SYSTEMS MODELING FOR THE LASER FUSION-FISSION ENERGY (LIFE) POWER PLANT

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A systems model has been developed for the Laser Inertial Fusion-Fission Energy (LIFE) power plant. It combines cost-performance scaling models for the major subsystems of the plant including the laser, inertial fusion target factory, engine (i.e., the chamber including the fission and tritium breeding blankets), energy conversion systems and balance of plant. The LIFE plant model is being used to evaluate design trade-offs and to identify high-leverage R&D. At this point, we are focused more on doing self consistent design trades and optimization as opposed to trying to predict a cost of electricity with a high degree of certainty. Key results show the advantage of large scale (>1000 MWe) plants and the importance of minimizing the cost of diodes and balance of plant cost.

I. INTRODUCTION

Fusion-fission hybrids were studied extensively in the 1970's and 1980's (e.g., Refs. 1-3), including laser-driven concepts,[4, 5] and are now receiving renewed interest. The laser inertial fusion-fission energy (LIFE) power plant is being developed at LLNL in collaboration with several university, laboratory and industrial partners.[6] We have developed a systems model for the LIFE power plant that incorporates cost and performance scaling relationships for the major subsystems of the plant including target physics, target fabrication, a diode pumped solid state laser, fusion-fission chamber (including the tritium breeding and fission blankets), heat transfer and power conversion systems, and other balance of plant components and buildings. We use the cost of electricity (COE) as the principal figure of merit. Due to large uncertainties in the evolving design and subsystem technologies, the COE is most useful for evaluating design trade-offs, design optimization and sensitivity studies. Therefore, we present normalized results to focus attention on understanding the design space as opposed to trying to predict the COE with a high degree of certainty. We begin the paper with a brief description of the model, and then present key results of design variations and sensitivity studies.

II. DESCRIPTION OF THE MODEL

The key components of the system model are described here. At this point the LIFE systems model can evaluate several design options that are being considered in the LIFE project. These include two classes of targets, central hot spot ignition (HSI) and fast ignition (FI); and different options for the fission fuel blanket, natural or depleted uranium (U/DU), plutonium (Pu), or spent nuclear fuel (SNF). The principal design variables are the target yield (Y) and pulse repetition rate or rep-rate for shot.

II.A. Target Physics

The target yield is directly related to the target gain (G) versus laser energy (E) scaling relationship (i.e., Y = E×G), and varies significantly with target type (HSI or FI), laser wavelength or frequency (0.53 μm = 2ω or 0.35 μm = 3ω), and illumination geometry (NIF-like or low incidence angle (LIA), i.e., 10° cone half-angle for FI targets). Figure 1 shows the target yield versus laser

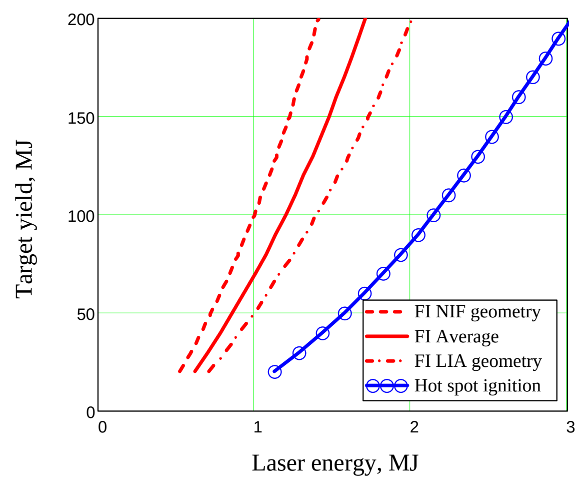

Fig. 1. Target yield versus laser energy for different targets and illumination geometries.

energy relationship used in the analyses for this paper. The HSI curve is for a 3ω laser. Three curves are shown for FI; the highest is for NIF-geometry compression and the lowest is for LIA compression, while the middle is the average of the two. We used the average case for the FI results.

II.B. Laser

The laser model is based on a diode pumped Nd-glass design.[7] This is chosen because it is seen as closer to proven technology with well known production capability of the solid state material, although crystals and ceramics might prove more attractive for later generation of LIFE plants if those technologies can be fully developed. The cost of the laser scales strongly with laser energy, but weakly with pulse rep-rate. The cost also depends on the pulse width, whether it is 10's of nanoseconds for the compression laser or 10's of picoseconds for the fast ignition laser. The laser efficiency depends on the frequency; it is 12% for 2ω and 10% for 3ω.

II.C. Target Factory

The target factor model is based on an indirect-drive target for both HSI and FI options. The hohlraum (and the cone in the case of FI) are high-Z materials, while the capsule and internal foam which defines the DT layer are low-Z materials. Lead is a good candidate material for the hohlraum and cone because it is inexpensive, manufacturable and is manually recyclable after two years of storage following implosion-induced activation.[8] Possible issues surrounding corrosion of the chamber walls by the liquid lead following implosion remain. Polymer capsules can be made using large-scale micro-encapsulation techniques.[9,10]

Preliminary cost estimates for the target fabrication facility were made using both top-down and bottom-up approaches. The top-down approach was made by estimating the cost of a typical factory and the associated costs. The bottom–up approach estimated the types and quantities of fabrication equipment needed for a throughput of 1.3 million targets/day (i.e., 15 Hz, at the middle of the 10-20 Hz range being considered for LIFE), and the costs associated with the operation of this equipment. It was assumed that low-cost, high-throughput methods such as metal stamping, deep drawing, molding, micro-emulsion and automated assembly can be used to fabricate these targets. Hydraulic presses for forming metals, for example, can process a 30 by 30 array of parts at 25 strokes/minute resulting it a maximum throughput of 375/s, far greater what is needed ever for a LIFE reactor. Other processes such as supercritical extraction processes for foam formation take 24 hours to perform an extraction on 27,000 parts using one extractor. Thus, a minimum of 48 extractors are required for a 15 Hz LIFE reactor. If lead is used for the hohlraum/cone and the capsule is a polymer, material costs (< $0.01 per target) will be negligible compared to processing costs.

At this point, there is significant uncertainty in which processes will actually be used for target fabrication. Some processes such as micro-encapsulation for forming capsules or foams have been demonstrated although fabrication yields are still being improved [10]. Other processes such as metal molding of hohlraums to the desired precision must be demonstrated. The cost estimates for the bottom-up approach were arrived at by summing the estimated cost of each of the individual processes on a per-part basis. The costs varied between $0.01 to $0.14 for each of the material costs, the hohlraum/cone metal-working costs, the capsule fabrication, the assembly, the DT fill and the recycling costs. The estimated range of per-target part is $0.09 to $0.33. The top-down approach used an estimated $200M factory cost with an annual budget of $21M for salaries and $70M utilities and maintenance resulting in a per-target cost of about $0.26. These preliminary cost estimates can be compared with cost estimates based on much more extensive analysis which estimate a per-target cost of about $0.28 to $0.41 for a more complex heavy ion fusion target.[11] While not definitive, the target costs can potentially be low enough to produce commercial power cost-effectively.

II.D. Chamber

The LIFE chamber including the fission blanket is costed based on the mass of material and estimated unit costs ($/kg) of those materials. The reference case has a radius of 2.25 m for a target yield of 38 MJ, and it scales as the square root of yield to keep the pulsed heating in the fuel within limits. The radial build of the Be neutron multiplier, fission blanket, reflector and structural walls is fixed, so the mass and cost of these regions also scale roughly as square root of yield.

II.E. Power Conversion and Balance of Plant (BOP)

The power conversion system is based on a high temperature modular molten salt Brayton cycle.[12] The conversion efficiency is calculated based on the maximum outlet temperature of the chamber. For the reference design with a peak outlet temperature of 630 °C, the conversion efficiency is ~42%. At this point, the BOP costs are scaled from fission reactor costs, but replacing the fission reactor pressure vessel with the LIFE chamber. Additional refinement of the model is still needed to account for differences in the molten salt versus water cooling. Future work will also include a more detailed analysis for the cost differences in building requirements, e.g., fission plants have containment buildings to deal with over pressurization in the event of an accident, whereas LIFE (and other fusion) plants are most concerned with tritium confinement. Current estimates for new and future fission reactors vary widely (~$2-6 B for a GWe plant). Changing a single number in the code (i.e. the fission plant $/kWe) allows us to renormalize and investigate the impact of such changes. Scaling from the reference power to other plant sizes is based on scaling factors given by Delene.[13]

II.F. LIFE Waste Handling and Storage

Although it is a very small contribution to the COE, we have accounted for handling and storage of the fission blanket material at the end of its ~50 year burn.

The waste disposal costs in the model include packaging and transporting the waste to a repository that would be constructed for LIFE waste. The costs were scaled from the 2001 Yucca Mountain Total System Life Cycle Cost estimate,[14] which was the latest estimate available at the time of the LIFE cost estimate. The Yucca Mountain costs were partitioned into those associated with commercial light water reactor fuel, and those associated with DOE waste. The LIFE repository was assumed to also have associated DOE waste, because the Yucca Mountain baseline does not dispose of all the existing DOE waste. The LIFE portion of the repository cost was scaled from the commercial light water reactor portion of the Yucca Mountain cost, eliminating historical expenses that were unique to the first-of-a-kind repository and increasing material costs for the waste packages and drip shields to account for the large increase in raw material costs since the Yucca Mountain cost estimate. It is expected that the updated Yucca Mountain costs recently released (Ref. 15) will not change the LIFE repository cost estimate significantly because the material cost increases have already been considered, and because much of the higher cost of the updated Yucca Mountain report are associated with the higher capacity assumed for cost purposes.

Because of the high burn-up of LIFE fission fuel, only a single Yucca-Mountain-size repository would be required for all LIFE waste that would be produced in one hundred years, even if LIFE plants supplied all U.S. electricity, with the size of the grid being about doubled from the current size.

III. RESULTS

III.A. Recirculating Power Fraction

A key benefit of the fission blanket is the energy multiplication, which ranges from ~4 for U/DU to ~8 for Pu and SNF. This increases the effective energy gain per pulse and reduces the recirculating power for the laser compared to a pure fusion design with the same target gain. Figure 2 shows the recirculating power fraction as a function of the target yield for HSI and FI targets assuming a blanket gain of 4. The recirculating power fraction (RPF) is less than 20% (often cited as a goal for IFE) with yields < 50 MJ even for HSI.

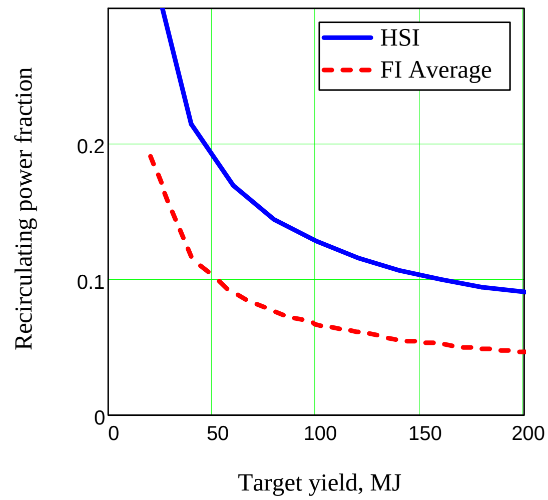

Fig. 2. Recirculating power fraction as a function of target yield for HSI and FI targets.

III.B. Laser Cost

Figure 3 shows the normalized laser cost as a function of laser energy for a 2 and 3ω designs at fixed rep-rate of 10 Hz. The 3ω laser has higher cost (~14%) primarily due to the lower conversion efficiency, i.e., it requires a larger system to provide the same energy on target. The effect of higher rep-rate is indicated by the added point at 1.5 MJ for the 3ω laser; going from 10 to

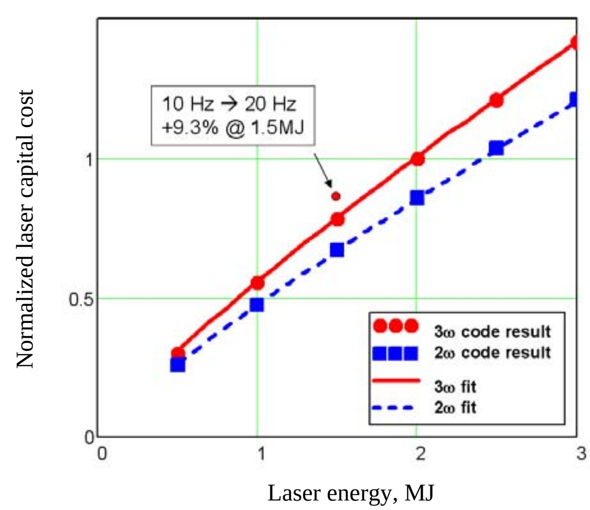

Fig. 3. Normalized laser cost versus laser energy for 2ω and 3ω designs.

20 Hz increases the cost by only ~9%. This is one reason larger plants, i.e., higher power at fixed laser energy (and thus target yield) are more cost effective as shown in the next section.

III.C. Normalized COE

Figure 4 gives the normalized COE as a function of target yield for three difference size power plants: net powers of 750, 1000 and 1500 MWe. Key parameters for the 1000 MWe normalization point are given in Table I.

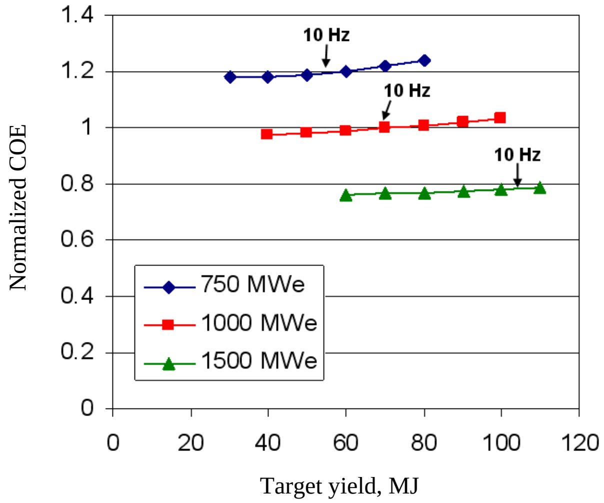

Fig. 4. Normalized COE versus target yield for different sized plants.

TABLE I. Parameters for Normalization Point.

Laser energy, MJ	1.85
Target gain	39.1
Target yield, MJ	72.3
Rep-rate, Hz	10
Fusion power, MW	723
Blanket energy multiplication	4
Thermal power, MWt	2890
Conversion efficiency, %	41.9
Gross electric power, MWe	1210
Laser efficiency, %	10
Laser power, MWe	185
Auxiliary power, MWe	25
Net electric power, MWe	1000

COE is clearly a strong function of net power but only varies weakly with target yield (and thus rep-rate). At fixed 10 Hz, the COE of the 750 MWe plant is 20% higher than the 1000 MWe plant, while the 1500 MWe plant is 20% lower (33% lower than the 750 MWe plant). This economy of scale is the result of a combination of factors including the laser cost scaling discussed above and the scaling for the power conversion and balance of plant cost, which overall scales like as $Pg^{0.6}$, where Pg is the gross electric power. The shape of the COE curves is typical of what we see for pure IFE except there is not a dramatic increase in COE at low target yield.[16,17] This is due to the higher blanket gain leading to small recirculating power fraction even at low yield.

The shapes of the COE versus yield curves for fast ignition targets (not shown) are very similar to those for HSI, but the COE is about 15-20% lower.

III.D. Sensitivity Studies

We have evaluated the sensitivity of the results to key design parameters and assumptions. Figure 5 shows the variation in the normalized COE as a function of relative changes in rep-rate, laser efficiency, diode cost, total laser cost, and power conversion and BOP cost. The normalization point is 1000 MWe plant with HSI target, 10 Hz, 2 ¢/W diodes, and a target yield of 72 MJ (E = 1.85 MJ). The COE is only weakly dependent on the rep-rate and laser efficiency. Diode cost is a significant factor representing ~30% of the laser cost even at 2 ¢/W diodes. The cost of diodes is expected to continue to decrease dramatically as a result of economies of mass production (Moore's law effect) and the introduction of new technologies such as vertical-cavity surface-emitting lasers (VCSELs); 1 ¢/W may be possible.[7] The power conversion plus BOP cost and total laser cost are the most important to control, which is not surprising since combined they comprise 95% of the plant capital cost.

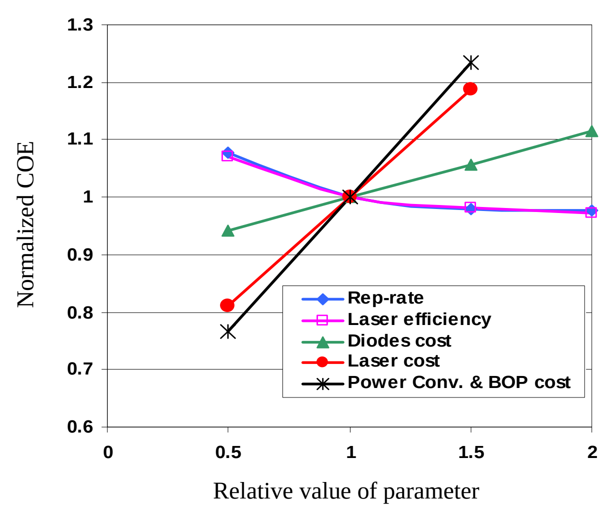

Fig. 5. Sensitivity of COE to design and parameter variations.

IV. CONCLUSIONS

Results of the system modeling and analyses reveal some interesting similarities and differences compared to results for pure IFE. Like all fusion systems, large plants are most cost effective. The fission blanket energy multiplication allows operation at modest target yields, reducing laser energy and cost. In fact, target yields of 50 or even less are adequate. The COE minimizes at highest possible rep-rate (over range examined – up to 20 Hz). High rep-rate laser operation, target injection, and chamber clearing are needed to approach this minimum. The laser cost is a major contributor (~40%) to total capital cost, and diodes are a significant fraction of that cost. Fast ignition will allow a lower COE for LIFE by about 15% or more depending on the cost and the efficiency of the ignitor laser. Future work will include continued improvements and refinement of cost and performance scaling models as more detail is developed for the LIFE power plant.

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REFERENCES

1. H.A. BETHE, "The fusion hybrid," *Phys. Today* **32,** 44-51 (1979).
2. J.A. MANISCALCO et al., "The Fusion Breeder-An Early Application of Nuclear Fusion," *Fusion Technology*, **6**, 584 (1984).
3. R.W. MOIR et al., "Design of a Helium-Cooled**.** Molten Salt Fusion Breeder**,"** *Fusion Technology,* **8**, 465-473 (1985).
4. J. MANISCALCO, "Fusion-Fission Hybrid Concepts for Laser-Induced Fusion," Nuclear Technology, **28**, 98-107 (1976).
5. R.W. CONN et al. "SOLASE-H, A Laser Fusion Hybrid Study," Fusion Research Program, Univ. of Wisconsin, UWFDM-270 (1979).
6. J.F. LATKOWSKI, R.P. ABBOTT, E.P. STORM, W.R. MEIER, "System Integration Issues for the Laser Inertial Confinement Fusion Fission Energy (LIFE) Engine," Proc. 18th TOFE, Sept. 28-Oct. 2, 2008, San Francisco, CA.
7. J. CAIRD et al., "Nb:Glass Laser Design for Laser ICF Fission Energy," Proc. 18th TOFE, Sept. 28-Oct. 2, 2008, San Francisco, CA.
8. L. EL-GUEBALY, et al., "Feasibility of target material recycling as waste management alternative," *Fusion Science and Technology,* **46**, 506-518 (2004).
9. M. TAKAGI, R. COOK, B. MCQUILLAN, J. GIBSON, S. PAGUIO, "Investigation of larger poly (a-methylstyrene) mandrels for high gain designs using micro-encapsulation," *Fusion Science and Technology*, **45**, 171-175 (2004).
10. D.T. GOODIN et al., "Developing a commercial production process for 500,000 targets per day: A key challenge for inertial fusion energy," *Physics of Plasmas* **13**, 056305 (2006).
11. D.T. GOODIN et al., "Progress in heavy ion-driven target fabrication and injection," *Nuclear Instruments and Methods in Physics Research A*, **544,** 34-41 (2005).
12. P.F. PETERSON, "Multiple-reheat Brayton cycles for nuclear power conversion with molten coolants," *Nuclear Tech.*, **144**, 279-288 (2003).
13. J.G. DELENE et al., "Nuclear Energy Cost Data Base - A Reference Data Base for Nuclear and Coal-fired Power Plant Power Generation Cost Analysis," DOE/NE-0095 (1988).
14. "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program," U.S. DOE report DOE/RW-0533 (2001).
15. "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007," U.S. DOE report DOE/RW-0591 (2008).
16. W.R. MEIER, "Systems Modeling for a Laser-Driven IFE Power Plant Using Direct Conversion," *J. Physics: Conference Series*, **112**, 032036 (2008).
17. W.R. MEIER, "Economic Systems Modeling for Laser IFE and the Potential advantages of Fast Ignition," *Proc. European Conference on Laser Interaction with Matter* (Madrid, Spain June 12-16, 2006) LLNL report UCRL-CONF-221936 (2006).