Reference: History of Inertial Fusion Energy Research at LLNL

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The potential application of Inertial Confinement Fusion (ICF) to energy production has been pursued by the community, including LLNL, since the recognition that it might be possible to achieve high gain ICF in the laboratory [1]. Over the decades, LLNL has contributed to multiple IFE studies, with signficant efforts, including the High Average Power Laser (HAPL) program, in the 1990's and 2000's for both laser and heavy ion driven concepts [e.g. 2-27]. A substantive recent effort was the Laser Inertial Fusion Energy (LIFE) study, which aimed to develop an accelerated path towards commercialization of IFE in anticipation of ignition (breakeven) on the National Ignition Facility (NIF). As a relatively recent effort (~2008 to ~2014) that studied, preliminarily developed, and integrated many aspects of what might be required to achieve IFE, the results from LIFE can provide one viewpoint and help inform the IFE community as we work to develop an appropriate path forward. This whitepaper summarizes these efforts briefly and provides a list of organized references for potential follow-up.

The LIFE study proposed and developed an accelerated pathway to IFE centered on the premise that early commercialization was very important for maximizing the benefits of fusion, in terms of avoiding carbon emission, high level nuclear waste, or plutonium produced, depending on potential future energy scenarios. The analyses projected that ~30-35% of the potential carbon reduction of fusion would be lost if commercialization was delayed from 2030 to 2040. The aggressive goals of this work sought to produce a viable path towards a demonstration facility in the 2020's timeframe, with the first commercialized plant in the mid-2030's, assuming ignition in the early 2010's. It was envisioned that continual improvements during scale-up would ultimately lead to a more cost-effective, mature design. LIFE included development of a science, technology, and engineering basis for a viable reactor concept and scale-up strategy within this framework, building on existing, and what was expected to be near-term extrapolation of, ICF fusion science and nuclear technologies where possible, and guided by systems, economic, and operational analyses for areas of R&D and technology choices with highest impact. Input from a range of stakeholders, such as from the utilities and the licensing community, was sought and incorporated. In addition, models for viable public-private partnerships, such as the formation of non-profit consortiums, were developed should the effort became fully established.

Detailed reactor concepts and their associated components were developed for both pure fusion and hybrid fusion-fission configurations, with a strong systems approach, before the effort was ramped down in the early/mid-2010's. The deep-burn fusion-fission configuration was developed first, followed by the pure fusion configuration. The concepts built on NIF's indirect drive approach for the target, driven by solid state diode pumped neodymium glass lasers in modular Line Replacement Units (LRU), and shot in a NIF scale target chamber buffered by xenon gas with lithium as the coolant and tritium breeder. The overall reactor was designed with strong modularity to ensure high systems reliability, availability, and maintainability, allowing for efficient exchange of modular components including a first wall made of near-term materials such as HT-9 and 12YWT steels. Detailed considerations and analyses for safety, minimization of required tritium inventory, and licensing were also integrated into the designs in order to enable deployment.

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As the community works to develop the appropriate next steps in a national IFE program, this work is one example of an integrated approach that can inform our planning. The published works from this period can be roughly organized by the following categories; the list might not be exhaustive but is sufficient for follow-up:

Overall Concept, Systems and Economic analyses:

T. M. Anklam et al., "LIFE: The Case of Early Commercialization of Fusion Energy", Fusion Sci. Tech. 60(1), 66-71 (2011).

M. Dunne et al., "Timely Delivery of Laser Inertial Fusion Energy (LIFE)", Fusion Sci. Tech. 60(1), 19-27 (2011).

W.R. Meier et al., "Systems Modeling for the Laser Fusion-Fission Energy (LIFE) Power Plant", Fusion Sci. Tech. 56(2), 647-651 (2009).

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W.R. Meier et al., "Fusion Technology Aspects of Laser Inertial Fusion Energy (LIFE)", Fusion Engineering and Design 89(9-10), 2489-2492 (2013).

S. Reyes et al., "LIFE: A sustainable solution for Developing Safe, Clean Fusion Power", Health Physics 104(6),641-647 (2013).

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T.M. Anklam, "LIFE: Recent Developments and Progress", LLNL Technical Report, LLNL-TR-480091, (2011).

T.M. Anklam, "LIFE Cost of Electricity, Capital and Operating Costs", LLNL Technical Report, LLNL-TR-480444, (2011).

T.M. Anklam, "LIFE Delivery Plan", LLNL Technical Report, LLNL Technical Report, LLNL-TR-480803, (2011).

T.M. Anklam, "Summary of LIFE Delivery Plan", LLNL Technical Report, LLNL-TR-639294, (2013).

Laser Technologies:

A. J. Bayramian et al., "A Laser Technology Test Facility for Laser Inertial Fusion Energy (LIFE)". Journal of Physics Conference Series (Online), 244(3) (2010).

A. J. Bayramian et al., "Compact Efficient Laser Systems Required for Laser Inertial Fusion Energy", Fusion Sci. Tech 60(1), 28-48 (2011).

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A. Bayramian et al., "A Compact Line Replaceable Unit Laser Driver for Laser Inertial Fusion Energy", in Conference on Lasers and Electro-Optics 2012, OSA Technical Digest (online) (Optica Publishing Group, 2012).

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J. Caird et al., "ND: Glass Laser Design for Laser ICF Fission Energy (LIFE)", Fusion Sci. Tech. 56(2), 607-617 (2009).

A. C. Erlandson et al., "Comparison of ND: phosphate glass, Yb:YAG and Yb:S-FAP laser beamlines for laser inertial fusion energy (LIFE) [Invited]", Optical Materials Express 1(7), 1341-1352 (2011).

LLNL Technical Reports (Available on OSTI.gov website-search by title or identifier number):

R. Deri et al., "The LIFE Laser Design in Context: A Comparison to the State-of-the-Art," LLNL Technical Report, LLNL-TR-477795.

<u>Target Design, Manufacture and injection:</u>

P. Amendt et al., "LIFE Pure Fusion Target Designs: Status and Prospects", Fusion Sci. Tech. 60(1), 49-53 (2011).

K. Carlisle and R. Miles, "Laser Inertial Fusion-based Energy (LIFE) – Developing Manufacturing Technology for low cost and high volume fusion fuel is critical to our future energy needs", Proceedings of the 36th International Matador Conference, 559-568 (2010).

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R. Miles, et al., "Challenges Surrounding the Injection and Arrival of Targets at LIFE Fusion Chamber Center", Fusion Sci. Tech. 60(1), 61-65 (2011).

LLNL Technical Reports (Available on OSTI.gov website-search by title or identifier number):

D. S. Holdener et al., "Convective Heating of the LIFE Engine Target During Injection", LLNL-SR-508392, (2011)

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R. Miles et al., "Thermal Studies of the Laser Inertial Fusion Energy (LIFE) Target during Injection into the Fusion Chamber", LLNL Technical Report, LLNL-TR-660043, (2014).

R. Miles et al., "Topics in LIFE Target Survival: 11-SI-004 Final Report", LLNL Technical Report, LLNL-TR-663242, (2014).

<u>Chamber and reactor design, and fuel cycle:</u>

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K.J. Kramer et al., "Neutron transport and Nuclear Burnup Analysis for the Laser Inertial Confinement Fusion-Fission Energy (LIFE) Engine", Fusion Sci. Tech. 56(2), 625-631 (2009).

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H. Uddin et al., "Integrated inertial fusion energy chamber dynamics and response", Fusion Engineering and Design 89(12), 3131-3148 (2014).

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E. Beckett and M. Fratoni, "Characterization of High Level Waste from a Hybrid LIFE Engine for Enhanced Repository Performance", LLNL Technical Report, LLNL-TR-455920, (2010).

J. DeMuth and A. J. Simon, "LIFE Chamber Chemical Equilibrium Simulations with Additive Hydrogen, Oxygen, and Nitrogen", LLNL Technical Report, LLNL-TR-416959, (2009).

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R.W. Moir et al., “LIFE Materials: Molten-Salt Fuels”, LLNL Technical Report, LLNL-TR-409526, (2008).

A. Caro, “LIFE Materials: Topical Assessment Report for LIFE, TOPIC: Solid First Wall and Structural Components Task: Radiation Effects on First Wall”, LLNL Technical Report, LLNL-TR-409726, (2009).

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