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FUSION-FISSION BLANKET OPTIONS FOR THE LIFE ENGINE

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The Laser Inertial Fusion Energy (LIFE) concept is being developed to operate as either a pure fusion or hybrid fusion-fission system. The hybrid version is designed to generate power and burn both fertile and fissile nuclear fuel. The fuel blanket is composed of TRISO-based fuel cooled by a molten salt. Low-yield (~25-40 MJ) targets and a repetition rate of ~10-15 Hz produce a 300-500 MW fusion source. When this fusion power is coupled to a compact (2-4 m diameter) target chamber, a 14 MeV neutron flux of ~2 × 10^{14} n/cm^2-s drives fissile production and destruction in the fuel blanket providing an additional energy gain of 4-8, depending on the fuel and design objective.

We employ a methodology using ^{6}Li as a neutron absorber to generate self-sustaining tritium production for fusion and to maintain constant power over the lifetime of the engine. In a single pass, fertile LIFE blankets achieve uranium and thorium utilization beyond 80% without chemical reprocessing or isotopic enrichment. Fissile blankets destroy more than 90% of the initial load of weapons grade plutonium or highly enriched uranium.

I. INTRODUCTION

Laser Inertial Fusion Energy (LIFE) is a new nuclear energy system being developed with two principal pathways for commercial exploitation.[1] One is based on a pure fusion system for base load electricity generation. The other couples the fusion system with a fission blanket that besides base load electricity generation enables a variety of fuel cycle-related missions[2]—destruction of weapons-grade nuclear material, transmutation of spent fuel, fissile fuel production, etc. Fusion-fission hybrid concepts have been considered many times in the past, but have never been developed to the point of demonstration.[3,4] Completion of the National Ignition Facility (NIF) and a recently successful demonstration of full system capability has brought renewed interest in Inertial Confinement Fusion (ICF) as a potential source of neutrons to drive a fission blanket.[5] The ICF fusion yield resembles a point neutron source and allows for a compact chamber. Expanding on NIF experience, a conceptual design of a LIFE hybrid plant has been developed and is shown in Fig. 1 with 576 lasers in top and bottom carousels, the balance of plant, and the fusion-fission chamber. This LIFE plant is envisioned to maintain common laser and building geometry and target injection/tracking systems with either pure fusion or hybrid fusion-fission blanket options, but the hybrid plants will require a lower fusion power (~10-15 Hz, 300-500 MW.)

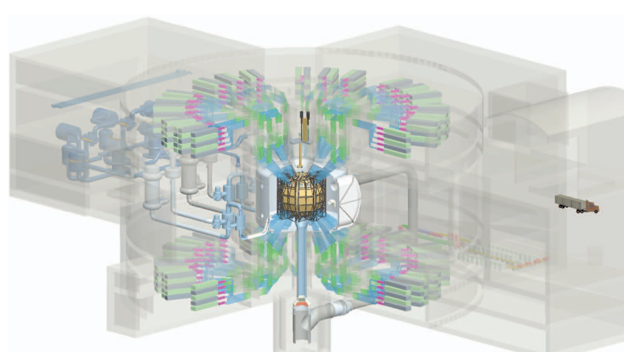

Fig. 1. Conceptual design of LIFE hybrid fusion-fission plant shows lasers, chamber and balance of plant.

This manuscript provides an overview of recent accomplishments in the design of a LIFE hybrid system. In particular it focuses on a new approach to blanket design based on modularity, high availability, and enhanced safety features. The description of this novel blanket design is presented in Section II. Section III reviews the nuclear design aspects describing the modeling approach and possible missions for fusion-fission hybrids.

II. HYBRID BLANKET DESIGNS

The blanket of a LIFE hybrid plant is composed of multiple concentric layers. In particular, a beryllium layer for neutron multiplication and a fission fuel layer for energy amplification. The fuel is in the form of TRISO particles carried in a graphite pebbles. All layers are cooled by a liquid salt, FLiBe (2LiF-BeF_2), that flows from the inner layer towards the outer layer. The LIFE hybrid design was originally proposed as a spherically symmetric system using oxide-dispersion strengthened (ODS) ferritic steel for the 1st wall and all blanket components.[6] Recent work has focused on the operability and maintainability of the power plant and this has led to the adoption of a modular design for the 1st wall and blanket. Such a design simplifies the process for replacing life-limited components, and thus increases overall plant availability. In particular, separating the 1st wall and blanket should facilitate replacement of neutron damaged 1st wall components without replacing the entire fission blanket structure.

Modularity also aids the removal of passive decay heat in off-normal events, and allows the blanket to be manufactured remotely and then assembled on site. Finally, it allows for the option to burn different fuels for a variety of missions in a single LIFE plant.

A conceptual design of a blanket module and assembled chamber is illustrated in Fig. 2.

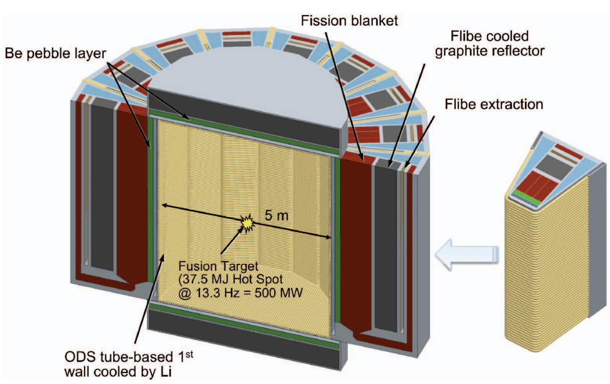

Fig. 2. Cross-sectional view of the design of the LIFE hybrid blanket, and a 1/16-sector module (ports for laser entry and the supporting structure are not shown for clarity)

The hybrid blanket modules form a cylindrical chamber surrounding the fusion target. Each module will have main coolant inlet/outlet and fuel insertion/removal connections at the top of the module. In the event of a main coolant line break, this configuration will keep the fuel pebbles wet and will aid in passive decay heat removal. Similarly, FLiBe-cooled nuclear graphite structures, connected to backup heat exchangers, surround the fuel region. Although only preliminary analysis has been performed, it appears possible to passively remove decay heat from each module in a manner that prevents the fuel and ODS structural supports from exceeding maximum temperature limits of 1600°C and 700°C, respectively. Fuel pebbles are isolated from the ODS by high temperature materials like nuclear graphite and SiC. Radiation damage, including neutron induced swelling, will require periodic replacement of these structures, currently estimated at every 1-2 years.

The hybrid blanket design currently relies on the fuel pebbles being neutrally buoyant in the FLiBe coolant. This allows for pebbles to be inserted and removed from the top of the blanket module. The flow loop is illustrated in Fig. 3 with radial coolant flowing off normal to the fuel flow. To generate the radial flow, FLiBe is injected to a plenum immediately behind the 1st wall tubes. Structural walls are perforated to support radial flow outwards through the blanket layers. Behind the FLiBe injection plenum is a 12cm thick beryllium blanket. This blanket is currently pebble-based, but solid Be or BeTi structures are also under investigation. Immediately behind the Be layer, but separated by a 1cm perforated graphite wall is the fission fuel region. As shown in Fig. 3, the FLiBe flows outward with an upward direction through the beds to a graphite reflector region, which is also pebble-based. The coolant then leaves through the top of the module via an exit plenum behind the graphite reflector. Although the recirculation of buoyant fuel pebbles has been demonstrated experimentally, pebble circulation for this system needs to be proven.[7,8] Similarly, flow conditions across the Be layer, fuel bed and graphite reflector for spherical geometry with similar radial dimensions have been shown to provide adequate cooling.[6] These results are currently being verified for the modular design.

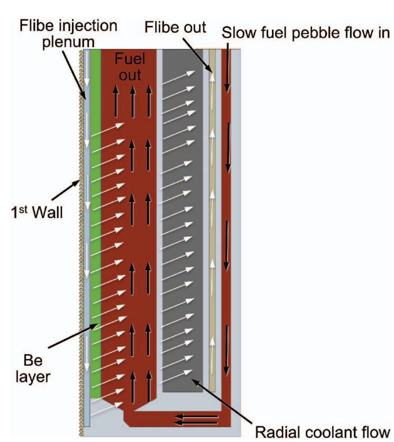

Fig. 3. Conceptual design of LIFE hybrid blanket module (1/16-sector) and assembled chamber.

The nuclear fuel for LIFE hybrid blankets is proposed to be a TRISO-based fuel kernel surrounded by additional porous and structural carbon-based layers contained in slow moving graphite pebbles. Similarly, the Be layer is composed of 1 cm diameter pebbles that will be periodically heat-treated and re-fabricated to counter neutron induced swelling and tritium holdup. The graphite reflector layer is 60% graphite pebbles and 40% FLiBe coolant, but solid graphite structures cooled by FLiBe channels are also being explored. A pebble-based reflector has the advantage of easy removal and replacement of the reflector as it is damaged and swells from neutron irradiation. Typical design parameters for LIFE hybrid blankets are given in Table 1.

TABLE I. Key LIFE design parameters

Item	Value
Chamber 1st wall radius (m)	2.5
Chamber Height (m)	6
1st wall coolant	Li
Fusion yield (MWth)	500
Fuel Form	TRISO
Primary coolant	$2LiF+BeF_2$
TRISO packing fraction (%)	20
Pebble packing fraction (%)	60
Be multiplier thickness (cm)	12
Graphite reflector thickness (cm)	75

Multiple fuel options are under investigation for LIFE hybrid systems: depleted uranium (DU), thorium weapon grade material, spent fuel, etc. In the case of a DU system, the TRISO fuel kernels are composed of uranium oxycarbide (UCO) with no enrichment. The initial heavy metal mass of 20 MT is loaded into the blanket giving approximately 1.25 MT per module in an 82 cm thick fission blanket. Fuel pebbles are assumed to pack at 60% with the remaining volume occupied by the primary coolant, FLiBe. Thorium designs to date employ similar blankets and are not expected to vary greatly from DU blanket designs, with the exception of a larger pebble fuel loading dictated by an optimal spectrum somewhat harder than in DU blankets. In the case of weapon-grade plutonium (wgPu), the fuel kernel takes the form of plutonium oxycarbide (PuOC). A 127 cm thick blanket is loaded with 6.5 MT of wgPu. Prior to insertion into the fission blanket, the wgPu fuel is down blended with zirconium carbide (ZrC) such that a fuel kernel contains 80% ZrC and 20% wgPu by volume. A burnable absorber (boron) is added to reduce reactivity at startup. This absorber is integral to the fuel pebble and guarantees that the system remains subcritical for the entire cycle with no need for active control systems.

III. NUCLEAR DESIGN

III.A Methodology

Neutronics and burnup simulations employ a control scheme that uses ^{6}Li enrichment in the coolant to control thermal power and tritium breeding ratio (TBR).[9] The requirement to operate at constant thermal power is such that early in the cycle excess tritium is produced (TBR > 1) and stored for later use when TBR falls below 1. The cycle ends when the full tritium inventory is exhausted or the system cannot sustain the prescribed power level.

For our transport calculations we utilize the three-dimensional Monte Carlo radiation transport code MCNP5 Version 1.42.[10] We also use a modified version of Monteburns 2.0, which in turn utilizes ORIGEN2.2 to perform isotopic depletion.[11,12] These models are coupled and controlled via custom software developed at LLNL to adjust the ^{6}Li enrichment in the coolants and track TBR, thermal power and various reaction rates of interest. The transport calculations use ENDF/B-VII.0 nuclear data Doppler broadened to 600°C or 900°C according to the material temperature and scattering kernels are added when applicable.[13]

Typical calculations begin with an initial externally sourced (1.77×10^{20} n/s—500 MW fusion) transport calculation to determine the operating thermal power and TBR. Next, the ^{6}Li concentration in the coolant that satisfies the desired operating conditions is iteratively searched for. TBR is exchanged for blanket gain by online ^{6}Li enrichment of the coolant where neutrons produce tritium instead of inducing fission. Following this calculation, the materials are depleted. Finally, the updated material definitions are propagated to the original input deck and the simulation proceeds to the next time step as is illustrated in Fig 4.

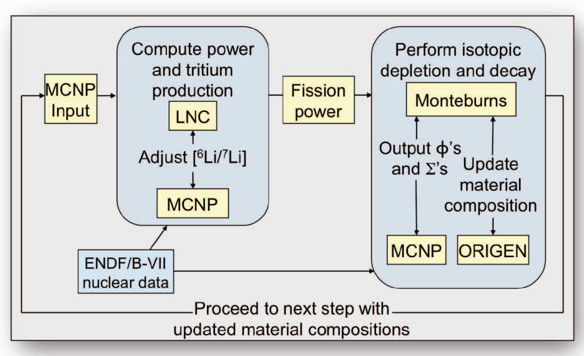

Fig. 4. Flow diagram of neutronics calculations for time dependent simulation of LIFE hybrid blankets.

III.B Fertile Fuel Blankets

Fertile fuels like depleted uranium (DU) or thorium (Th) can be used in a LIFE hybrid blanket to generate electricity while maximizing the natural resource utilization. This energy production mode does not require the fuel to be initially enriched or to be reprocessed to achieve high burnup, assuming the fuel can be designed to survive high irradiation limits (>200 dpa in carbon at 99% FIMA). In a driven system, fertile fuels like ^{238}U and ^{232}Th capture excess fusion neutrons to produce fissile material in a blanket via the reactions

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

and

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow[21.8\,\mathrm{min}]{\beta-} {}^{233}Pa \xrightarrow[27\,days]{\beta-} {}^{233}U. \tag{2}$$

The fissile material produced in these reactions is fissioned immediately, releasing energy with an effective gain (total thermal power to fusion power ratio) of 4-8. The process continues until the fertile fuel is fully consumed, or the output thermal power falls below desired limits and the fuel is discharged to waste. The system is designed to tailor the spectrum to maximize the conversion ratio early in time and maximize fission later .

DU blankets require an initial ramp up period to reach full power of approximately 90-120 days as fusion neutrons are captured to produce fissile ^{239}Pu for fission. Full power operation (keff ~ 0.65) is then maintained to a fuel burnup of 75%-85% Fission of Initial Metal Atoms (FIMA), depending on the operational blanket gain, illustrated in Fig. 5. Two thermal power curves are shown for blanket gains of 3 and 4. Blanket gain can be adjusted based on desired power output, discharge burnup, tritium supply, and economics considerations.

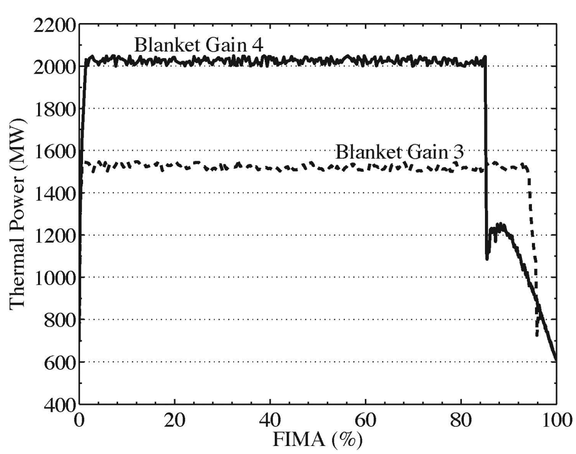

Fig. 5. DU fission blanket gain can be maintained to differing levels for decades.

The steep drop in power for both curves is due to exhaustion of the tritium inventory at which point ^{6}Li enrichment is restored to ~0.15% to increase the TBR above 1.02 and return to self-sufficient operation. At this point, the fission fuel could be discharged to waste, shuffled with fresh fuel to regain power or completely burned down, albeit at a continuously decreasing thermal power. The different operational phases are seen in the variation of the blanket neutron spectrum shown in Fig 6. The spectrum initially, besides the spike at 14 MeV, contains a large thermal peak, but as fissile fuel is produced in the blanket, the spectrum hardens. After consuming much of the fissile fuel, the spectrum is again softened at end of life (EOL). For the fertile fuels to be burned in excess of 99% FIMA, decades long operation is required when using a 20 MT heavy metal load. These long time scales lead to tritium decay, which impacts overall fusion fuel cycle dynamics. Efforts to minimize loss to decay can be made by externally supplying tritium from a plant dedicated to supporting hybrid plants, or by consuming smaller fuel batches at each time.

The behavior of thorium-fuelled systems resembles that described for DU systems.

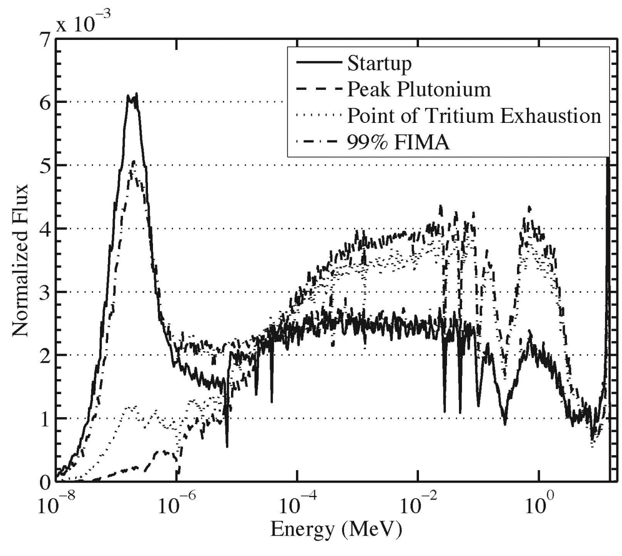

Fig. 6. The neutron spectrum in a representative LIFE hybrid blanket shows how the spectrum changes from startup to end of life.

III.C. Fissile fuel blankets

Destruction of wgPu is currently being performed internationally using a mixed-oxide (MOX) process whereby the highly enriched material is down blended with uranium oxide and fabricated into reactor fuel.[14] In the United States, a MOX fabrication facility is under construction at the Department of Energy's Savannah River site as a means to dispose of 34 metric tons (MT) of surplus wgPu.[15] The recycled fuel will be consumed in civilian nuclear reactors. Although in a less weapons-usable form, some of the plutonium will remain in the fuel after burning. Outstanding issues related to verification of in-process inventory also exist. Alternatively, a LIFE hybrid blanket could employ a single fuel fabrication step and continued irradiation until full burnup of the Pu or HEU. Since it is a subcritical, externally driven system, the excess Pu can in principal be destroyed without any reprocessing. Furthermore, it has been shown that the fuel can be irradiated to the extent that it becomes unusable for weapons.[16]

Fissile fuel can be burned in LIFE hybrid blankets with additional considerations to maintain sub-critical operation. The current blanket design uses 6.5 MT of heavy metal to generate the thermal power curve shown in Fig. 7. Some key differences exist between fertile and fissile LIFE blankets. First, fissile fuels do not require a power ramp up period to reach full power as the maximum fissile material content exists in the blanket at startup. Next, a much higher gain is possible (8-10 or higher) based on reactivity and thermal constraints. As shown, a blanket gain of 8 (keff~0.85) allows for destruction of the wgPu and minor actinides at a rate of ~1.2 MT per effective full power year. Lastly, the fuel loading and incineration rate can be designed to eliminate tritium decay as an issue over the course of the burnup. In the case of a wgPu system, tritium inventory is not exhausted until after full power operation is no longer sustainable (>86% FIMA for the described blanket design). This coupled with the fact that the entire burn of a wgPu load can be reduced to 11-12 years, implies self-sufficient tritium production in a fissile blanket can be made more readily than in fertile blankets.

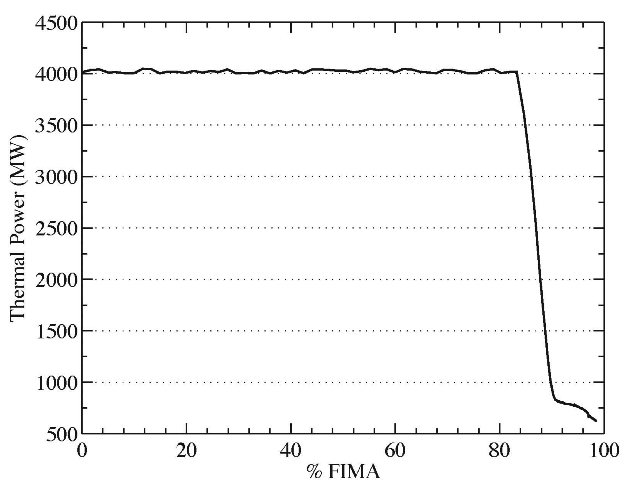

Fig. 7. WgPu thermal power as function of burnup shows continuous blanket gain of 8 until ~85% FIMA.

III.D. Fuel Production for Critical Reactors

Although DU or Th can be burned directly in LIFE hybrid blankets to produce energy, it is also possible to produce fissile fuel for use in critical reactors. Under this operational mode, the blanket neutron spectrum in the fuel is optimized for maximum neutron capture in the target fertile material while minimizing fission. This option could be viewed as an alternative to direct fuel enrichment for reactor fuel and is being explored further. For instance, ^{232}Th fuel could be used to produce fissile ^{233}U thereby removing the need for enrichment from the fuel cycle. It may also be possible to irradiate the fuel after removal from a fission reactor to "recharge" the fuel for another cycle in a reactor. This will depend largely on the fission product buildup, as well as impact on reactor performance, and remains as future work.

III.E. Alternative Fuel Forms

The current fuel design employs TRISO particles encapsulated in graphite spheres that flow through the system. However, additional fuel forms including solid hollow core and inert matrix fuels have been suggested as fuel designs that could potentially withstand ultra high burnup (99.9% FIMA) and associated high damage rates (~200-300 dpa for fertile fuels) and are thus being explored.[17,18] Also, given the cylindrical geometry of the hybrid blanket module, we are exploring the use of prismatic blanket designs as well as direct utilization of light water reactor Spent Nuclear Fuel (SNF) rods. Re-cladded fuel rods could be burned or recharged without further chemical reprocessing. This is especially attractive as 90%-95% of original fuel energy content remains in the SNF and represents a presently untapped resource of nuclear fuel.

IV. CONCLUSIONS

LIFE hybrid blankets continue to be explored and developed as a parallel option to pure fusion blankets. In order to increase plant availability and enhance safety a new blanket design was developed featuring cylindrical geometry rather than spherical and high modularity. A closed blanket configuration with fuel insertion and removal located above the active blanket level allows the fuel always wet and enables passive decay heat removal.

Hybrid blankets not only produce energy to generate electricity, but can also be used to accomplish multiple missions related to fission power: (1) incineration of excess nuclear weapons material; (2) maximization of resource utilization exploiting depleted uranium energy content; (3) enabling a thorium fuel cycle either by fission in situ or by production of fissile fuel for critical reactor; (4) incineration of existing spent fuel legacy. LIFE hybrid blankets can fulfill these missions in a unique manner where fuel enrichment and reprocessing is not used. Similarly, hybrid blanket designs can be designed to be tritium self-sufficient such that an external source of tritium is not needed. The strong fusion source provides enough excess neutrons to generate sufficient tritium while burning the fission fuel in a subcritical manner. The deeply subcritical blanket design avoids prompt criticality concerns. This coupled with a modular design with passive safety features alleviates safety concerns.

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