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Timely Delivery of Laser Inertial Fusion Energy (LIFE)

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TIMELY DELIVERY OF LASER INERTIAL FUSION ENERGY (LIFE)

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The National Ignition Facility (NIF), the world's largest and most energetic laser system, is now operational at Lawrence Livermore National Laboratory. A key goal of the NIF is to demonstrate fusion ignition for the first time in the laboratory. Its flexibility allows multiple target designs (both indirect and direct drive) to be fielded, offering substantial scope for optimization of a robust target design.

In this paper we discuss an approach to generating gigawatt levels of electrical power from a laser-driven source of fusion neutrons based on these demonstration experiments. This "LIFE" concept enables rapid time-to-market for a commercial power plant, assuming success with ignition and a technology demonstration program that links directly to a facility design and construction project.

The LIFE design makes use of recent advances in diode-pumped, solid-state laser technology. It adopts the paradigm of Line Replaceable Units utilized on the NIF to provide high levels of availability and maintainability and mitigate the need for advanced materials development.

A demonstration LIFE plant based on these design principles is described, along with the areas of technology development required prior to plant construction.

I. BACKGROUND

The starting point for this study has been the requirement to deliver commercial fusion power soon enough to make a difference to current energy policy – by offering an attractive option for baseload electricity production from 2030 onwards. Delivery of fusion on this timeframe requires a demonstration plant in the 2020s and thus a shift from the paradigm of incremental construction of large-scale research facilities. These historically have been deemed necessary due to the uncertain nature of the physics, materials and technology requirements.

The approach advocated here adopts a power plant design that uses the physics scheme currently being tested on the NIF, coupled to a driver solution using existing manufacturing technology and a concept of plant operations that overcomes the need to wait for advanced material development. The project to deliver a power plant based on this approach is known as Laser Inertial Fusion Energy (LIFE). While substantial technology demonstration and integration is still required, the design of each subsystem is consistent with performance levels using known technology options.

II. POWER PLANT REQUIREMENTS

A set of Primary Criteria for a fusion power plant has been derived in consultation with the electric power generation industry, taking as a starting point the Utility Requirements Document used for the Advanced Light Water Reactor.[1] This follows on from earlier work with the magnetic fusion community that addressed power plant requirements.[2]

These end-user needs have been coupled with an analysis of the likely economic context of fusion power delivery and the commercial impact of different technology options for the power plant.[3]

Working backward from these Criteria allows the power plant design process to focus on operational characteristics that are familiar to the end-users (utilities), delivery industries (vendors) and regulators. It allows trade-off decisions to be made on the wide array of possible development and risk reduction activities, and enables down-selection of options consistent with the final goal of robust, economically competitive electricity production. Criteria that drove the design process include:

- Cost of electricity
- Rate and cost of capital build
- Licensing simplicity
- Reliability, Availability, Maintainability and Inspectability (RAMI)

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- Predictable shutdown
- Quick restart after shutdown
- High capacity credit and capacity load factor
- Protection of capital investment
- Safety of operations
- Offsite environmental impact (global and local)
- Acceptability to the public (e.g., urban siting)
- Timely delivery

While a number of these criteria (e.g., cost of electricity) are difficult to predict in an absolute sense with acceptable accuracy, a cost model can still be constructed that demonstrates the relative benefit of different design choices. For example, an option in which additional capital investment leads to a reduced cost of electricity can be assessed by comparing the operational savings to the cost of amortization of the increased capital.

Other criteria (e.g., RAMI, capacity factors) drive fundamental design choices in the overall power plant architecture, subsystem configurations, and acceptability of certain technology options. For example, as will be shown below, the impact of designing a laser subsystem that can be maintained while the plant remains operational is of over-riding importance. This allows the overall plant availability to remain high even if the reliability or longevity of a critical subsystem is relatively low.

The criteria have been quantified wherever possible to help establish objectives for the LIFE design and assess its performance in comparison to alternative energy sources. Economic measures and the requirements for timely delivery are detailed by Anklam et al.[3]

According to the North American Electric Reliability Corporation, plant availability in the U.S. for baseload electricity sources over the past decade have been in the 88-91% range, while unplanned shutdowns have been at the 2.5-4% level. This imposes a high bar for a technologically intensive solution such as fusion, but must be addressed if the plant operations are to be compatible with grid requirements. In particular, the predictability of shutdowns for gigawatt scale plants is very important. This means that the operations must not be threatened by potential instabilities in the physics performance or intermittent failures in the fusion technology.

In this respect, inertial fusion has a clear benefit compared with quasi-steady-state reactors. The pulsed mode of an IFE "engine" ensures that the system is insensitive to occasional failures in the fusion production. That is, failed implosions impact only the plant output (with a requirement for 1 in 10^3 reliability, thus <0.1% impact on net power), rather than leading to plant shutdown – as could be the case for plasma disruptions in a continuous system. Of course, as with any integrated system, the component parts of an IFE engine (driver, injector, etc.) must remain operational for extended periods, requiring a high level of production assurance. This calls for a parallel, modular driver architecture in which individual units can be replaced during ongoing plant operations. It also calls for a suitable design margin in the remaining system, and subsystem redundancy in units where parallel performance is not practical (e.g., fuel injection).

Similarly, as with other approaches to fusion, high availability requires long-lifetime materials in the high threat environments (first wall and blanket modules, vacuum / gas barriers, final optics, etc.). This is partially mitigated in the LIFE design by establishing an operating regime that allows for periodic replacement of these parts.

The immaturity of many areas of fusion technology places high risk on the capital investment required for large-scale power plants. In order to move directly to a fully integrated facility, solutions must be established that allow for improvements or corrections to the high-risk subsystems (such as the blanket) without requiring wholesale changes to the rest of the plant. By adopting a design approach that permits modular, replaceable units throughout the plant, such risks can be managed.

Finally, an approach needs to be adopted that has a high likelihood of public acceptance and an expeditious licensing regime. Along with acceptable capital cost, these issues have dominated the rollout of conventional nuclear power over the past few decades and are among the most important areas to resolve for the proposed fleet of small, modular reactors (SMRs). For LIFE, these issues translate to the need to capitalize on the inherent safety characteristics associated with IFE. These can enable site location adjacent to the high load centers of cities and industry. In terms of design, the requirement is to minimize the tritium inventory and any induced activation of components in the fusion operations building.

III. MEETING THE REQUIREMENTS

A system solution proposed in 2008/9 was to adopt a fusion-fission hybrid design that relaxed the requirements on the fusion engine and the associated materials performance.[4] Whereas this still represents an intriguing option, the licensing timeframe for such plants is highly uncertain.

Following consultation with the utility industry and others, the LIFE design has been focused on a pure fusion power plant for gigawatt net electrical output, while keeping open the hybrid option for future plants. Figure 1 provides an overall layout of the LIFE power plant site.

The approach has been designed to take full advantage of U.S. leadership and prior investment in this area, enabling a direct step from NIF to an operational power plant. This reduces the cost and delay associated with a more conventional approach that requires multiple phased facilities to mitigate the risk arising from unproven physics, use of novel materials and new technologies.

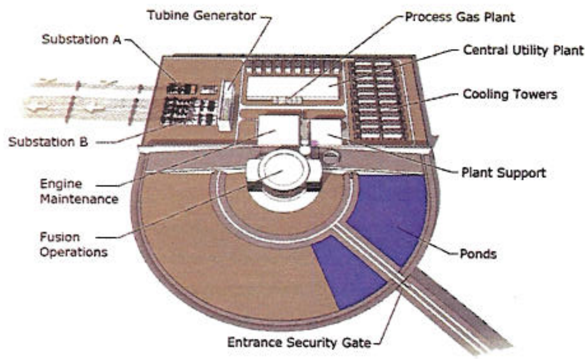

Fig. 1. The LIFE power plant integrates the fusion operations building (100 m diameter) with an engine maintenance area, tritium plant, and conventional utilities on a site consistent in scale with existing baseload plants.

Throughout, the rigor of a "facility point design" has been adopted, along with extensive consultation with the relevant industries. A detailed (370-element) work breakdown structure (WBS) for the power plant was established, covering the main subsystems (conventional power block, plant support facilities, supervisory control system, fusion engine, target injection and tracking system, laser system, fusion fuel operations equipment, tritium plant, power conversion, and system integration). The technical solution adopted for each area had to demonstrate its compatibility and self-consistency with the rest of the plant. Design choices were then made based on the overall plant response to a proposed technology option, incorporating Monte Carlo assessment of performance and cost. Similarly, error budgets (for efficiency, availability, etc.) are distributed throughout the plant in a balanced manner. The features that resulted are outlined below.

III.A. Demonstrated Plasma Performance

The goal of the National Ignition Campaign (NIC) is to demonstrate ignition by the end of 2012. Assuming success, the details that emerge will be used as the basis for LIFE, allowing direct evidence of the required physics design for a power plant to be obtained on the NIF. IFE driver/target illumination combinations other than one based directly on NIF evidence would almost certainly require a new ignition demonstration facility due to the strongly nonlinear coupling between driver and target that far exceeds our ability to predict with the required level of confidence.

The facility specifications required to produce robust, reproducible gain are obviously not yet established. A conservative approach has therefore been adopted for the purposes of this pre-conceptual design study. This utilizes established design methods[5] coupled to tolerances on the laser, target and alignment systems extracted from NIC specifications. While improvements on these "first generation" designs can be expected and can be adopted as they are proven, they are not assumed here.

The efficiency of the driver in converting energy from the electrical grid to the energy needed to compress the capsule, coupled with the energy "gain" of the capsule, must be sufficient to yield substantial net energy. With the efficiency of a plant-scale laser driver calculated to be 18% (15% after accounting for the required cooling systems),[6] coupled to a blanket gain of 1.2, a thermo-electric conversion efficiency of 44% (see below), and incorporating the house electrical load for ancillary systems, then a fusion target gain of only 60 to 70 (fusion energy / laser energy) leads to a commercially acceptable net electrical output and recirculating power fraction. The overall plant gain is optimized at 4.5. This represents a tradeoff between capital investment (e.g., adoption of more laser diodes to drive greater efficiency) and operational cost. Calculations indicate that gain in this range is achievable from indirect-drive capsules with driver energy of around 2.2 MJ at 351nm.[5]

The separability of target performance does mean, however, that future designs (such as direct-drive or alternate indirect-drive solutions) can readily be incorporated as long as they maintain the same interface characteristics to the rest of the plant. That is, they must use the same irradiation geometry, meet an achievable beamline performance, be consistent with the target injection and survival constraints, yield an acceptable threat to the first wall, and be compatible with the gas handling system, tritium plant and waste processing stream. These integrated requirements are non-trivial, but do offer a reasonable phase space for future improvements.

III.B. Use of Available Materials

The pace of fusion delivery has been driven in large part by the long time scales associated with advanced materials development and their operational certification for high-threat, structural components.

The first wall and blanket environment must be able to cope with high fluences of charged particles, x-rays and neutrons while retaining mechanical integrity, low levels of activation and high levels of performance in converting thermal energy to electricity and breeding tritium.

Advanced materials are still required for these sub-systems in the long term, but an intermediate solution is made possible that allows construction of early plant(s) alongside the materials development program, rather than having to await its success. This is achieved by adopting the NIF "line replaceable unit" (LRU) concept for the entire first wall and blanket subsystem, in combination with a gas-protected wall design to substantially reduce wall damage.[7]

High-Z gas (e.g., xenon) is introduced at sufficient density (~4 to 6 μg/cc) to capture the ions from the exploding target within a 10- to 20-cm gas radius. This effectively eliminates the problem of ionic bombardment on the 5- to 6-m radius chamber (e.g., from fusion products or target debris), which has been a principal limiting factor in previous IFE designs. Use of a conventional, gas-protected steel wall avoids the need for solutions that require substantial offline development before they could be considered (e.g., wetted walls, nano-structured materials, or magnetic deflection schemes).

Similarly, the gas reduces the thermal insult from the x-ray pulse to a level consistent with using available steel materials (pulsing the chamber from 600 °C ambient to a peak of 800 °C each shot).

Neutron-induced damage can be maintained at suitably low levels by treating the chamber modules as line replaceable units with a limited operational life. A lifetime of 1 full-power year is calculated for the demonstration plant using steels such as modified HT-9 (assuming 5 to 10 displacements-per-atom (dpa) can be tolerated). Production of low activation steel in the required tubular geometry has recently allowed near-term tests of material quality and mechanical performance. Over the longer term, following the materials development program and testing in the initial phase of the LIFE plant, use of an oxide dispersion strengthened (ODS) ferritic steel should allow operation for over 4 years between chamber replacements (running at 20–25 dpa / year).

In this way, a demonstration plant can be constructed with high confidence and used to test emergent materials in a relevant fusion environment. Because IFE operates as a point source, re-entrant modules can be used to expose candidate materials or components to a high neutron fluence – potentially up to 5 to 10 times that required for the chamber wall. This allows rapid assessment of new materials and a relatively short qualification time scale.

III.C. Protecting Plant Availability

The components of the LIFE plant must sustain economic operations at high availability and reliability and ability to be inspected and maintained.

The LIFE approach has been, wherever possible, to decouple the reliability of high-threat, limited life components from impacting the overall plant availability. As a consequence, shutdown times for the plant associated with the fusion-specific equipment are calculated to be reduced to the few-percent level – well within the allocated availability budget.

This concept is applied, for example, at the level of laser beamlines, which have been designed with an innovative new architecture to reduce their physical size by over an order of magnitude compared to the NIF (see Fig. 2). A beam-box 10.5 m long has been designed as a line replaceable unit. This allows off-site manufacture and maintenance and changeover of individual beamlines while the plant is operational.

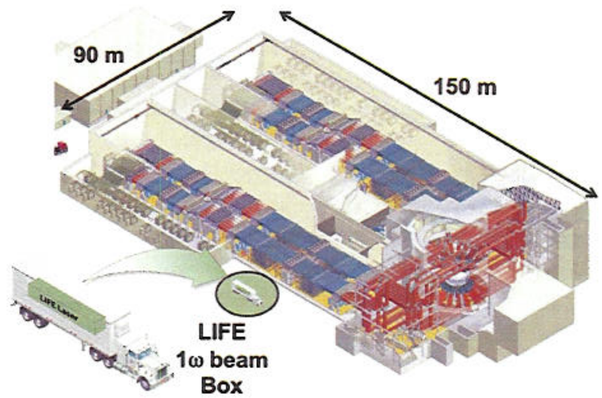

Fig. 2. LIFE beamlines (8.1 kJ, 1ω, 16 Hz) are configured into a box with dimensions 10.5 × 2.2 × 1.35 m to allow offsite factory manufacture, truck transportation, and ease of maintenance consistent with power plant operational requirements. This scale is shown in comparison to NIF.

This approach allows mean-time-to-failures (MTTFs) as low as 1000 to 2000 hours to be tolerated (roughly an order of magnitude smaller than the anticipated MTTF, providing good margin for robust operations). When coupled with a suitably large number of beamlines and an ability to swap beam boxes within an operational shift (8 hours), this allows continuous electricity production to be maintained. Overall plant availability is calculated using Monte Carlo operational models to be impacted by less than 1%. This represents a dramatic shift from most prior IFE plant designs, which were reliant on extremely high levels of driver reliability (years rather than weeks) to sustain an acceptable level of plant operations. This is an area where additional up-front capital expenditure (~10% of the laser cost) and attention to the plant concept of operations results in a substantial improvement in performance.

The beam boxes are arranged in an annular array, following the NIF geometry but without the need for a complex switchyard, and with only one optic per beamline in the high threat fusion environment. This aids access to the optics, which need to be amenable to remote replacement. The choice of a small, thin silica Fresnel lens simplifies this complex requirement and removes the need for an additional tritium gas barrier.

Other final optic designs that have been proposed in the past, such as grazing incidence metal mirrors (GIMMs) or multilayer parabolic mirrors, seem inconsistent with operational demands, such as tolerance to alignment errors, deposition of particulates, and the ability to be replaced during operations.

The plant design incorporates a dual-walled neutron shield and a pair of offset neutron pinholes through this shield. The pinholes allow optical passage inwards while reducing the residual radiation in the laser hall to a level that allows free movement of personnel (~ 0.04 rem / year). This greatly simplifies the maintenance regime and should also benefit the licensing process and build cost of the facility. The layout of the engine is shown in Fig. 3.

Without an approach similar to that described above, the plant intermittency resulting from failure of individual components in any fusion system would likely be deemed unacceptable for a baseload source of energy.

A related philosophy has been applied to the fusion chamber. A first wall / blanket architecture has been designed that allows a NIF-scale chamber to be used that is line-replaceable and decoupled from the optical system and the vacuum infrastructure.

Traditionally, a hermetically sealed first wall has been used to form the vacuum barrier, with ports to allow the drive radiation to enter. This imposes severe constraints on the design flexibility. Here, a modular design is adopted in which a series of tubes act as the first wall, backed by a thick blanket. This "chamber" is split into a set of independent modules that can be withdrawn to a maintenance bay in isolation or as a complete unit.

Decoupling the optical system from the coolant pipe work in the chamber will also reduce the vibration experienced by the final optic assembly and any alignment and tracking hardware connected to the vacuum chamber.

The entire unit can be transported on rails within a suitable enclosure to the hot cell decommissioning and maintenance area. A replacement chamber would be kept pre-assembled in preparation for operation. By removing the need to disconnect and reconnect any vacuum pipe work and by decoupling the chamber from the optical infrastructure, a relatively rapid exchange can be achieved.

If the entire process of chamber removal and insertion spanned one month, then a wall lifetime of four years (see above) would only impact the plant availability by 2%. Periodic maintenance at this level is required for conventional plant operations anyway.

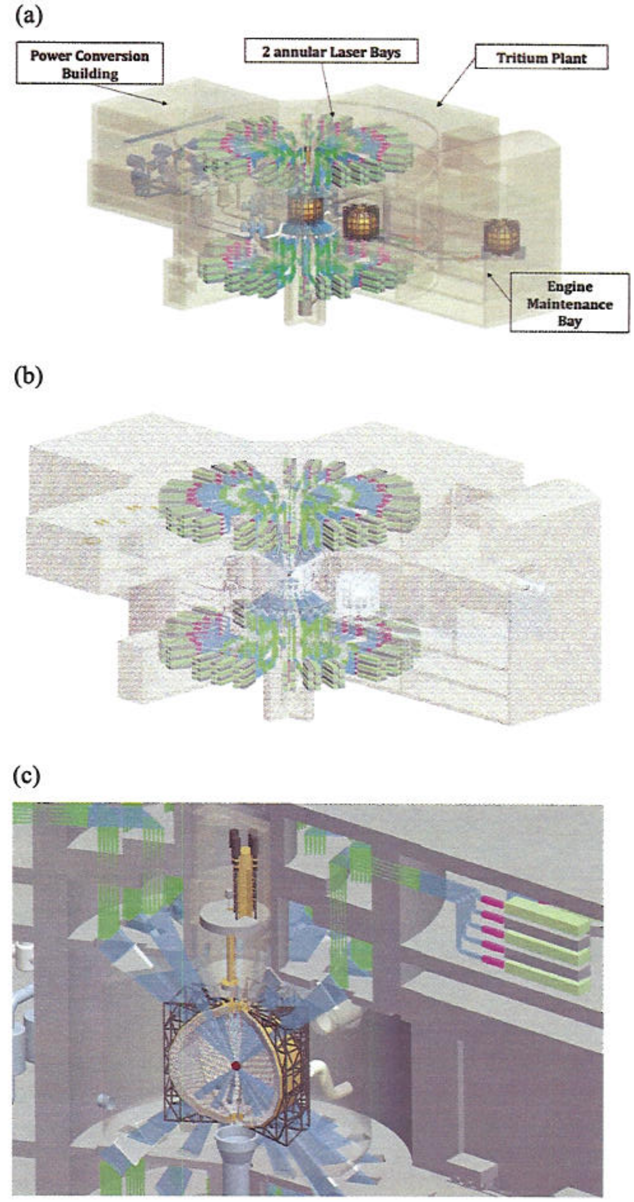

Fig. 3. Layout of the LIFE power plant Fusion Operations Building. (a) Overall layout of the building, with the fusion chamber shown in three positions: in its operational state, en route to the maintenance bay, and within this bay. (b) The annular arrays of lasers are highlighted, within the 100-m diameter cylindrical central section of the plant. The upper and lower laser bays contain rings of beam-boxes in a NIF-like irradiation geometry. (c) Cut-away view of the Fusion Operations Building, showing target chamber, beam paths through the dual neutron pinholes, into the upper laser bay. The target injector is shown at the top of the chamber, with 4-module redundancy to ensure robust operations.

III.D. Safety and Security of Fuel

Many fusion plant designs require large quantities of tritium for start up and operations (with estimates of 40 to 60 kg per GW power plant, which is high compared to the available global inventory). This limits both the feasibility of integrated system tests and substantially reduces the rate of rollout of a fleet, leading to unacceptably slow market penetration.

A range of design choices made for the LIFE design act to reduce the in-process tritium inventory. The high fractional burn-up in an IFE capsule (~30% for the LIFE designs) relaxes the tritium breeding requirements,[8,9] while the use of only milligram quantities of fuel per shot and choice of a pure lithium coolant substantially reduce the amount of material entrained in the facility – to around 600 g for the entire site. The coolant inventory is just tens of grams.

Calculations of the mobilization of tritium and activated steel (for example in the event of a major accident) indicate that the safety response of a LIFE plant represents a key motivating factor for its deployment.

III.E. Delivery to Market

After ignition on NIF, the next step needs to be a technology demonstration program (see next section) coupled to detailed design of the integrated LIFE plant. Such coupling is essential if informed decisions are to be made and system-wide consistency is to be maintained. Construction of the LIFE plant would be based around production of ~400-MW net electricity to demonstrate full system performance. The facility is designed to be able to be up-powered to 1000-MW net output, with suitable retrofitting of thermal plant equipment.

The first phase of the LIFE plant is designed to demonstrate all the required technologies and materials certification needed for the subsequent rollout of electric power. It could also provide tritium fueling for start-up operation of the subsequent steps. This phase is often termed "LIFE.1" in the papers referenced below.

Estimates of the technology development program requirements, along with manufacturing and construction time scales and estimates of the licensing process indicate that this plant could be commissioned and operational by the mid 2020s, assuming ignition on NIF in 2012 and a funded program thereafter.

Delivery in this timeframe is possible only if driver characteristics and target illumination solutions demonstrated by NIF ignition are adopted. Deviation from a defined physics platform adds unacceptable technical risk.

Greatest uncertainty in the time required for delivery rests in the details of the licensing regime to be adopted for such power plants – an issue that needs concerted attention.

Economic assessments show that the plant design is competitive both in terms of capital cost and cost of electricity – see Anklam et al.[3] This paper also shows that the timeliness requirements for commercial delivery are compelling. Rollout from the 2030s would remove 90–140 gigatonnes of CO_2-equivalent carbon emissions by the end of the century (assuming U.S. coal plants are displaced and the doubling time for roll-out is between 5 and 10 years). Delaying rollout by just 10 years removes 30–35% of the carbon emission avoidance, which at \$100/MT translates to a net present value of 140–260 B\$. If IFE is to be a meaningful component of the solution, a focused delivery program is urgently needed. Similar arguments hold for other low carbon sources of energy.

IV. DEVELOPMENT REQUIREMENTS

There remain significant technical hurdles to overcome in order to deliver a working fusion plant on the required time scale at acceptable cost. The most challenging aspects are not development of individual subsystems, but rather their integration into an operational plant. As demonstrated with the NIF (and other large-scale undertakings such as the Large Hadron Collider and X-ray Free Electron Laser), it is highly advisable to tackle such issues through concurrent development programs within an engineering project tasked with self-consistent system delivery. This avoids sub-optimization of component systems, drives timely delivery, substantially reduces overall costs, and allows balanced investment decisions based on mission need and residual technical risk. IFE success is thus reliant on timely adoption of a top-level facility design.

In progressing the technical development program, it is critically important to start from the power plant design and associated regulatory requirements to determine an overall balance of priorities. By integrating economic models (considering capital and running costs, supply chain availability and timeliness of delivery) with performance models, substantially different optimization choices are made compared to analyses that consider performance alone. We see qualitative changes in parameters such as the desired driver efficiency, target gain, choice of coolant, and overall plant architecture.

The separability of the subsystems of an IFE plant remains a beneficial feature, but is more appropriate to the operational phase of a power plant rather than in its developmental phase – an issue that is often misunderstood when technology programs are being formulated. A modular design provides high maintainability and system availability, while also offering through-life operational improvements based on the likely advances to emerge from ongoing physics, materials and system optimization studies.

More generally, it is of course recognized that there are other potential routes to fusion energy production that would offer complementary benefits to a commercial rollout strategy over the longer term and would incorporate many common design solutions (for example in structural materials, tritium handling and the thermal-electric system). All potential solutions would directly benefit from the early demonstration of a continuously operating fusion plant (both in terms of technology development and in terms of public/policy awareness).

LIFE power plant designs could be adapted for alternate target designs based on experience from the NIF, guided by the specific mission need. The performance of the initial LIFE facility could also be expected to provide sufficient confidence for wider development and rollout of different system solutions for subsequent fleets, which benefits other, less mature, approaches to fusion.

IV.A. Technology Risk Reduction

The LIFE project to date has established a design approach that allows trade-offs between technical areas to be made by quantifying risk to delivery (via Technology, Manufacturing and System Readiness Levels) and economic impact (expressed at a top level as cost of electricity, $/MWh, and capital intensity, $/W).

An integrated technology demonstration program has been prepared, feeding into the construction schedule for the facility. Based on the plant work breakdown structure, this program currently incorporates 470 functional requirements, 970 work statements and 185 milestones integrated into a 250-element schedule. Technology delivery time scales and costs were derived in consultation with over 30 vendors and experience with the NIF and other projects.

This plan yielded a set of key technical issues to be resolved and demonstrated in order to deliver commercial fusion energy. Each issue was ranked according to its impact, were it not to be resolved, and assigned a technical readiness level requirement as a function of project phase.

The initial phase of the LIFE facility itself will play a critical role in this program. This will: (i) demonstrate integrated operation of an IFE plant – encompassing a closed fuel cycle, thermal cycle and electric conversion system, (ii) establish a robust concept of operations for a commercial power plant, (iii) understand the RAMI characteristics of the (coupled) subsystems emerging from the technology program, (iv) provide a relevant fusion environment for full-scale testing of materials, components and systems, (v) provide qualification and certification data for licensing of the commercial phase of the plant by the NRC, and (vi) drive vendor readiness via early facilitization and adoption of key technologies.

Within this technology demonstration program, some of the required developments are:

- **Blanket design**. Detailed neutronics calculations indicate a blanket gain of between 1.1 and 1.4 is attainable (currently optimized at 1.2), alongside sufficient tritium breeding ratio (>1.1) and high thermo-electric conversion efficiency. A robust engineering design remains to be developed and will likely undergo significant design modifications during early operation of the LIFE engine. Suitably flexible interface characteristics with the wider plant need to be enabled, making full use of the ability to field independent, replaceable sectors of the first wall and blanket chamber.
- **Thermo-electric plant**. The ability of a LIFE plant to generate high temperatures in the first wall and blanket opens up the potential for high efficiency thermal-to-electric conversion. In consultation with utility customers and turbine manufacturers, Rankine cycle designs have been adopted for LIFE, based on demonstrated super-critical steam systems. Use of fluid temperatures below 600 °C enables the use of steel pipe work. This results in an overall conversion efficiency of 44% and cost effective implementation. Earlier work explored the potential of even more efficient designs using a closed Brayton cycle and advanced pipe work. These are conceptually possible, but are incompatible with the design philosophy of using readily available technology solutions. Future incorporation of these systems remains possible, taking advantage of ongoing research for the solar thermal and Gen-IV fission communities.
- **Laser system**. Advances at LLNL in beamline architecture show the ability to shrink the laser footprint and reduce the required power load by very significant factors compared to flashlamp-pumped systems such as NIF. These designs make use of the substantial progress made in high average power, diode-pumped, solid-state lasers over the past few years (including recent demonstration of 100-kW average power operation). Prior experience at LLNL with the Atomic Vapor Laser Isotope Separation program (AVLIS) demonstrated continuous operation for 10 years with 99% availability for a high-power laser system operating at 25 kW and multi-kHz repetition rate. This program also demonstrated the operational solution of confining the lasers to line replaceable boxes.

  Integrated laser designs have been developed for LIFE that are calculated to achieve the required performance characteristics using Nd:glass gain media, helium cooling and diode technology.[6] Diode costs represent the major cost center for the laser, but draw from a highly competitive supply chain associated with the mass markets for similar solid-state components. Performance levels and anticipated prices for the diodes were established via consensus of a wide cross section of the semiconductor laser market, based on known production methods and with anticipated investment in the required production capacity. They indicated diode price points consistent with commercially viable rollout (1.8 to 3.3 ¢/W for diodes for a single plant, dropping to ~0.7 ¢/W for continuous production). This marks a step-change from just a few years ago, bringing IFE driver technology into an affordable range for plant construction.

Further development of high efficiency (>10%), high repetition rate (10–20 Hz), pulsed diode-pumped solid-state laser (DPSSL) beamlines is under way for a variety of international projects, including the $1B European ELI project.[10]

For LIFE, an integrated demonstration of a full-scale DPSSL beamline is a key near-term objective.[6] Work is required to optimize the design, quantify performance and explore component longevity. Development of robust, high throughput production methods for the optics, in particular the final focusing system, frequency converters and gain isolation components is required.

- **Target production**. Power plant operations will require on the order of 10^6 targets per day. The inertial fusion program to date has developed and used a wide range of techniques to produce targets to the required specifications, but at necessarily high cost per target given the very small production numbers. Techniques are being developed to produce large quantities of targets, including capsule fabrication, DT fuel filling, and hohlraum production, as well as methods to deliver them accurately to the center of the target chamber, but much work remains to be done.[11] To date, models of target production factories that include capital amortization, personnel costs and operational consumables indicate that mass production will yield costs of $0.2-$0.3 per target, in which the material cost is <$0.05 per target. What remains is to demonstrate high volume production using such techniques while maintaining control over the specifications. Work on NIF to establish acceptable tolerances in the manufactured components is required following the demonstration of ignition.

  Ramp-up of initial operations in the LIFE plant will allow phased introduction of bulk target manufacture and handling systems.

- **Target injection and engagement**. The chamber must be capable of being restored sufficiently to its initial condition after each shot to allow insertion of the next target and for transmission and focusing of the next pulse of energy to that target. Dynamic thermal calculations show that the indirect-drive hohlraum can be modified to act as an effective thermal shield (protecting the cryogenic DT capsule from injection into the 5000- to 7000-K gas and from radiation from the 900-K walls). The relatively high-density chamber gas is essential for the chamber to survive the ensuing target implosion. Tracking and engagement studies show that NIF-level tolerances on beam placement can be maintained for a dynamically inserted target. And chamber dynamics calculations suggest that only very small (<1%) clearing ratios should be needed. This obviates the need to evacuate the whole chamber, which would impose intolerable constraints on the vacuum system performance and cost. Uncertainties remain with regard to the thermal and aerodynamic environment and its impact on the target performance. Down-selection of injector, tracking and engagement technologies awaits results from prototype tests.
- **Tritium plant**. There is a clear requirement to minimize the in-process tritium inventory (for safety / licensing reasons as well as to ensure tritium supply does not constrain the rate of commercial plant roll-out). The scale, cost and design philosophy of the tritium processing plant is closely tied to the material content of the targets and the clearing rate of the xenon-filled chamber. Careful iteration of these terms taking into account the impact on the tritium systems is under way.
- **Integrated facility design**. A number of important design choices must be made at the facility level; for example, whether an initial LIFE plant could be upgraded to a larger-scale fusion or hybrid system. Maintenance solutions for the LIFE engine and other key components need detailed engineering designs. Vibration and other environmental response functions need to be fully quantified, failure mode analyses and other safety assurance studies need to be completed, and regulatory requirements on facility construction need to be addressed.

These broad technical requirements demand a nationwide partnership between industry, national labs, government, non-governmental organizations and academia within the context of a single delivery project. Advantage should also be taken of work under way in Europe and Asia in closely related areas.

V. SUMMARY

A goal-oriented, evidence-based approach has been proposed to allow LIFE power plant rollout on a time scale that meets policy imperatives and is consistent with utility planning horizons. The system-level delivery builds from our prior national investment over many decades and makes full use of the distributed capability in laser technology, the ubiquity of semiconductor diodes, high volume manufacturing markets, and U.S. capability in fusion science and nuclear engineering.

The LIFE approach is based on the ignition evidence emerging from NIF and adopts a line-replaceable unit approach to ensure high plant availability and to allow evolution from available technologies and materials. Utilization of a proven physics platform for the ignition scheme is an essential component of an acceptably low-risk solution. The degree of coupling seen on NIF between driver and target performance mandates that little deviation be adopted from the NIF geometry and beamline characteristics. Similarly, the strong coupling between subsystems in an operational power plant mandates that a self-consistent solution be established via an integrated facility delivery project.

The benefits of separability of the subsystems within an IFE plant (driver, chamber, targets, etc.) emerge in the operational phase of a power plant rather than in its developmental phase. An optimized roadmap for IFE delivery needs to account for this to avoid nugatory effort and inconsistent solutions.

For LIFE, a system design has been established that could lead to an operating power plant by the mid-2020s, drawing from an integrated subsystem development program to demonstrate the required technology readiness on a time scale compatible with the construction plan.

Much technical development work still remains, as does alignment of key stakeholder groups to this newly emerging development option. If the required timeline is to be met, then preparation of a viable program is required alongside the demonstration of ignition on NIF. This will enable timely analysis of the technical and economic case and establishment of the appropriate delivery partnership.

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