LIFE: THE CASE FOR EARLY COMMERCIALIZATION OF FUSION ENERGY

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This paper presents the case for early commercialization of laser inertial fusion energy (LIFE). Results taken from systems modeling of the US electrical generating enterprise quantify the benefits of fusion energy in terms of carbon emission, nuclear waste and plutonium production avoidance. Sensitivity of benefits-gained to timing of market-entry is presented. These results show the importance of achieving market entry in the 2030 time frame. Economic modeling results show that fusion energy can be competitive with other low-carbon energy sources. The paper concludes with a description of the LIFE commercialization path. It proposes constructing a demonstration facility capable of continuous fusion operations within 10 to 15 years. This facility will qualify the processes and materials needed for a commercial fusion power plant.

I. INTRODUCTION

The world is entering a transformational phase in the generation and use of electrical power. In developing countries, economic growth has spurred a dramatic increase in the need for new electrical power plants. In the United States, Japan and Europe, growth in demand is less, but aging power plants will need to be replaced in coming decades. A substantial fraction of this replacement needs to be in the form of low-carbon, base load energy generation.

Figure 1 illustrates the situation in the United States. In this relatively conservative scenario, demand for electricity roughly doubles by century end. Demand is calculated by extrapolating the EIA projected growth rate to 2100 and assuming 50% electrification of transport sector by 2050. (Ref. 1) Retirements are based on ages of existing US power plants and assumption of 80 year life for coal and nuclear and 60 year life for natural gas plants.[2]

Essentially, the entire fleet of existing power plants will be retired by 2060. The equivalent of ~ 900 new GW-Class power plants will need to be built to fill the gap by 2100. Even without any increase in demand, the requirement is still more than 400 GW of new build. How this gap is filled will have profound implications for national and global security and environment.

This paper assesses the benefits of having a fusion energy option in a time frame that is relevant to filling this capacity gap and outlines a path to do so using Laser Inertial Fusion Energy (LIFE).[a,3]

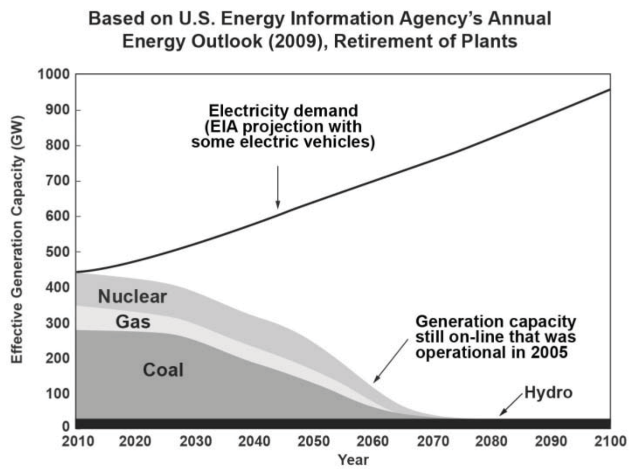

Fig. 1. Future demand and capacity for US grid.

II. BENEFITS OF EARLY COMMERCIALIZATION OF FUSION ENERGY

In Figure 2, the benefits of early commercialization of fusion energy are quantified as cumulative CO_2 emissions avoided between now and 2100. The assumption in this scenario is that each fusion power plant built means one less coal fired plant. The x-axis is the year in which the first commercial fusion plant begins operation. The rate of fusion's market penetration is constrained by demand, as shown in Figure 1, and by the ramp up of the supply chain needed to build fusion plants. The upper curve in Figure 2 corresponds to a doubling of build capacity (i.e., the rate at which plants can be built) every 5 years and the lower curve every 10 years. As a point of comparison to this rate of capacity introduction, note that during the 25-year period from 1960 to 1985, the global fission power industry experienced consistently

[a] See Ref. 3 for a similar assessment by Meier, et. al.

high growth in the capacity to build new power plants. The three year rolling average of capacity addition increased from 100 MW/yr to 30,000 MW/yr while the overall installed capacity grew from <100 MW to ~300,000 MW. This represented a build-capacity doubling time of <4 years that lasted for 25 years.[4]

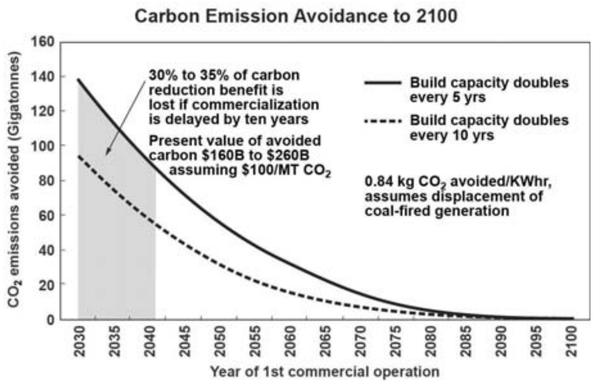

Fig. 2. Carbon emission avoidance if fusion displaces coal plants. US electricity generation currently accounts for ~2.4 GT CO_2/yr.

The potential benefit is large; between 100 and 140 GT of CO_2 avoidance, if first commercial fusion operations were to begin in 2030. The benefits of early commercialization are striking. CO_2 avoidance is 30% to 35% less if commercialization occurs in 2040 rather than 2030.

Because the grid is being recapitalized over the next several decades, there is strong motivation to commercialize in time to participate in this process. Once recapitalization is complete, market opportunities are limited to meeting increases in electricity demand. If this occurs, the benefits accrued during this century will be significantly less.

If we assign a cost to CO_2 emission of $100/MT, typical of what is discussed in policy circles, we can calculate that the present value of the avoided carbon ranges between about $300B and $600B (5% discount rate). This is certainly much less than the cost of fusion technology development and indicates a good return on investment.

If LIFE were assumed to displace coal plants that have carbon capture and sequestration installed, the metric would be CO_2 sequestration avoidance. The quantities avoided would be large and somewhat greater than those shown in Figure 2 because carbon capture reduces the thermal efficiency of the coal plant.

The same type of avoidance analysis can be done if LIFE is assumed to displace new light water reactors with a once-through fuel cycle. In this case, the metric is high-level nuclear waste avoidance. The analysis shows that, if first commercial operation were to commence in 2030, 230,000 to 360,000 MT of high-level nuclear waste can be avoided (3.0 to 4.5 additional "Yucca-Mountain-Equivalents"). Again, early commercialization is extremely beneficial. If commercialization occurred in 2040 rather than in 2030, waste avoidance decreases by 85,000 to 110,000 MT.

If instead of light water reactors, LIFE is assumed to displace fast reactors with reprocessing, the metric is plutonium avoided. Reprocessing technology requires that the spent fuel be stored for 5 years (PUREX process). This allows for enough radioactive decay so that radiation levels do not interfere with chemical separations. As a hypothetical fast reactor fleet grows, the amount of plutonium being stored outside of the reactor becomes large, and this raises proliferation concerns.

This is illustrated in Figure 3. The y-axis is the amount of plutonium in storage in year 2100 that would be avoided if fusion plants were built instead of fast reactors. The x-axis is again the date of first commercial fusion plant operation. Between 3000 and 4000 MT of stored plutonium is avoided if first commercial operation is in 2030.

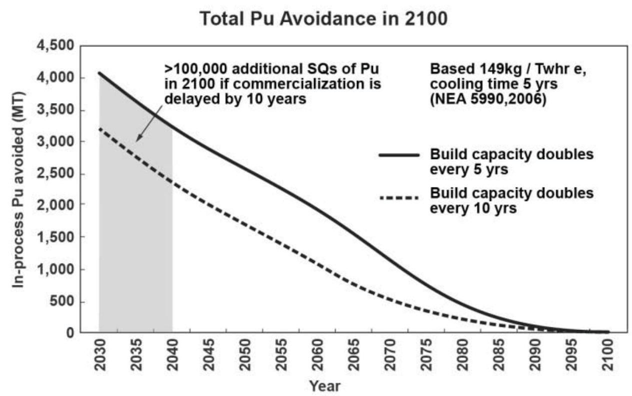

Fig. 3. In-storage plutonium avoidance. Results show a significant reduction in proliferation potential, particularly when scaled to a global level.

The International Atomic Energy Agency defines a "significant quantity" of plutonium as 8 kg; enough to be of concern for nuclear weapon proliferation. When one considers that a commercialization date of 2040 rather 2030 would increase the amount of plutonium in storage in the year 2100 by more than 800,000 kg (100,000 significant quantities) it is easy to see why early commercialization of fusion energy could greatly reduce proliferation concerns.

III. THE LIFE APPROACH TO COMMERCIALIZATION

The LIFE concept is being developed at Lawrence Livermore National Laboratory in partnership with many other national laboratories and organizations. The concept has been described previously in the literature.[5] The literature describes both a pure fusion LIFE concept as well as a fusion-fission variant. This paper deals exclusively with the pure fusion concept.

The commercialization approach leverages the science and technology being demonstrated on the National Ignition Facility (NIF). LIFE will utilize the same fundamental laser technology and target physics as used on the NIF: Neodymium-doped glass gain media, multi-pass architecture with spatial filtering, indirect-drive hot spot ignition fusion target.

However, the details of the designs are being changed to provide a more compact, modular laser architecture – needed for high availability power plant operations, active thermal management – needed to operate at higher repetition rates (10 to 20 Hz), diode pumping rather than flash lamps – needed to achieve power plant level laser efficiency (~10% to 20%), and fusion targets capable of being mass-manufactured.

The commercialization path can be described in terms of three point designs:[b] LIFE.1, LIFE.2 and LIFE.3. LIFE.1 would produce 400 MW of fusion power and is designed to maximize the use of existing materials and technology; LIFE.1 is envisioned as being operable ten to fifteen years from ignition on the NIF.

LIFE.1 will provide a test bed to demonstrate the unit operations needed for a commercial power plant. In addition, it will provide the continuous fusion environment needed to qualify materials and processes.

An accelerated testing scheme will be used in LIFE.1 where samples of materials are inserted in test ports that are re-entrant to the chamber first wall. Samples are thus exposed to radiation damage rates that are much higher (> 4×) than at the LIFE.1 first wall.

LIFE.2 is a 1 GW_e-commercial power plant – either a new facility or an up-powering of LIFE.1. We envision that both LIFE.1 and LIFE.2 will be NRC licensed, although there is likely an option, if desired, to operate LIFE.1 under a DOE Authorization Basis. LIFE.2 uses the same laser technology that LIFE.1 does, but uses more advanced, radiation resistant structural material (oxide dispersion strengthened steel) to enable higher temperature, higher power density operations. The structural material will be qualified on LIFE.1.

LIFE has a natural economy of scale because the efficiency of converting laser energy into fusion energy increases as the power plant is scaled to larger electrical output.[c] As investor confidence is gained, it is expected that this economy of scale will motivate the design of larger plants. In addition, it is reasonable to project additional improvements in target efficiency, lower fusion target costs and higher operating temperatures. The LIFE.3 design captures these improvements and provides insight into the potential economics for a mature LIFE technology. Table I summarizes the LIFE point designs.

TABLE I. LIFE Point Designs

	LIFE.1	LIFE.2	LIFE.3
Laser Energy (3ω)	1.3 MJ	2.4 MJ	2.0 MJ
Repetition Rate	14.8 Hz	14.8 Hz	14.8 Hz
Plant Electrical Gain	1.3	4.4	7.0
House Power Fraction [a]	0.77	0.25	0.16
Thermal to Electric Efficiency	43%	48%	53%
First Wall Material,[b] Radius	RAFMS, 3.7 m	ODS, 5.6 m	ODS, 6.2 m
First Wall Neutron Loading, Lifetime (full power equivalent)	1.9 MW/m^2, 20 dpa/yr, 0.9 yr life	4.5 MW/m^2, 50 dpa/yr, 4.5 yr life	4.5 MW/m^2, 50 dpa/yr, 4.5 yr life
Fusion Yield, Target Gain	27 MJ, Gain 21	147 MJ, Gain 64	180 MJ, Gain 94
Fusion Power	400 MW	2200 MW	2660 MW
Availability Allocation	50%	92%	92%

[a] Also know as recirculating power fraction
[b] RAFMS is a low activation ferritic/martensitic steel and ODS is an oxide dispersion strengthened steel

IV. LIFE ECONOMICS

In order for LIFE to achieve significant market penetration, it will need to demonstrate economics comparable to or better than other low-carbon electrical energy technologies. To assess this aspect of commercialization, we have developed a pre-conceptual design level estimate of capital costs and cost of electricity.

The LIFE plant is divided into ~ 50 cost centers. Laser system costs are estimated using a bottom up methodology. Unit costs are derived from vendor quotes and data from the NIF project. Because many of the laser system components are produced in large quantities, we estimate cost reductions due to manufacturing learning. The learning rates used in our estimates were informed by experience with NIF.

Costs for the fusion engine, tritium plant and power conversion systems are taken from studies in the literature and scaled to the LIFE operating point using standard scaling relations.[6-10]

Fusion target unit costs are derived from a target manufacturing study.[11] Annual non-fuel operations, maintenance and incremental capital costs are assumed to

[b] A point design is a self-consistent set of parameters that define a particular design point.

[c] For constant repetition rate, fusion power scales linearly with fusion yield. Fusion yield is the product of laser energy and target gain. Since target gain scales with laser energy, fusion power scale as laser energy raised to a number >1. So laser energy and capital cost increase more slowly than fusion power. Power plant equipment costs also have an economy of scale with power. The combination of these effects results in a reduced capital intensity for larger plants ($/kW).

scale as percentages of the plant total capital cost. Percentages were derived from the 2009 MIT publication on the Future of Nuclear Power.[12]

Indirect cost multipliers come from the Gen IV cost estimating guidelines.[13] Capital and indirect cost differentials between nuclear grade and conventional systems and structures were taken from a General Atomic study.[14] Plant availability for a 10th of a kind plant is set to 92%; high availability is enabled by the modular architecture of the plant design.

Cost of electricity is calculated using the discounted cash flow methodology described in the 2009 MIT report.[10]

Design parameters for the three systems are summarized in Table I. All three systems have an estimated capital cost in the range of $4B to $6B. Cost of electricity is shown in Figure 4, plotted against cost of carbon and compared to estimates for alternate generating technologies. The costs for alternate technologies were derived from a recent paper by Nicholson.[15]

The upper end of the range indicated for LIFE pertains to the LIFE.1, first-of-a-kind, plant. The lower end of the range corresponds to the LIFE.3 system. Estimated cost of electricity for LIFE is comparable with other base load energy sources and less than the cost of fossil fuel generation for cost of carbon that exceed $50 to $100/MT.

Of course, LIFE cost estimates are based on a pre-conceptual design, so additional work is needed. However, the results shown in Figure 4 are indicative and illustrate the economic potential of the LIFE technology.

Figure 5 shows the results of a Monte Carlo sensitivity analysis on cost of electricity. The most highly

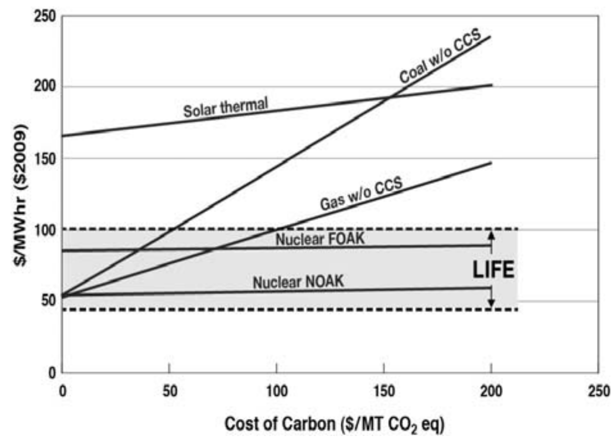

Fig. 4. Economic comparison to other low carbon technologies.

leveraged economic parameter is the fusion chamber structural material. This highlights the importance of ongoing developments in oxide dispersion strengthened steel technology. This material enables high temperature operation and appears to have excellent radiation damage resistance.[16] It also highlights the importance of LIFE.1 in providing the continuous fusion operation environment needed to qualify these materials for use in commercial fusion applications.

The next two most highly leveraged parameters are the fusion target cost and target efficiency. This is a favorable attribute of LIFE technology because target development can be conducted parallel to other development activities and advances in target design or manufacturing can be validated by testing on the NIF.

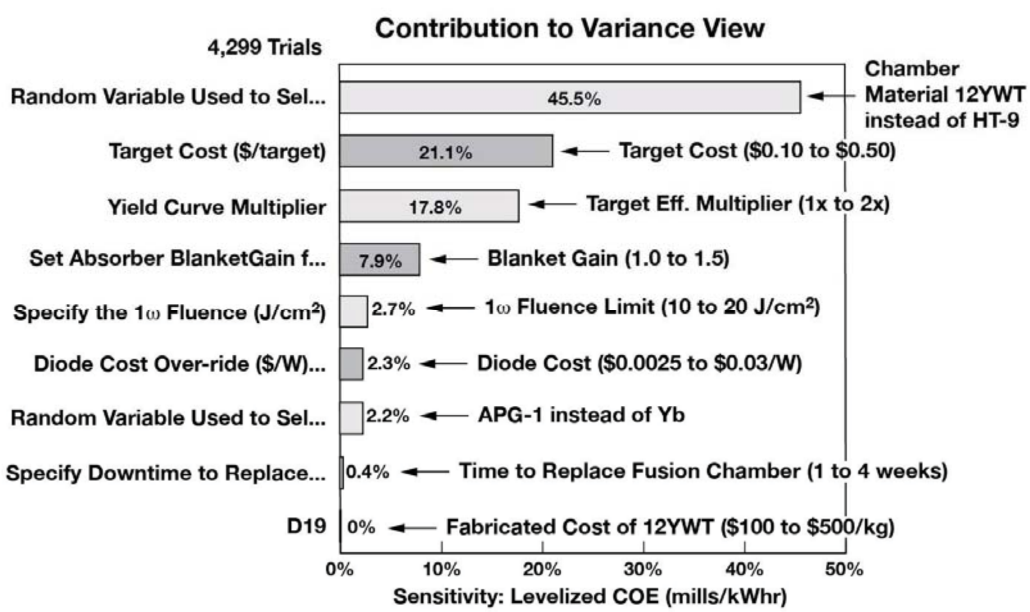

Fig. 5. Monte Carlo sensitivity analysis on cost of electricity.

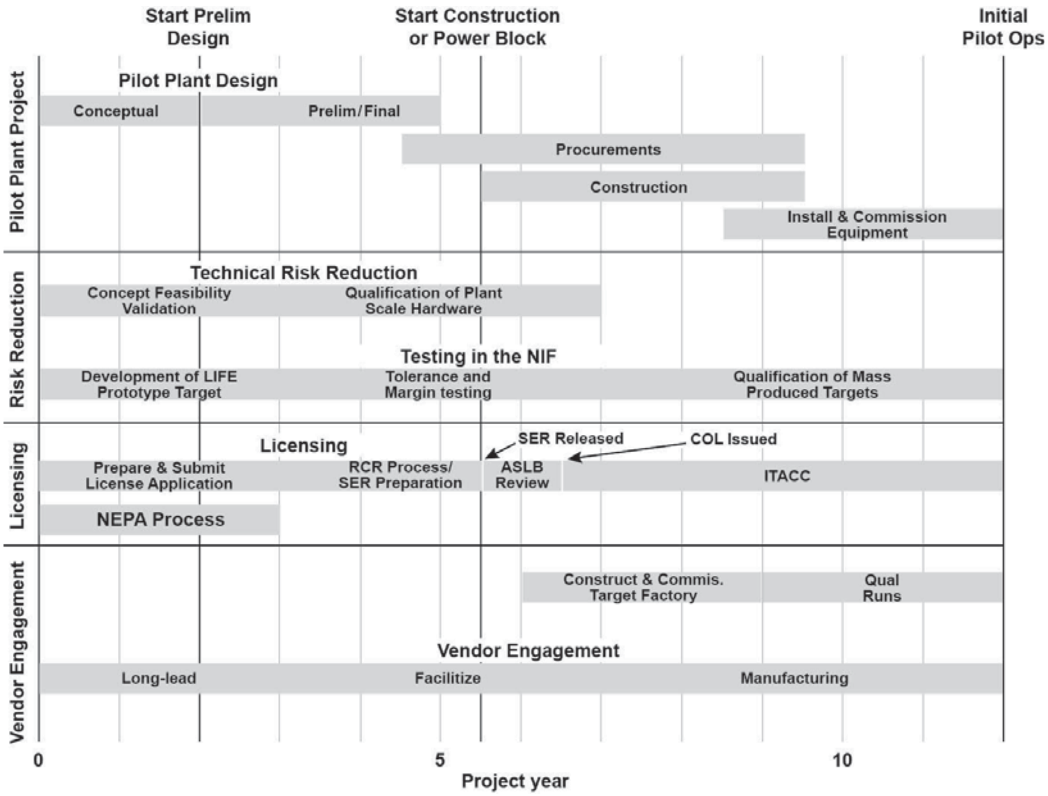

Fig. 6. Design and build schedule.

V. COMMERCIALIZATION SCHEDULE

Figure 6 shows an indicative schedule that achieves first pilot operations roughly 12 years from project start. Design and construction durations are informed by previous experience in building the NIF and other large capital projects. What remains is to fully integrate this design and construction schedule with the schedule for the supporting R&D activities.

Supporting R&D is initially directed toward demonstrating feasibility of the constituent technologies. This provides a basis for initiating preliminary design of the pilot plant. R&D activities then transition to testing of plant scale hardware. This forms the basis initiating plant construction and release of plant equipment procurements.

Examples of technical risk reduction activities include: mass production of fusion targets, development of high average power laser components, and fusion engine structural materials.

VI. CONCLUSIONS

Our evaluation of LIFE technology shows that there is a compelling case to accelerate the development of fusion technology and to set a goal to achieve first commercial operation in the 2030's or earlier.

Our proposed approach to achieving this goal is to leverage the science and technology being demonstrated on the NIF and to design and build a fusion power demonstration plant within ten to fifteen years of NIF ignition. The design of the demonstration plant maximizes the use of existing materials and processes in order to minimize the need for R&D.

Once a continuous fusion system is in operation, it enables the qualification of materials and processes needed for commercial fusion power.

A pre-conceptual level evaluation of LIFE economics shows that LIFE economics compares well with other low carbon technologies. A design and build schedule shows first pilot plant operations 10 to 15 years from project start, contingent on integrating supporting R&D with design and construction activities.

This approach to commercialization of fusion energy carries technical risk and is aggressive. A national commitment is required to build a team involving industry, national laboratories, academia, government, regulatory agencies and international partners. Yet the need is urgent and the benefits are compelling.

It is our hope that this study will motivate other stakeholders to take a fresh look at the fusion energy option. The next steps are to conduct the conceptual level design studies and the technology demonstrations needed to move fusion commercialization forward with the degree of focus and urgency that is required.

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