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ATTAINABLE BURNUP IN A LIFE ENGINE LOADED WITH DEPLETED URANIUM

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ABSTRACT

The Laser Inertial Fusion-based Energy (LIFE) system uses a laser-based fusion source for electricity production. The (D,T) reaction, beside a pure fusion system, allows the option to drive a sub-critical fission blanket in order to increase the total energy gain. In a typical fusion-fission LIFE engine the fission blanket is a spherical shell around the fusion source, preceded by a beryllium shell for neutron multiplications by means of (n,2n) reactions. The fuel is in the form of TRISO particles dispersed in carbon pebbles, cooled by flibe. The optimal design features 80 cm thick blanket, 16 cm multiplier, and 20% TRISO packing factor. A blanket loaded with depleted uranium and depleted in a single batch with continuous mixing can achieve burnup as high as ~85% FIMA while generating 2,000 MW of total thermal power and producing enough tritium to be used for fusion. A multi-segment blanket with a central promotion shuffling scheme enhances burnup to ~90% FIMA, whereas a blanket that is operated with continuous refueling achieves only 82% FIMA under the same constraints of thermal power and tritium self-sufficiency. Both, multi-segment and continuous refueling eliminate the need for a fissile breeding phase.

Key Words: depleted uranium, hybrid, inertial confinement fusion, source-driven, subcritical

1. INTRODUCTION

The Laser Inertial Fusion-based Energy (LIFE) system is an engine for power production from laser-driven inertial fusion [1,2,3]. Placed at the center of a spherical chamber, a deuterium-tritium cryogenic target reaches fusion conditions when ignited by 48 laser beams focused all at the same time on the target. Each fusion reaction produces 17.6 MeV of energy and one neutron. Therefore, the system can either produce energy from fusion only or can be coupled to a subcritical fission blanket driven by fusion-born neutrons. A fusion-fission engine relies on a low yield fusion source (37.5 MJ @ 13.3 Hz) capable to deliver $\sim 2 \cdot 10^{20}$ 14.1 MeV neutrons per second. As typical of source-driven systems, LIFE can in principle be fed with any fission fuel—enriched, natural, or depleted uranium, weapon grade plutonium, thorium, spent nuclear fuel. This paper describes the fundamental neutronic features of a fusion-fission LIFE engine fueled with depleted uranium (DU) and analyzes possible operation modes for the subcritical blanket.

2. MODEL AND METHODOLOGY

LIFE configuration is based on a NIF (National Ignition Facility)-like hot-spot illumination geometry (Figure 1) [1]. The fusion point-source is located at the center of a 250 cm radius chamber filled with xenon gas. The chamber is closed by a spherical ODS first-wall coated with tungsten. Beyond this a series of shells: a dedicated liquid LiPb layer for first-wall cooling, an injection plenum for the fission blanket's coolant, a multiplier layer, the fission blanket and a reflector (Table I). A 3 mm thick ODS wall separates each shell and 48 entrance ports for laser beams penetrate each layer. The blanket coolant flows radially outward starting from the injection layer and moves from one layer to the next through perforated walls. Flibe ($LiF-BeF_2$) is the preferred coolant for the blanket, but alternative candidates are also under consideration. The multiplier layer is filled with metallic beryllium pebbles coated with ODS and cooled by flibe—60% and 40% volume, respectively. High-energy neutrons from the source are multiplied by means of (n,2n) reactions on beryllium. The fission blanket contains fuel and coolant. Liquid fuel and a few options for solid fuel are under evaluation; in this paper we will limit the analysis to solid fuel in the form of TRISO particles [4] dispersed in 2 cm diameter carbon pebbles (Table II). TRISO packing, and multiplier and blanket's thickness are design parameters.

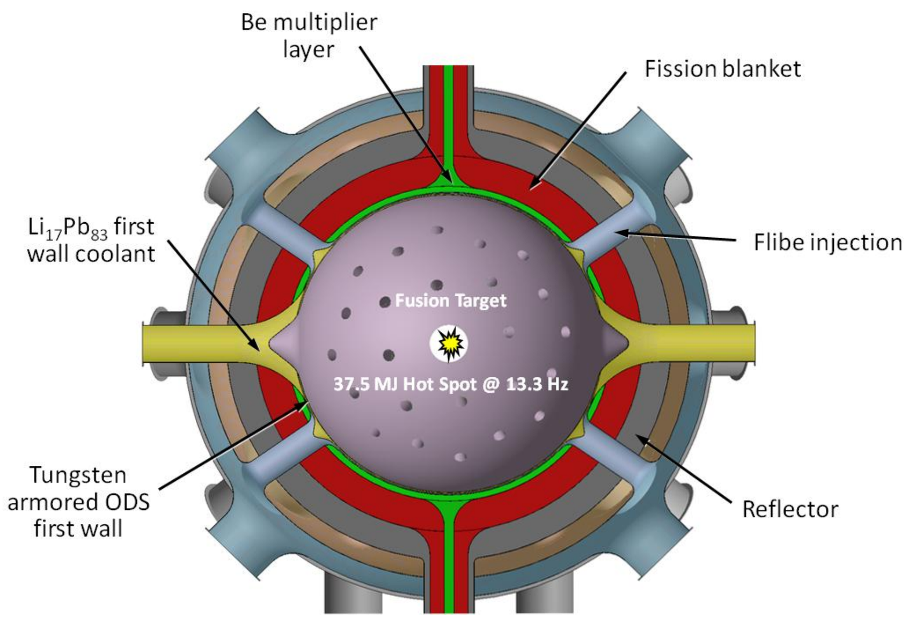

Figure 1. Vertical cross-section view of a LIFE engine.

Table I. Dimensions of the LIFE engine components for the reference design.

Component	Thickness (cm)
First-wall	3
LiPb layer	8
Injection plenum	3
Multiplier	16
Blanket	80
Reflector	75

Table II. Properties of TRISO particles.

Layer	Density (g/cm^3)	Outer radius (μm)
Fuel kernel (UOC)	10.5	300
Buffer	1.10	402
Inner PyC	1.95	432
SiC	3.20	492
Outer PyC	1.95	512
Matrix	1.70	-

The reference LIFE engine at regime produces 2,000 MW thermal—500 MW of which from fusion. The reheated Brayton cycle efficiency is 43%; coolant pumps requires 20 MW, the laser 175 MW; the net electric output is 665 MW [3]. Each LIFE engine is also required to meet the following constraints: (1) to be tritium self-sufficient, producing tritium from capture reactions on ^{6}Li; (2) to be subcritical at any point in time. The enrichment of ^{6}Li in the coolants—flibe and LiPb, controls total thermal power level and tritium breeding ratio (TBR), defined as the ratio of tritium produced to tritium consumed by fusion. When LIFE is loaded with depleted uranium an initial fissile breeding period is required in order to achieve 2,000 MW. This is typically shorter than one year. Once the system is at full power ^{6}Li enrichment is varied to maintain this condition. Figure 2 describes a typical power history for a LIFE engine. The initial breeding phase is usually referred to as "power ramp-up", whereas the constant power phase is called "power plateau". The power level drops either when the fuel inventory is not large enough to maintain the same power production or when the tritium inventory is exhausted (Figure 3) and TBR needs to be increased back to unity. The later is the usual case for depleted uranium blankets. Once at full power, TBR is above unity and tritium accumulates, so that its excess allows operating with TBR below unity towards end of life (Figure 3). This balance is not even as part of tritium is lost by radioactive decay. After power drops, a LIFE engine can continue to function below nominal power if valuable from the economical or waste reduction point of view. In this paper we will limit the attention to systems operating at full power only.

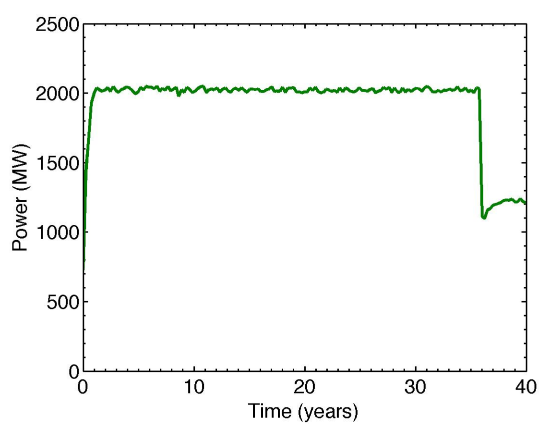

Figure 2. Power as a function of time in a LIFE engine with 80 cm thick blanket, 16 cm thick multiplier, and 20% TRISO packing factor.

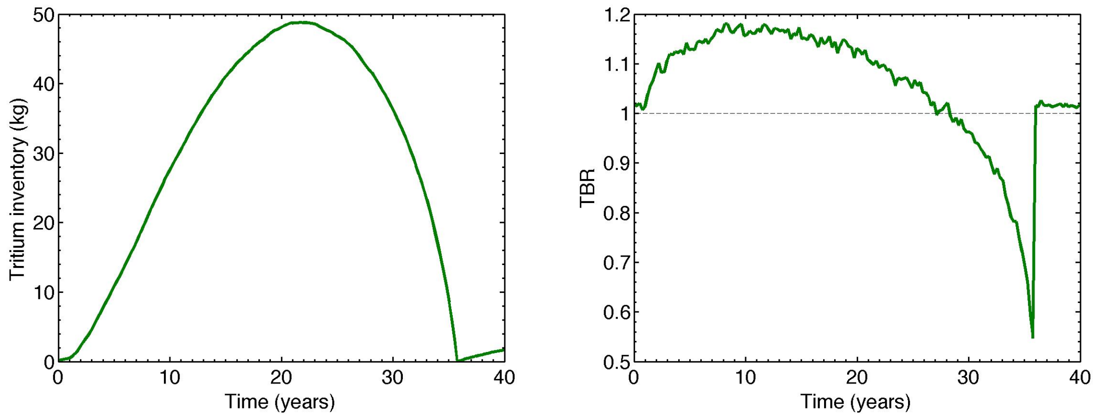

Figure 3. Tritium inventory and Tritium Breeding Ratio (TBR) as a function of time in a LIFE engine with 80 cm thick blanket, 16 cm thick multiplier, and 20% TRISO packing factor.

LIFE was modeled using MCNP5 Version 1.42 [5]. The model includes detailed TRISO and pebbles, disposed according to a simple cubic and a body centered cubic lattice, respectively. Materials and cross-sections (ENDF/B-VII) are assumed at the nominal operating temperature. Scattering kernels apply to graphite, metallic beryllium and iron (ODS). Depletion calculations were performed by MONTEBURNS that couples MCNP with ORIGEN2.2 [6]. A newly developed code, called LIFE Neutronics Code (LNC) [2], controls ^{6}Li enrichment adjusting its level at every depletion step according to TBR and thermal power constraints.

3. OPERATION MODE

A LIFE system can be operated in multiple ways. The reference design [2] assumes that the fuel is loaded in a single-batch and uniformly depleted until discarded. Pebbles are never removed from the system, but are continuously re-circulated in a closed loop to obtain a uniform burnup. In this mode DU can be depleted up to ~85% FIMA, but multiple-batch and continuous refueling can potentially improve the attainable burnup and eliminate the need for the power ramp-up phase, excluding the first load. The following sections will examine and compare these three operation modes.

2.1. Single-batch with continuous mixing

First, we optimized the design of a LIFE engine operated in a single-batch mode with continuous pebbles mixing. The optimal configuration was searched as a function of three design parameters—blanket thickness, TRISO packing factor, and multiplier layer thickness, and the design performance was evaluated by two metrics—attainable burnup and ramp-up time, under the constraints that the system (1) is tritium self-sufficient, and (2) maintains a total thermal power level of 2,000 MW, after the ramp-up phase is completed.
The optimal multiplier thickness was found to be about 16 cm (Table III). As the multiplier becomes thicker more neutrons are produced by (n,2n) reactions on Be, but at the same time the spectrum softens and more neutrons are absorbed in ^{6}Li. Figure 4 shows that for a 16 cm thick multiplier the ratio of neutron produced-to-neutron absorbed in the multiplier is close to one for the entire core lifetime. A thicker multiplier absorbs more neutrons than those produced, a thinner has a more favorable

production-to-destruction ratio, but over all less neutrons are available both to produce tritium and to drive the blanket. The net neutron balance through the optimal multiplier is basically null meaning it serves mainly as a tritium producer rather than a blanket driver.

Table III. Attainable burnup as a function of multiplier thickness in a LIFE engine with 80 cm thick blanket and 20% TRISO packing factor.

Multiplier thickness (cm)	Burnup (FIMA%)
0	– [a]
8	71.55
16	84.53
24	64.77

[a] Nominal power is never achieved

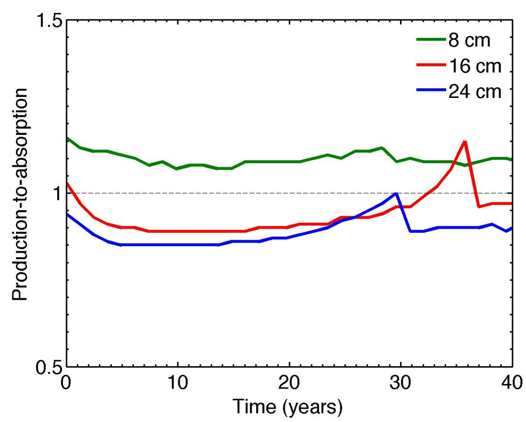

Figure 4. Ratio of neutrons produced-to-absorbed in the multiplier layer as function of burnup and layer's thickness.

Figure 5 and Figure 6 show the attainable burnup as a function of TRISO packing factor and blanket thickness, respectively. The optimal combination features a TRISO packing factor of ~20% and a blanket thickness of ~80 cm. Smaller blankets do not carry enough fuel to maintain longer the prescribed power, larger blankets do not build up enough tritium early in time because the fuel mixing spread fissile material away from the inner part of the blanket. In order to reach 2,000 MW, typically, the system requires a minimum initial load of ~10 t of heavy metal (HM), therefore low packing factor (<10%) or thin blanket (<30 cm) are not feasible. The optimal design features an initial load of ~33 tHM dispersed into 1.4 millions pebbles and the corresponding blanket operates at a power density of 15-20 MW/m^3.
The fission energy production is prevalent in the blanket inner region with a radial power peaking factor of ~8 (Figure 7).

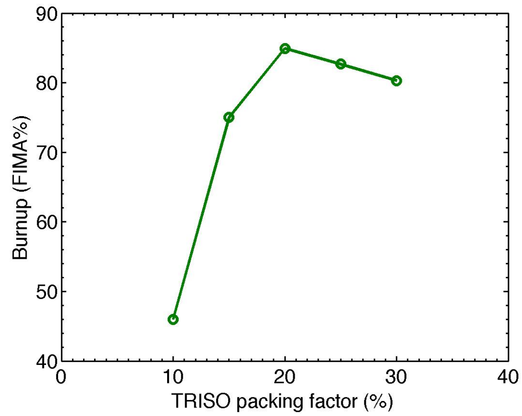

Figure 5. Attainable burnup as a function of TRISO packing factor in a LIFE engine with 80 cm thick blanket and 16 cm thick multiplier.

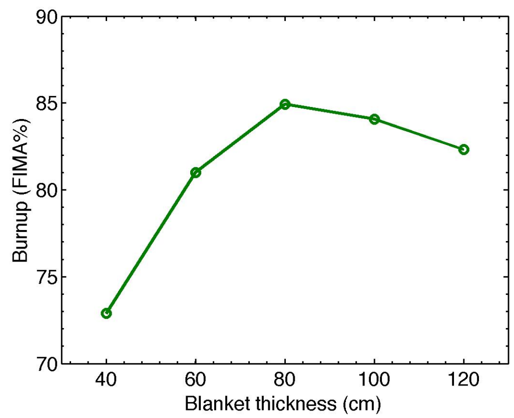

Figure 6. Attainable burnup as a function of blanket thickness in a LIFE engine with 16 cm thick multiplier and 20% TRISO packing factor.

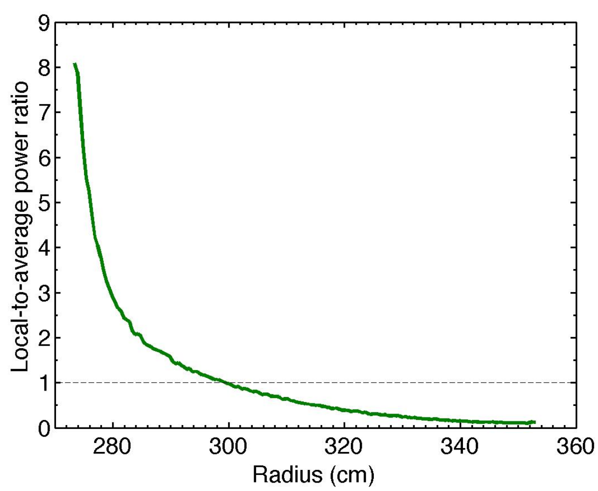

Figure 7. Radial fission power distribution in a LIFE engine with fuel at ~30% FIMA—80 cm thick blanket, 16 cm thick multiplier, and 20% TRISO packing factor.

2.2. Multi-batch with out-in promotion shuffling scheme

In a multi-batch mode the LIFE blanket is subdivided into equal-volume segments and pebbles are continuously re-circulated within the same segment. Once the power drops below nominal level, the inner most segment is discharged, other segments are moved inward, and the outer most is filled with new pebbles. The reference model used in this case is the optimal design described above—16 cm multiplier, 80 cm blanket, 20% packing factor.
Configurations with 3, 5, and 7 segments were analyzed. In this preliminary analysis we assumed no physical separation between segments. The typical pebbles plug-flow motion suggests that no barrier is necessary, but it needs to be verified that the same applies in spherical geometry as in a LIFE system.
It was found that a segmented blanket can be constantly operated at full power and does not require a ramp-up phase, but for the first load (Figure 8). The fuel promotion shuffling can potential be performed without shutdown, but in case this is required a cycle length matching the first-wall lifetime (~5 years) is to be preferred. In multi-batch mode the attainable burnup extends to ~90% (Table IV). The power distribution in a segmented blanket strongly varies through the cycle (Figure 9): at beginning of cycle (BOC) peaks strongly in the inner segment, but progressively moves towards the next segment. The maximum power peaking factor (~11) is at BOC in the inner side of the blanket.

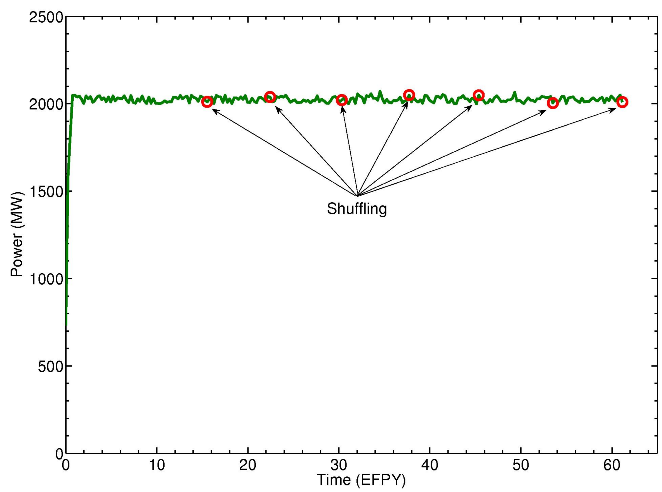

Figure 8. Thermal power as a function of time for a five-segments LIFE blanket.

Table IV. Attainable burnup and cycle length for multi-segments LIFE blankets.

Segments	Burnup (%FIMA)	Cycle length (EFPY)	Ramp-up time (days)
1	84.9	36.0	294
3	87.6	12.6	202
5	89.3	7.6	242
7	90.1	4.9	241

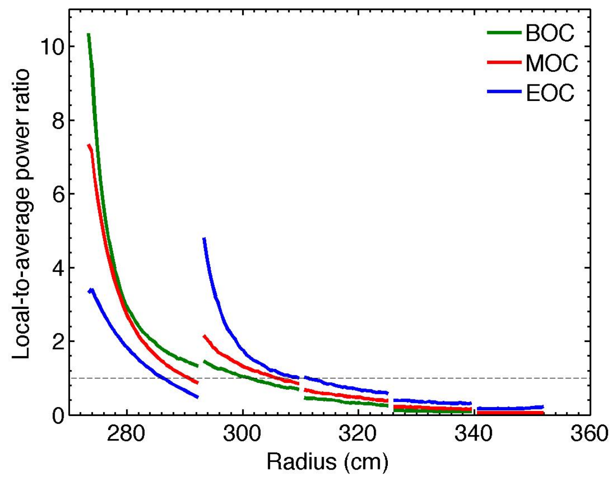

Figure 9. Fission power production as a function of radius in a five-segments blanket at the beginning, middle, and end of a depletion cycle.

2.3. Continuous refueling

In continuous refueling mode the LIFE engine is envisioned to operate similarly to a pebble bed reactor: each pebble is continuously circulated through the core until its burnup reaches a given limit; at this point it is discarded and replaced with a new pebble. Eventually the blanket reaches an equilibrium status. To model this process we applied a similar methodology as described in Reference 7. In this preliminary analysis a single spectral zone was assumed for the blanket and the equilibrium fuel composition was searched with the constraints of tritium self-sufficiency—TBR ~1. Table V shows the total power at equilibrium as a function of pebbles residence time in the blanket. To achieve a power level of 2,000 MW the residence time is limited to 34.5 years, corresponding to ~82% FIMA. Differently from critical reactors, the continuous refueling mode penalizes and not improves burnup, despite the fact that operating at TBR always one prevents tritium loss due to decay. In the single-batch mode, indeed, towards end of life, despite being deeply burnt, pebbles can still stay in the blanket because the excess of tritium produced earlier in time allows to function with TBR below one. Figure 10 shows the power produced in a pebble as a function of its burnup in continuous refueling versus the constant power level in single-batch mode. The continuous refueling mode besides the radial power peaking factor introduce a life power peaking factor that is determined by the power distribution among pebbles with different burnup level and in first order independent of pebbles location. This extra power peaking factor is ~1.7.

Table V. Power level at equilibrium and corresponding attainable burnup as a function of pebbles residence time in a LIFE engine with 80 cm thick blanket and 20% TRISO packing factor.

Residence time (years)	Power (MW)	Burnup (FIMA%)
24.7	2219	67.5
34.5	2027	82.3
39.5	1927	87.0
49.3	1758	94.1

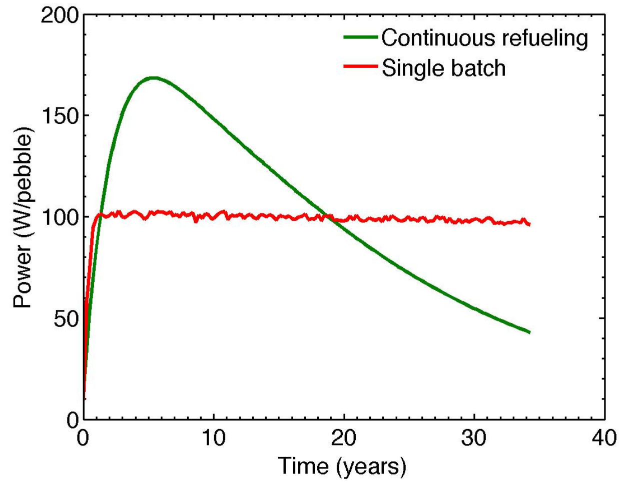

Figure 10. Average fission power per pebble as a function of depletion time in continuous refueling and in single-batch mode.

4. CONCLUSIONS

The Laser Inertial Fusion-based Energy (LIFE) system is an engine for electricity generation from fusion. LIFE can produce energy from fusion only, but also has the option to couple the (D,T) source with a subcritical fission blanket. In this paper we analyzed a fusion-fission LIFE system fuelled with depleted uranium (DU) in the form of TRISO particles dispersed in graphite pebbles and cooled with flibe ($LiF-BeF_2$). The system configuration is similar to NIF with spherical shell layers built around the source and perforated with 92 ports for laser beams access. A beryllium multiplier precedes the fission blanket to multiply the source-neutrons by means of (n,2n) reactions.

Under the constraints to (1) be tritium self-sufficient and (2) operate at a nominal thermal power of 2,000 MW—including 500 MW from fusion, a LIFE system can burn depleted uranium up to 85% FIMA when operated in a single-batch mode with continuous pebbles mixing. The optimal design—defined as the one that maximize burnup, features a 16 cm thick multiplier, 80 thick blanket and 20% TRISO packing factor, corresponding to an initial load of ~33tHM. It takes ~10 months to reach full power and ~36 years to reach the final maximum burnup.

If the LIFE blanket is operated in a multi-batch mode with out-in promotion shuffling scheme, burnup approaches ~90% FIMA and the fuel cycle can be tuned to match first-wall lifetime in order to reduce shutdown periods. Furthermore, with exclusion of the first load, a segmented blanket eliminates the need for a fissile breeding phase at power below nominal.

A continuous refueling operation, in which pebbles are individually replaced once they reach a pre-established burnup limit, does not improve burnup.

The LIFE blanket is characterized by a power distribution that is strongly peaked at the inner boundary. The power peaking factor is as high as 8 in single-batch mode and slightly larger for a segmented blanket (~11). The continuous refueling mode introduces an extra peaking factor (~1.7) due to the burnup heterogeneity among pebbles.

If economically valuable or if necessary for waste reduction purposes, a DU LIFE engine attains burnup beyond 90% FIMA operating below nominal power after the plateau phase.

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