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HIGH LEVEL REQUIREMENTS FOR AN IFE DEVELOPMENT PROGRAM

(Submission to the call for white papers on research opportunities in Inertial Fusion Energy)

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Executive Summary: This White Paper lays out a framework to help guide the formulation of an IFE technology program that explicitly takes account of the needs of the end-user power plant design, construction, licensing, commissioning and operational phases. This viewpoint seeks to ensure that near-term decisions are consistent with the long-term goals, and seeks to minimize effort spent on developments that are incompatible with an integrated system solution.

Topical Area: General, including complete IFE concepts

A useful structure to focus the assessment of an IFE technology development program is to consider a pre-commercial, utility-scale demonstration plant. This would act as the key step from physics demonstration of fusion gain to a commercial plant. Such a facility requires resolution of all the technical elements of a power plant, but can adopt a bootstrapping approach to regulatory approval, and does not need to be constrained to achieve a competitive market position. The plant would quantify the technical, regulatory, and commercial performance terms that need to be established for rollout of a subsequent fleet.

The approach of working backward from the integrated requirements of a representative end-user power plant is deemed necessary as a result of the wide variety of IFE concepts and technologies, and the highly complex and interdependent nature of the individual sub-systems. This requires that the path to a self-consistent solution needs to be actively managed [1].

The design of such a plant would need data from a precursor technology program, along with physics performance studies, safety / licensing / environmental imperatives, end-user requirements, supply chain considerations, and financial constraints. These data need to be integrated in a system-level model that incorporates a self-consistent point-design to derive a set of viable plant solutions.

The overall scope of work should consider the time-dependent risk appetite of the sponsors of the technology program and subsequent plant delivery. Specifically, this should assess risk on the axes of: physics performance, technology, project execution, regulation and deployment, supply chain, plant operations, and commercial market risk.

Specific objectives for an example program are listed below, starting from the demonstration plant and then projecting backwards to the technology development phase.

(1) Demonstration Plant Objectives

A. Self-consistency of solution

- The primary objective is to provide an existence proof that an inertial fusion power plant can be designed, built and commissioned with characteristics that are scalable to commercially relevant performance, schedule and cost.
- The plant should also demonstrate that the equipment and systems required for an IFE Plant can be procured at the appropriate scale, and that the supply chain is sufficiently robust to support the rollout of follow-on plants.
- It must also show that a fusion power plant can be licensed, and that the licensing protocols are significantly simpler and more predictable than for nuclear fission.

B. Operation as an Integrated System

- The plant needs to combine the physics performance from a high-gain, single-shot demonstration (i.e., NIF) with the technologies required for rep-rated operation, to produce a continuously operating source of thermal energy.
- It must demonstrate integrated operation over an acceptable period (repeated fusion performance, blanket thermo-mechanical operation, closed tritium cycle, waste management, etc.). As two examples:
    i. It must show that fuel targets can be assembled, filled and delivered to the fusion chamber at the required rate and fidelity, and with an acceptable cost scaling.
    ii. It should quantify the reliability and availability of each sub-system, and demonstrate an appropriate monitoring and maintenance regime.

C. Safe and Acceptable to the Public

- The plant must demonstrate that it can be operated safely from a public and worker protection perspective and that routine emissions do not exceed regulatory or public acceptance limits.

- It must enable the testing of chamber materials performance, inspection/certification protocols, and system-wide accident scenarios to define the design-basis and beyond-design-basis, and provide the required data to scale to full operational performance.
- It must show that waste streams can be disposed of or recycled in a manner that meets regulatory and public acceptance requirements.

D. Commercial Viability Projection

- It must show levels of plant availability that are sufficient to justify scale-up to a commercial fleet – including demonstration of power plant-like operability and maintainability (i.e. with a credible workforce and service model), and development of grid-compatible startup/shutdown protocols.
- It must qualify the fusion chamber materials that are required to scale up in power density to the needs of a commercial operating parameter space (NRC, ASME, lifetime, replacement time, etc).
- It would ideally generate revenue by selling electricity that can be used to partially offset the cost of building the plant – perhaps via a scale-up step as part of the qualification process.

(2) Technology Development and Capability Demonstration Program to Inform the Plant Design

The following list is intended to provide a very high-level representative set of examples for a near-term IFE technology program, guided by the above plant considerations. Clearly, each area is highly complex and so this is not intended to be anything other than indicative of the need for a broad-based approach that embodies the guiding principles of: overall program balance, requirements-driven goals, system-level evaluation and down-selection, and pursuit of self-consistency and timely delivery.

The program's approach should be to enable modularity of sub-systems to the greatest degree possible, so that the constituent technologies can be developed and demonstrated separately and in a parallel fashion.

A. Laser design, development and testing

- **Objectives**: Reduction-to-practice of the underpinning laser system architecture, with a goal of multi-kW operation at multi-kJ beamline performance with giga-shot durability.
- **Task**: Construction of an intermediate energy system to inform the overall architecture and system integration solutions (e.g. with respect to stability, margin and longevity), followed by a full-scale prototype beamline to demonstrate the appropriate performance, reliability, and efficiency. An optical test system will be needed for lifetime testing, damage mitigation, and in-service maintenance solutions.

B. Laser beamline manufacture, packaging and deployment

- **Objectives**: Integration of intermediate- and then full- scale systems into a line-replaceable, hot-swappable "laser box". It is noted that a packaged solution will have applications in a wide range of immediate-term markets.
- Assess the potential for emerging technologies such as additive manufacturing (for optics, lightweight frames, and segmented fusion chamber). These disruptive approaches offer substantial advances in cost and performance, and build from the leadership established by NNSA programs.
- **Task**: Build a beam-box mechanical mock-up and then performance prototype; demonstrate the required approaches to maintainability and servicing; and test options for advanced component manufacture and integration.

C. Semiconductor laser diode development and testing

- **Objectives**: Optimization of laser diode performance and manufacture, tackling the single highest cost element of the plant, with direct application to other diode-based laser systems.
- **Task**: Development of suitably high power, packaged diodes. Adoption of automated assembly and batch processing solutions required for high-volume, low-cost delivery.

D. High performance fuel (target) design

- **Objectives**: The program needs to deliver a near-neighbor demonstration of fusion performance. This needs modeling and NIF-based testing of IFE relevant designs (e.g., DT-wetted foams, chamber-compatible materials, flight-tolerant assembly, etc) to demonstrate ignition and gain-scaling at a level that provides an acceptable risk to scale to the plant.
- **Task**: Verification of IFE-compatible designs and manufacturing tolerances. Testing of in-chamber performance (e.g., measurement of energy partition of fusion products; interaction with any chamber gas; and likely state of the waste stream).

E. Mass manufacture of fuel targets

- **Objectives**: Design, demonstration and vendor preparation for mass manufacturing operations and construction of prototype assembly stations using materials and techniques that can deliver the required tolerances, tritium inventory, reactor environment compatibility, and cost scaling.
- **Task**: Development of scalable manufacturing process for all components, and operation of an integrated fuel assembly station.

F. Integrated fuel injection, tracking and engagement

- **Objectives**: Demonstrate that the target can be injected and engaged in a representative thermo-mechanical environment while remaining structurally intact and in the desired physical state and orientation. Quantify the likely rate of dud events to inform the chamber/optics design. Quantify the failure and maintenance cycles for the injector (e.g. barrel wear), and in-chamber tracking/engagement system requirements.
- **Task**: Construction and optimization of prototype injection and engagement system.

G. Tritium processing system development and testing

- **Objectives**: Optimization of tritium extraction, confinement, containment and processing technologies and materials, consistent with an on-site inventory for the plant that fits within the regulatory regime for predictable licensing.
- **Task**: Design and test prototypes for chamber exhaust systems, blanket systems, and tritium processing systems.

H. Fusion engine (chamber) design, manufacture and testing

- **Objectives**: The integrated chamber solution is perhaps the single most difficult element to develop in the absence of an integrated prototype plant. The chamber needs to enable successful target and driver delivery; capture and transmit thermal power with high efficiency; be resistant to activation, decay heat, radiation damage, swelling, and corrosion; breed sufficient tritium; remove residual target debris; reset for the next pulse; withstand the peak stresses of each pulse along with time-averaged creep and degradation; and maintain sufficient longevity and availability for sustained multi-year operation.
- **Task**: First wall and heat transfer loop design, with construction of prototype. Optimization for safety and performance of the integrated engine system, including testing of key sub-systems such as the primary heat transfer loop. Extraction of data on corrosion, chemical reactivity, thermo-mechanical and nuclear performance to inform the chosen coolant materials, and overall plant design and safety analysis. Technology evaluation for remote handling of activated engine components and systems.

I. Advanced material development and testing

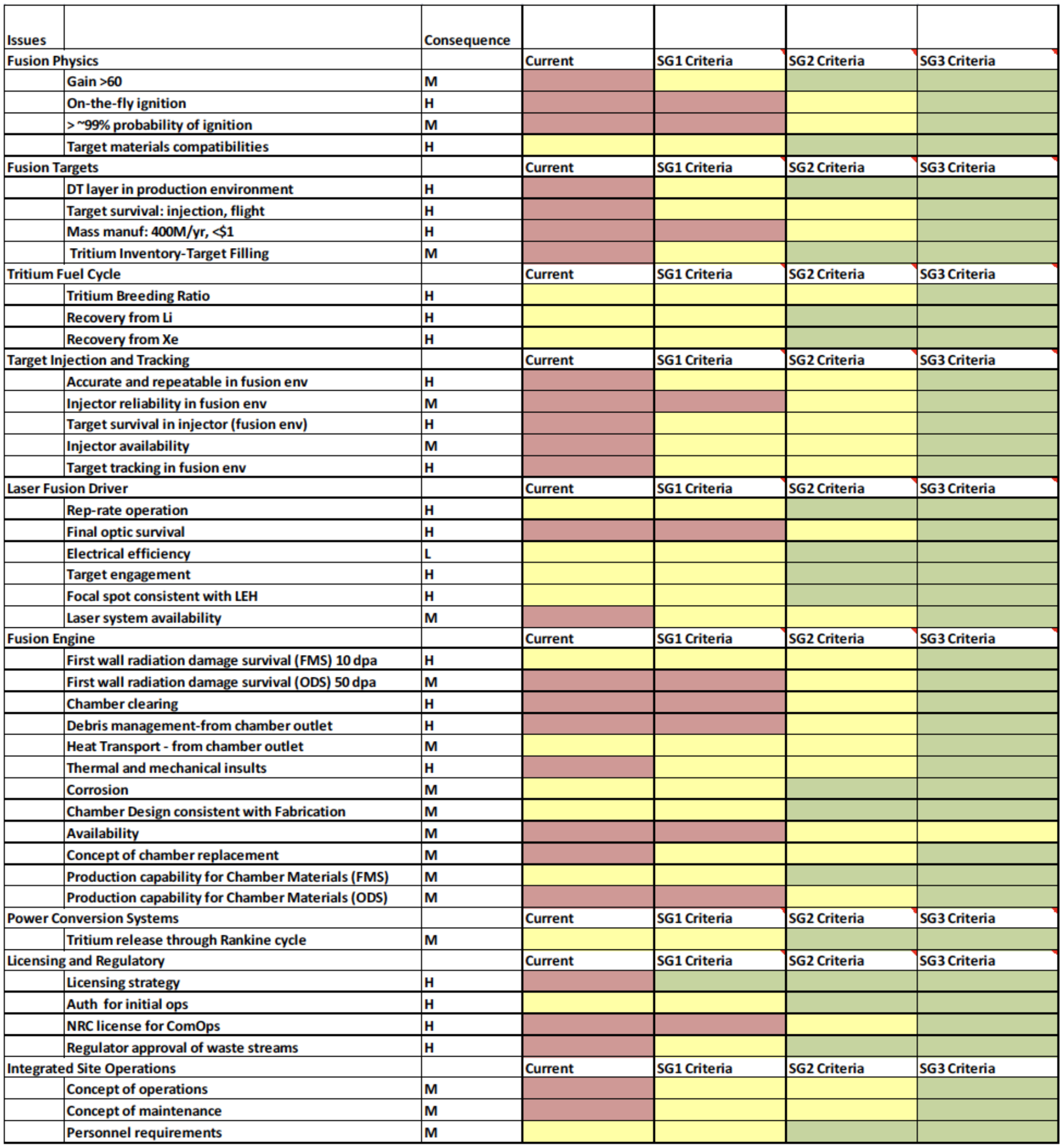
- **Objectives**: The chamber materials will require specialized manufacture (e.g. low impurity steels or composites), and extensive component evaluation and lifetime testing to demonstrate the ability to be fabricated into necessary shapes and configurations with practical joining processes. Tests will be needed to quantify resistance to radiation damage, including swelling and helium embrittlement; high-temperature strength and resistance to creep; and resistance to corrosion and environmental cracking at high-temperature.

- **Task**: Neutron and ion beam tests, with mechanical strength evaluation. Accelerated development of next-generation materials.

J. Integrated power plant design

- **Objectives**: Establish a robust, quantifiable basis for overall plant requirements and design optimization.
- **Task**: Build an integrated system model and point design framework to inform the technology development priorities, assess key tradeoffs, and evaluate plant-level performance characteristics.

An example of a time-phased IFE technology development plan was published for the LIFE concept [2]. This is not intended to be exclusive of other approaches, but provides a representative assessment of relative technical risk as a function of phase. A summary chart from this paper is shown in Figure 1.



Issues		Consequence				
Fusion Physics			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Gain >60	M	🟥	🟨	🟩	🟩
	On-the-fly ignition	H	🟥	🟥	🟨	🟩
	> ~99% probability of ignition	M	🟥	🟥	🟨	🟩
	Target materials compatibilities	H	🟨	🟨	🟩	🟩
Fusion Targets			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	DT layer in production environment	H	🟥	🟨	🟩	🟩
	Target survival: injection, flight	H	🟥	🟨	🟨	🟩
	Mass manuf: 400M/yr, <$1	H	🟥	🟥	🟨	🟩
	Tritium Inventory-Target Filling	M	🟥	🟨	🟩	🟩
Tritium Fuel Cycle			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium Breeding Ratio	H	🟨	🟨	🟨	🟩
	Recovery from Li	H	🟨	🟨	🟩	🟩
	Recovery from Xe	H	🟨	🟨	🟩	🟩
Target Injection and Tracking			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Accurate and repeatable in fusion env	H	🟥	🟨	🟨	🟩
	Injector reliability in fusion env	M	🟥	🟥	🟨	🟩
	Target survival in injector (fusion env)	H	🟥	🟨	🟨	🟩
	Injector availability	M	🟥	🟨	🟨	🟩
	Target tracking in fusion env	H	🟥	🟨	🟨	🟩
Laser Fusion Driver			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Rep-rate operation	H	🟨	🟨	🟩	🟩
	Final optic survival	H	🟥	🟥	🟨	🟩
	Electrical efficiency	L	🟨	🟨	🟩	🟩
	Target engagement	H	🟨	🟨	🟩	🟩
	Focal spot consistent with LEH	H	🟨	🟨	🟩	🟩
	Laser system availability	M	🟥	🟨	🟨	🟩
Fusion Engine			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	First wall radiation damage survival (FMS) 10 dpa	H	🟨	🟨	🟨	🟩
	First wall radiation damage survival (ODS) 50 dpa	M	🟥	🟥	🟨	🟩
	Chamber clearing	H	🟥	🟥	🟨	🟩
	Debris management-from chamber outlet	H	🟥	🟥	🟨	🟩
	Heat Transport - from chamber outlet	M	🟨	🟨	🟨	🟩
	Thermal and mechanical insults	H	🟥	🟨	🟨	🟩
	Corrosion	M	🟨	🟨	🟩	🟩
	Chamber Design consistent with Fabrication	M	🟨	🟨	🟩	🟩
	Availability	M	🟥	🟥	🟨	🟨
	Concept of chamber replacement	M	🟥	🟨	🟨	🟩
	Production capability for Chamber Materials (FMS)	M	🟨	🟨	🟩	🟩
	Production capability for Chamber Materials (ODS)	M	🟥	🟥	🟨	🟩
Power Conversion Systems			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium release through Rankine cycle	M	🟨	🟨	🟩	🟩
Licensing and Regulatory			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Licensing strategy	H	🟥	🟩	🟩	🟩
	Auth for initial ops	H	🟨	🟨	🟩	🟩
	NRC license for ComOps	H	🟥	🟥	🟨	🟩
	Regulator approval of waste streams	H	🟥	🟨	🟩	🟩
Integrated Site Operations			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Concept of operations	M	🟥	🟨	🟨	🟩
	Concept of maintenance	M	🟥	🟨	🟨	🟩
	Personnel requirements	M	🟨	🟨	🟩	🟩

***Figure 1**: Technical risk assessment summary, extracted from reference [2], plotting a qualitative assessment of residual risk after each of 3 major development phases (SG1 to SG3).*

References

[1] M. Dunne, T. Anklam, W. Meier, 2021, “Inertial Confinement Fusion Power Plants”, Greenspan, E. (Ed.), Encyclopedia of Nuclear Energy, vol. 3. Elsevier, pp. 807–821. https://dx.doi.org/10.1016/B978-0-12-819725-7.00170-7

[2] T. Anklam, “Overview of the LIFE Delivery Plan – Response to a request for information from the National Research Council”, LLNL-TR-480803, April 2011, https://doi.org/10.2172/1117836