Economic Evaluation of Electrical Power Generation Using Laser Inertial Fusion Energy (LIFE)

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Background and Motivation

With the completion of the National Ignition Facility (NIF) and upcoming ignition experiments, there is renewed interest in laser fusion-fission hybrids and pure fusion systems for base load power generation. An advantage of a laser fusion based system is that it would produce copious neutrons (~ 1.8×10^{20}/s for a 500 MW fusion source). This opens the door to hybrid systems with once through, high burn-up, closed fuel cycles.

With abundant fusion neutrons, only modest fission gain (5 to 10) is needed for power production. Depleted uranium can be used as the fission fuel, effectively eliminating the need for uranium mining and enrichment. With high burn up, a hybrid would generate only 5% to 10% the volume of high-level nuclear waste per kilowatt hour that a once through light water reactor (LWR) does. Reprocessing is no longer needed to close the fuel cycle as the spent fuel can, after interim cooling, go directly to geologic disposal.

While the depleted uranium fuel cycle offers advantages of simplicity and proliferation avoidance, it has the most challenging fuel lifetime requirements. Fissile fuel such as plutonium, or plutonium and minor actinides separated from spent nuclear fuel, would have roughly twice the fission gain and incur only about 25% of the radiation damage to reach the same burn up level as depleted uranium. These missions are interesting in their own right and also provide an opportunity for early market entry of laser fusion based energy sources.

A third fuel cycle option is to burn spent fuel directly, without prior separation of the plutonium and minor actinides. The neutronic and economic performance of this fuel cycle is very similar to the depleted uranium system. The primary difference is the need to fabricate new LIFE fuel from spent LWR fuel. The advantage of this fuel cycle is that it would burn the residual actinides in spent nuclear fuel, greatly reducing long term radio-toxicity and heat load, while avoiding the need to chemically separate spent LWR fuel.

Summary of Evaluation

This evaluation is based on the laser inertial fusion energy (LIFE) concept being developed at Lawrence Livermore National Laboratory (Moses, 2009). Previous systems studies of the LIFE concept can be found in the literature (Meier, 2009), (Meier, 2009). This study assumes a solid-fuel, once through fuel cycle. Fission gain for the depleted uranium fuel is 5 and fusion gain is 28. The corresponding values for fissile fuel are 10 and 16. Recirculating power fraction is in the range of 17% for both designs. The heat transfer system uses molten salt coolants and a Helium-Brayton power cycle. Thermal efficiency is calculated at 46% (650C max coolant temperature).

For purposes of comparison, we also evaluate a pure fusion version of LIFE. The pure fusion system has a fusion gain of 59 and an absorber blanket gain of 1.35; due to exothermic reactions within the blanket. We assume that, without nuclear fuel, the pure fusion system can operate at a maximum coolant temperature 50C higher than the hybrid designs. This yields a thermal efficiency of ~50%.

Costs for the balance of plant and power block are scaled from fission reactor design and economic studies in the literature (General Electric, 1995), (Delene, 1988), (MIT, 2003). Laser system costs are scaled from NIF project cost data.

- For the power block and balance of plant, the model uses the cost account structure and costs taken from the General Electric report. To account for recent escalation in projected nuclear construction costs, we escalate the total capital cost in the General Electric study to that in the recent MIT update on the future of nuclear power[1] (MIT, 2009).
- The General Electric report pertains to a 670 MWe reactor. We use the cost account scaling exponents provided in the Delene report to scale these costs to the LIFE Plant operating point.
- The scaled costs are then assigned to the functionally equivalent cost centers in the LIFE Plant. For some cost centers, such as electrical equipment, this approach is straightforward. For others, such as the equivalence between reactor vessel and internals and the LIFE target chamber and vacuum vessel, the analogy is more tenuous. To address this, we directly calculate the cost of the target chamber and vacuum vessel. These are ranging level estimates done by calculating the mass of these components and applying a fabrication cost multiplier. In addition, we also add a cost center to account for tritium storage. The fidelity of these estimates will improve as the design of the system matures.
- Laser system costs are scaled from National Ignition Facility historical data and are adjusted to account for diode laser pumping rather than flash-lamps, changes to gain media geometry to permit gas cooling and smaller facility size enabled by the compact laser system architecture proposed for LIFE. We also assume commercial availability of laser gain media with ~1ms storage lifetime (*eg.* Yb:S-FAP). Costs are for an N'th-of-a-Kind laser system where N=10. Credit is taken for cost reductions due to manufacturing learning associated with the high production volumes necessary to field a fleet of power plants[2].
- Fixed operations and maintenance (O&M) costs are assumed to be 1.4% of overnight capital cost/year. Variable O&M is assumed to be $0.42 per megawatt hour. Incremental

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[1] The capital cost of the reference nuclear plant used in the LIFE cost scaling model is set to $4000/kWe for a 1000 MWe plant size.

[2] Crawford Learning Model

capital cost is 1% of overnight capital cost/year. These values are the same as those assumed in the 2009 MIT report for LWR's.

- The depleted uranium fission fuel is assumed to cost $1000/kg of heavy metal[3]. Fissile fuel is assumed to cost $10,000/kg to account for spent LWR fuel separation operations and more complex handling and fabrication processes. Spent fuel disposal for the LIFE Plant is assumed to be 10% of the LWR cost to account for greatly reduced waste volume.
- Fusion fuel costs are estimated for production quantities of an indirect-drive, CVD diamond-cryogenic capsule with a lead hohlraum ($0.25/target) (Miles, 2009). Fusion system repetition rate is 10 Hz.
- For the pure fusion system, we assume that the cost of power block support equipment is 25% less than for the hybrid system and that target chamber cost is 50% less. This is to account for the fact that the pure fusion system doesn't have fission fuel and would have reduced complexity in these two areas. However, because the pure fusion target chamber is larger than for the hybrid, net target chamber cost is actually higher for pure fusion, even though per mass cost is less.
- COE values for LWR's, coal and natural gas are derived using the financial methodology documented in the 2009 MIT report. We deviate from the MIT analysis in several areas:
  - We use the same weighted cost of capital for all of the technologies (7.8%). The MIT report used a higher cost of capital for LWR's compared to coal and gas. While this may be valid in the current environment, we are projecting costs for construction that would occur several decades into the future. It is unknown how the relative financial risk of different technologies will be perceived at that time.
  - We do not escalate the "constant dollar" cost of fuel; again we thought it made little sense to assume an escalation rate when we are projecting so far into the future.
  - We assume that all of the plants in the study have a 72 year life, the same as the LIFE depleted uranium burner. While this may be artificial for some of the other technologies, such as natural gas, not equating plant lifetimes would bias the comparison against those technologies.
- Differential costs for carbon capture and sequestration are LLNL-estimated values (Simon, 2009).
- All values pertain to a 1000 MWe plant with assumed availability of 85%.

The results (Figure 1) show that cost of electricity for the two LIFE hybrid systems is in the range calculated for coal, gas and light water reactors; the differences are well within the uncertainties of the evaluation. The fissile fuel burner has about the same COE as the DU burner; higher fission gain in this system is partially offset by the higher cost of the fuel form. However, the fissile fuel burner has less demanding fuel lifetime and fusion gain requirements. This could reduce time-to-market assuming that the needed infrastructure to manufacture the fuel is available when needed. Although not shown, COE for a system that burns spent LWR fuel, but

[3] Fission fuel burn-up is assumed 99%.

without prior separation of the plutonium and minor actinides, is within a few percent of the COE for the DU burner.

The pure fusion system has a cost of electricity ~ 4% higher than the depleted uranium burner. Given the uncertainties, there is no reason at this point to favor hybrids over pure fusion based on economics alone. Both systems need fully functional fusion drivers. However, the fusion yield for the pure fusion case is roughly four times that for depleted uranium design and nine times that for the spent fuel burner. NIF testing will ultimately answer the question about how easily, or not, high fusion yields are attained. In the interim, both variants of the LIFE concept are plausible for early deployment. It is arguable that, without the need for fission fuel, the pure fusion system would have a shorter time-to-market than a hybrid.

A surprising result from this study is that the COE for the LIFE systems is only about 10% higher than for LWR's; surprising because the hybrid has many of the same costs as an LWR, but also has a fusion driver. The reason for the equivalence is that the higher thermal efficiency for LIFE, combined with somewhat lower capital costs for the LIFE target chamber and containment building as compared to an LWR reactor vessel and internals, offsets the additional cost of the driver and recirculating power load. To see the effect of thermal efficiency, we have included a bar that shows the impact of artificially raising the thermal efficiency of an LWR to 46%. As expected, the LWR COE is then significantly less than that of the hybrids.

When we compare LIFE economics to LWR's, we are comparing technologies of vastly different maturity levels. Clearly the uncertainties in the LIFE estimates are much larger than for LWR's. The other side of technical maturity caveat is that LIFE has technical headroom for cost reduction. For example, if the development of an advanced target based on fast ignition proves out, the estimated cost of electricity for the pure fusion variant of LIFE would be essentially equal to that for LWR's.

The LIFE systems as well as LWR's have an estimated COE well below that for coal and gas with carbon capture and sequestration. Of course, the same comment about technical headroom in the LIFE concept also applies to carbon capture and sequestration.

Figure 2 is the distribution of capital costs across the major cost centers (total capital cost $4B for the fissile fuel burner). Most of the cost is associated with the fusion/fission engine and balance of plant. The laser driver accounts for only about 20% of total capital. Special materials costs are dominated by the cost of the molten salts.

Figure 3 shows the sensitivity of COE to +/-50% variations in the major cost centers. Not surprisingly, COE was most sensitive to the variations in power block and balance of plant cost; these are the two largest cost centers. Although sensitivity to fuel cost is relatively low, volume production of fusion targets has yet to be demonstrated. Sensitivity of COE to laser system cost variations is relatively low. This is consistent with the earlier observation that the laser driver only accounts for about 20% of plant capital cost.

Conclusions

We have completed a concept level evaluation of the economic feasibility of using LIFE for base-load power generation. While uncertainties are large, the study shows that economically competitive base load generation is plausible for both fusion-fission and pure fusion variants of

LIFE. Results from NIF testing and an evaluation of time-to-market will ultimately determine the most favorable commercialization pathway.

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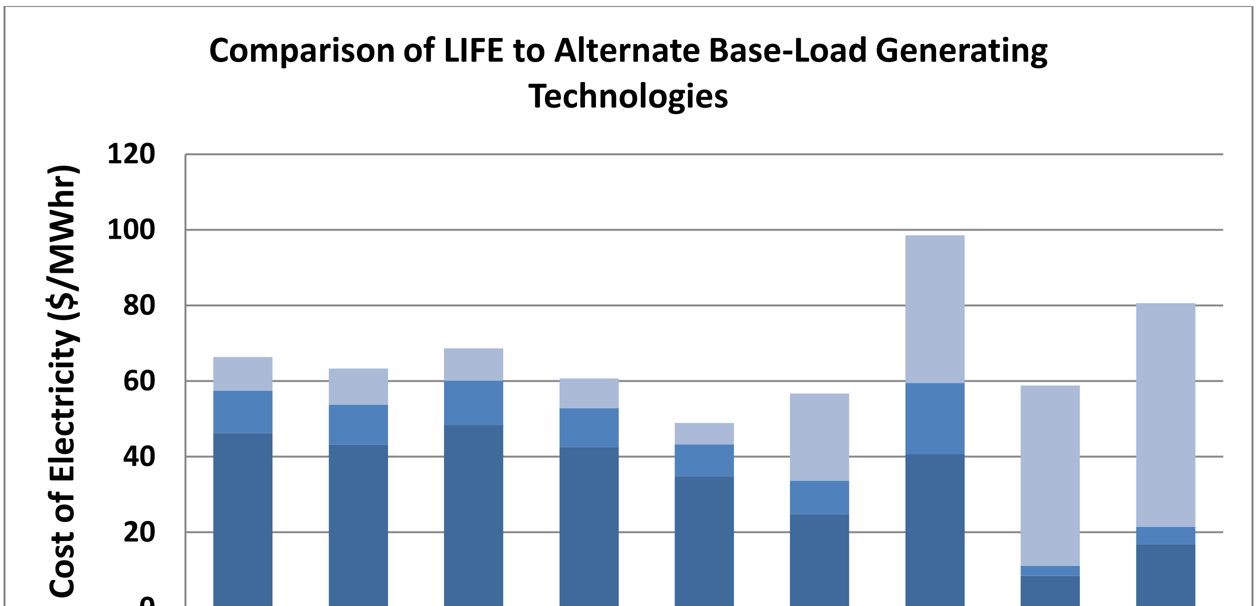

	LIFE-DU	LIFE-Spent Fuel	LIFE-Pure Fusion	LWR	LWR (46% eff)	Coal	Coal w/CCS	Gas	Gas w/CCS
Fuel	8.88	9.55	8.55	7.9	5.7	23.06	39.01	47.6	59.08
O&M	11.26	10.55	11.72	10.2	8.4	8.85	18.85	2.68	4.66
Capital	46.23	43.17	48.38	42.6	34.8	24.78	40.65	8.5	16.83

Figure 1: COE Comparison: All plants are 1000 MWe. Cost of coal is $2.60/MMBTU, cost of natural gas is $7.00/MMBTU; the same values as used in the 2009 MIT report.

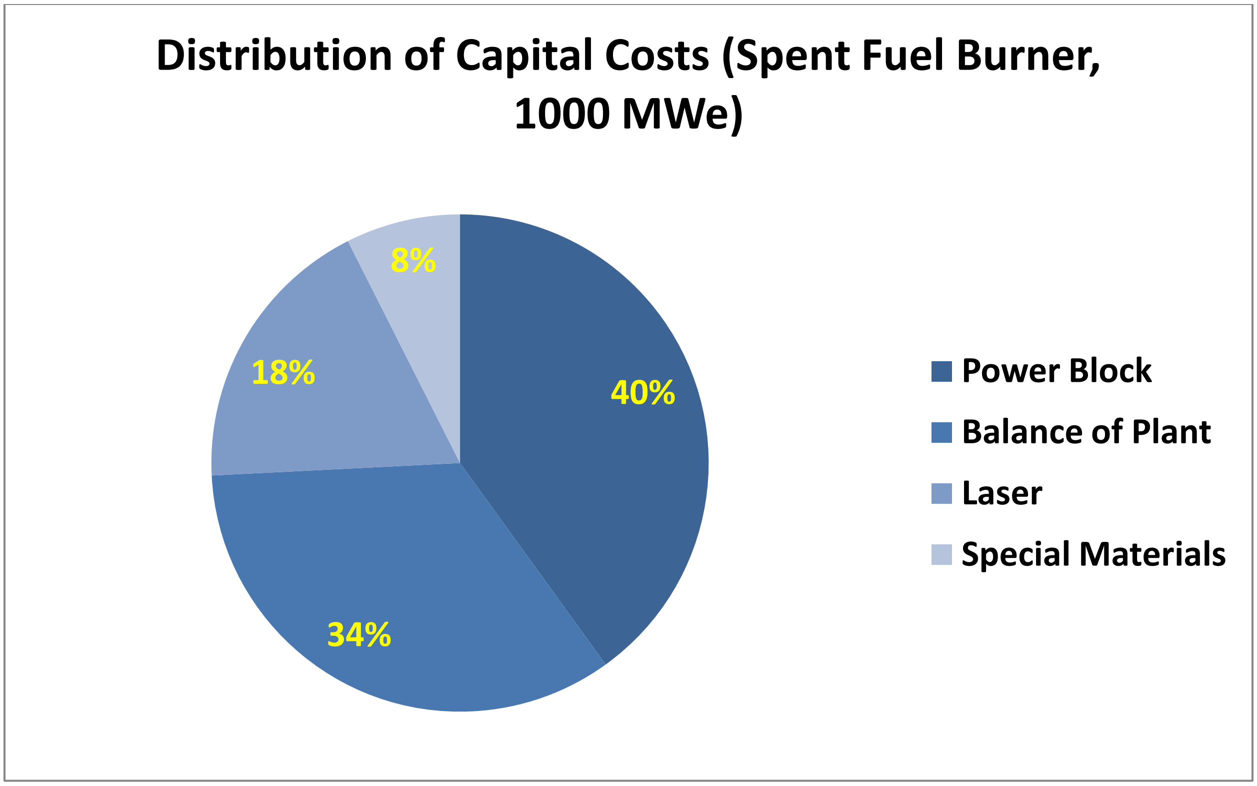

Figure 2: Distribution of Capital Costs for Spent Fuel Burner

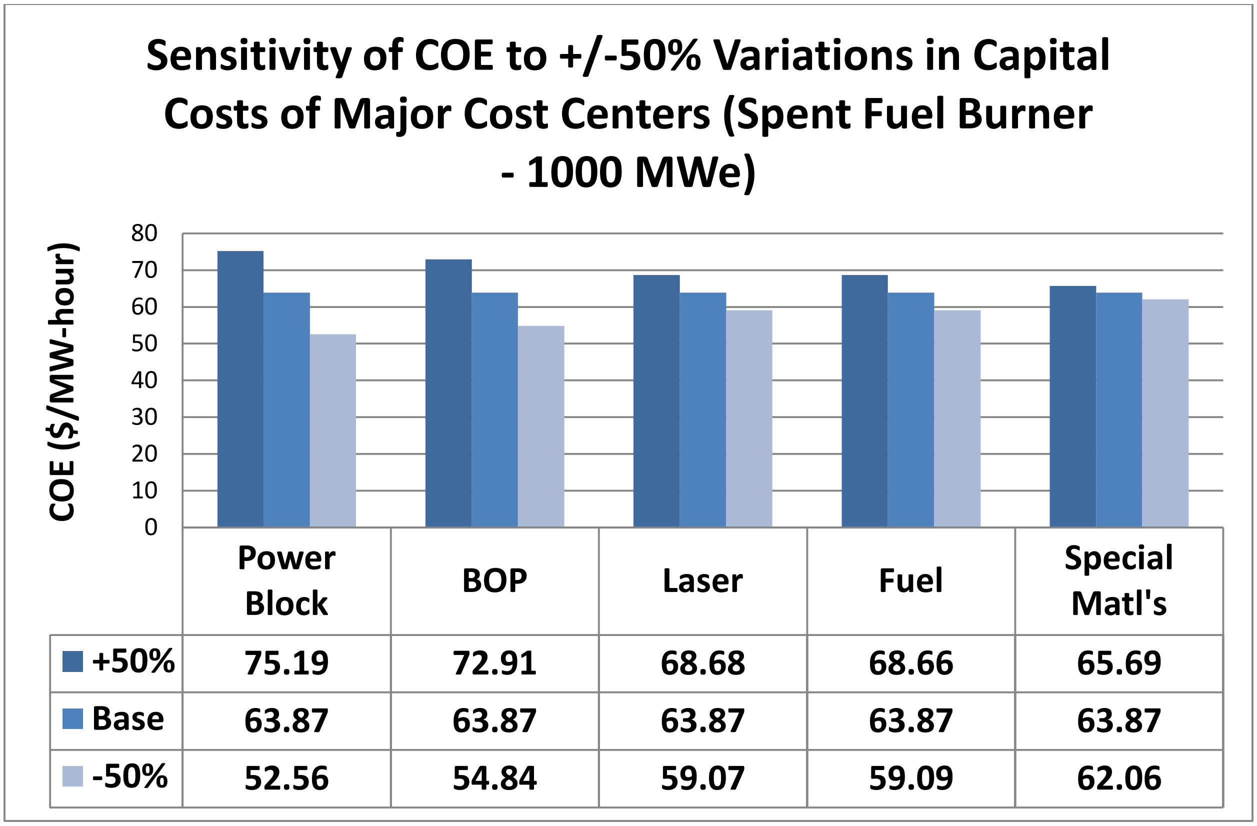

Figure 3: Sensitivity Study for Spent Fuel Burner

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