. Horie, K. Miyagi, K. Nakahara, and H. Matsumiya. Safety performance of the 4S reactor on ATWS events - statistical estimation of uncertainty. *Progress in Nuclear Energy*, 50(2-6):179–184, August 2008.