

Progress and critical issues for IFE blanket and chamber research

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Abstract

Research has been initiated in the U.S. Virtual Laboratory for Technology on IFE chamber and target technologies. The critical issues, and the approaches taken to address these issues, are discussed. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Advances in high-gain target designs for inertial fusion energy (IFE), and the initiation of construction of large megajoule-class laser facilities in the US (National Ignition Facility) and France (Laser-Megajoule) capable of testing the requirements for inertial fusion ignition and propagating burn, have improved the prospects of IFE.

Accordingly, there have recently been modest increases in the US fusion research program related to the feasibility of IFE. These research areas include heavy-ion accelerators, krypton fluoride (KrF) gas lasers, diode-pumped, solid-state lasers (DPSSL), IFE target designs for higher gains, feasibility of low cost IFE target fabrication and accurate injection, and long-lasting IFE fusion chambers and final optics. Since several studies of conceptual IFE power plant and driver designs were completed in 1992–1996 [1–5], US research in the IFE blanket, chamber, and target technology areas has focused on the critical issues relat-

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ing to the feasibility of IFE concepts towards the goal of achieving economically competitive and environmentally attractive fusion energy. This paper discusses the critical issues in these areas, and the approaches taken to address these issues. The US research in these areas, called IFE Chamber and Target Technologies, is coordinated through the Virtual Laboratory for Technology (VLT) formed by the Department of Energy in December 1998.

2. IFE power plant requirements

A group of about 40 US researchers participating in the IFE Chamber and Target Technologies areas met in Pleasanton, CA, on March 18, 1999, to review the technical requirements and critical feasibility issues and recommended plans for IFE chamber and target technology research. The areas considered included IFE chamber design and development, including protection of final optics; IFE target development, low cost fabrication, precision injection and tracking; IFE safety and environmental research for the driver, chamber, and target factory.

The basic technical system requirements for any approach to fusion chambers and target systems for inertial fusion power plants are:

1. Maintaining chamber conditions suitable for target injection, driver beam propagation, and target ignition with high-energy gain at pulse rates of ~ 5 Hz.
2. Protecting the fusion chamber walls and driver beam interfaces so that these components can last for several years, and hopefully for the life of the plant, or be easily replaceable in sections, if needed.
3. Extracting fusion energy with high-temperature coolants for efficient conversion to electricity, while regenerating the tritium fusion fuel for targets with small just-in-time inventory.
4. Manufacturing precision targets at economically low cost and accurately injecting them into the center of the fusion chamber at pulse rates of ~ 5 Hz.

5. Reducing the volume of radioactive waste generation, inventory, and possible release fractions to levels low enough that no public evacuation is needed in worst-case accidents.

3. Critical issues

Past conceptual IFE design studies [1–5] have identified many different driver/chamber/target options, and the critical technical issues associated with them. With limited resources, feasibility tests on only a few options can be pursued at any one time, so the US effort will focus primarily on two of the most promising options over the next 4 years (phase I): (1) renewable liquid-wall chambers (HYLIFE-II [2]), with indirect-drive targets and ion accelerator drivers; and (2) dry-wall chambers (Sombbrero [1]), with direct-drive targets and laser drivers (KrF and DPSSL). The most critical top-level issues for these two approaches are sufficiently different to be listed separately below:

For thick liquid wall chambers with ion indirect drive targets:

1. Chamber: can thick liquid walls be formed, maintained, and evacuated from the chamber? Can rates of vapor condensation, droplet clearing, and flow recovery allow pulse rates of 5 Hz?
2. Driver and chamber interface: can superconducting quadrupole focusing magnet arrays be physically consistent with chamber/target solid-angle limits, for the required number of beams, standoff distance to the target, and transverse magnet dimensions and neutron shielding thickness? How much residual chamber vapor can be tolerated for heavy-ion beam propagation?
3. Target fabrication and injection: can hohlraums with several foam X-ray converters and an internal cryocapsule mount be mass manufactured consistent with target precision requirements, at a cost less than US\$0.3 per target, and withstand acceleration forces of injection?
4. Environment and safety: can a level of safety be achieved consistent with 'no-public-evacua-

tion-plan' requirements (< 1 rem (0.01 Sv) site boundary dose) for credible accidents, for example, possible temperature excursions of liquid coolant spills, including activated hohlraum materials?

For dry-wall chambers with laser direct-drive targets:

1. Chamber: can first wall blankets be designed to tolerate the range of uncertainty of surface ablation rates, thermal conductivity loss and swelling due to damage from neutrons and chamber gas heating due to pulses of X-rays and target debris? Can graphite channels last long enough against erosion due to Li_2O granule abrasion?
2. Driver and chamber interface: can the final optics be adequately protected from laser, neutron, X-ray, and debris damage sufficient to survive $> 10^8$ shots before replacement? Can the final optics have sufficient mechanical stability under pulsed heating and gas shocks to maintain microradian-pointing accuracy for acceptable target illumination? Can laser beams propagate in chamber gas densities sufficient to protect the first wall and final optics?
3. Target fabrication and injection: can direct-drive capsules survive injection (after separation from a sabot) into a hot chamber consistent with ΔT_{DT} temperature limits for 'beta-layering', and can the injection tracking be sufficiently predictable with turbulence in the chamber gas?
4. Environment and safety: can tritium inventories in the first wall and chamber structures and buildings be kept small enough to meet the 'no-public-evacuation-plan' criteria? Can replaced chamber materials be recycled to minimize annual waste volumes?

4. Research and development approaches

The near-term US research in the IFE Chamber and Target technology area over the next four years is referred to as phase I. The phase I objectives for both heavy-ion and laser-IFE approaches are to show that plausible technical solutions may

exist for the most critical issues to meet the above IFE power plant requirements. The phase I research will carry out assessment studies, small-scale experiments, and simulations. Later research (called phase II) would demonstrate more integrated non-nuclear tests at closer to full fusion chamber scale. During the phase I research period, information generated regarding the above critical issues for chambers and target fabrication/injection, and on the consistency of those with driver capabilities and target physics requirements for high gain, will be explored with integrated systems analysis as required to assess overall feasibility for IFE. The small-scale-experiments and integrated systems analysis may suggest alternative solutions to the indirect-drive and direct-drive approaches to IFE suggested above.

4.1. Liquid chamber R&D

Liquid wall chamber concepts use either a thin liquid layer (e.g. Prometheus, Osiris, and HI-BALL concepts) to protect chamber structures from short-ranged target emissions (X-rays and debris) or a thick liquid layer to protect structures from neutron damage and reduce activation (e.g. HYLIFE-II). The major phase I research objectives for liquid chamber R&D are to determine the feasibility of (1) establishing the desired flows and configurations of liquid protection schemes and (2) clearing the chamber of droplets, condensing the vapor, and recovering liquid flows from simulated disruptions, in times that scale to less than 1/5 s at full size.

The emphasis for indirect drive is on thick liquid flow protection of chamber walls. Current work using scaled experiments on liquid chamber fluid dynamics is underway at UCB, UCLA and the Georgia Institute of Technology. Fig. 1 shows an example of a thick-liquid hydraulic test facility at UCB, using water jets to simulate Flibe molten salt jets (such as in HYLIFE-II). Fig. 2 shows an experiment that uses 10-ns laser pulses to test the fracture strength of liquids that would be subjected to such forces from short pulse neutron heating. Argonne National Laboratory and Idaho National Engineering and Environmental Laboratory have also recently proposed R&D activities

using their facilities and expertise to address issues related to liquid chambers.

If this research shows that thick liquid wall chambers are feasible, then IFE power plant economics would benefit both from avoiding the cost of periodically replacing blankets, as well as from the higher plant availability due to avoiding the time needed to replace blankets.

4.2. Dry wall chamber R&D

Dry-wall chamber concepts (e.g. Sombrero) rely on a low-density (< 1 Torr), high- z gas to prevent X-ray and debris damage to the first wall, which is a carbon/carbon composite in the case of



Fig. 1. This UCB facility uses transient flow into a large vacuum vessel to study single jets (currently) and partial-liquid pockets with a few jets (future plans). Water can be used to simulate Flibe jets at $1/2$ – $1/4$ geometric scale with dimensionless Re , Fr and We numbers matching those in a power plant chamber.



Fig. 2. Target assembly for a liquid-fracture strength experiment called ‘Popoff’ at UCLA. This experiment measures the fracture strength of characteristic liquids such as Li, Pb, Flibe, and LiPb. Loaded by rapid tensile strains typical of shock loaded and rapidly heated thick jets and thin films in IFE wall protection schemes.

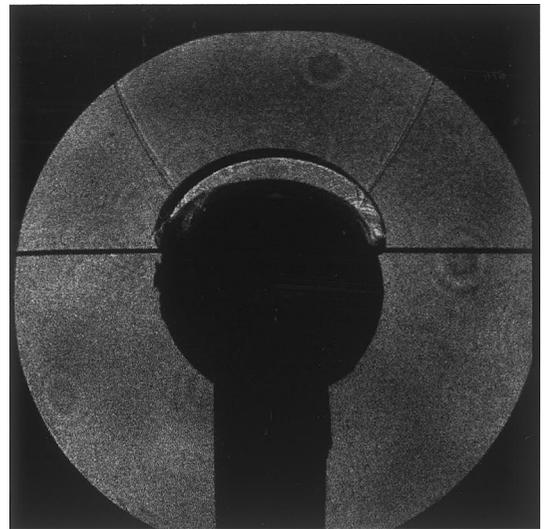


Fig. 3. The University of Wisconsin shock tube simulates blast flow around target chamber structures. This shows an image of a gas hitting and reflecting off a curved solid structure in an IFE experiment. This apparatus provides a testbed for structural response of target chambers and final optics to shocks.

Sombrero. The major phase I research objective for dry-wall chambers is to determine the plausibility of achieving dry-wall chamber lifetimes > 1 year between replacements, taking into account the damage due to neutrons, X-rays, and target debris. Pulsed plasma and X-ray sources at the Sandia National Laboratory might be used to simulate some IFE chamber conditions. Modeling and experiments on gas-protected chamber dynamics are continuing and future work is planned at the University of Wisconsin (UW), UCSD, Sandia National Laboratory, and UCLA. Fig. 3 shows an experiment at the UW using a large gas-driven shock tube to test the shock loading of non-planar structures for IFE chambers. Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNL) are also interested in working with the IFE element of the VLT on assessments of materials issues.

New materials may have an important impact on the feasibility of dry-wall chambers for direct drive IFE. It may be possible to develop 4-D weaves of carbon composites that are more tolerant of neutron-induced swelling. Also, there are some aluminum-loaded silicon-carbide composite samples undergoing in situ thermal conductivity measurements in the HFIR reactor [6], which may show improved thermal conductivity compared to conventional SiC composites. If the improvements are large enough to extrapolate to 50–100 W/m K at between 1500 and 2000°C, then SiC composites may be usable in gas-protected dry-wall chambers

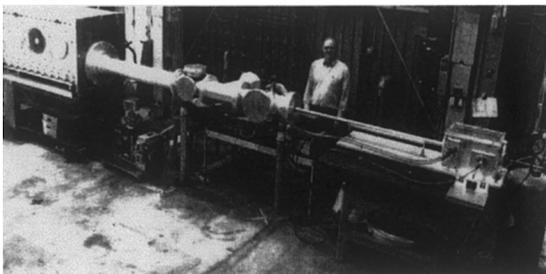


Fig. 4. This gas gun experiment at the Lawrence Berkeley National Laboratory has demonstrated that indirect-drive injection requirements can be met with 100 m/s velocity injection velocity from a gas gun to an accuracy of 5 mm, with a tracking accuracy for beam steering within 200 μm .

for direct-drive, with reduced tritium inventories in the first wall.

If dry-wall chambers and direct-drive targets can be shown to be feasible with the above research, and if tritium and other activation in the shielding and building can also be reduced by improved design, then IFE plants with very low radioactive inventories and high degrees of safety might be achieved.

4.3. Driver chamber interface

The interface of the driver beam with the fusion chamber is an important area of R&D for the IFE/VLT. For heavy ion drivers, near term efforts will be to produce a self-consistent design for final-focus/chamber interface consistent with heavy-ion target requirements and protection of the focus magnets from radiation damage and excess nuclear heating. Recent driver designs require beams of the order of 100 or more from each of the two sides for indirect drive targets, so the physical packing of these magnets presents a design challenge. For lasers, the key issues are the design and survivability of the final optics. Options include grazing incidence metal or liquid metal mirrors, and hot ($\sim 400^\circ\text{C}$) fused silica diffractive optics or transmission gratings. A 10-Hz, Nd:YAG laser experiment has begun at UCSD to establish laser damage fluence limits for IFE final optics and for first wall ablation analysis. UW, ORNL and others are proposing laser chamber research on radiation damage effects.

4.4. Target fabrication and injection

At the heart of an inertial fusion explosion is a target that has been compressed and heated to fusion conditions by the driver beams. For direct drive, the target is a spherical capsule containing deuterium–tritium (DT) fuel. For indirect drive, the capsule is contained within a metal container or hohlraum, which converts the driver energy into X-rays to drive the capsule. The target factory at an inertial fusion power plant must produce about 10^8 targets each year with high precision of manufacture, fill them with DT fuel, and layer the fuel into a symmetric and smooth

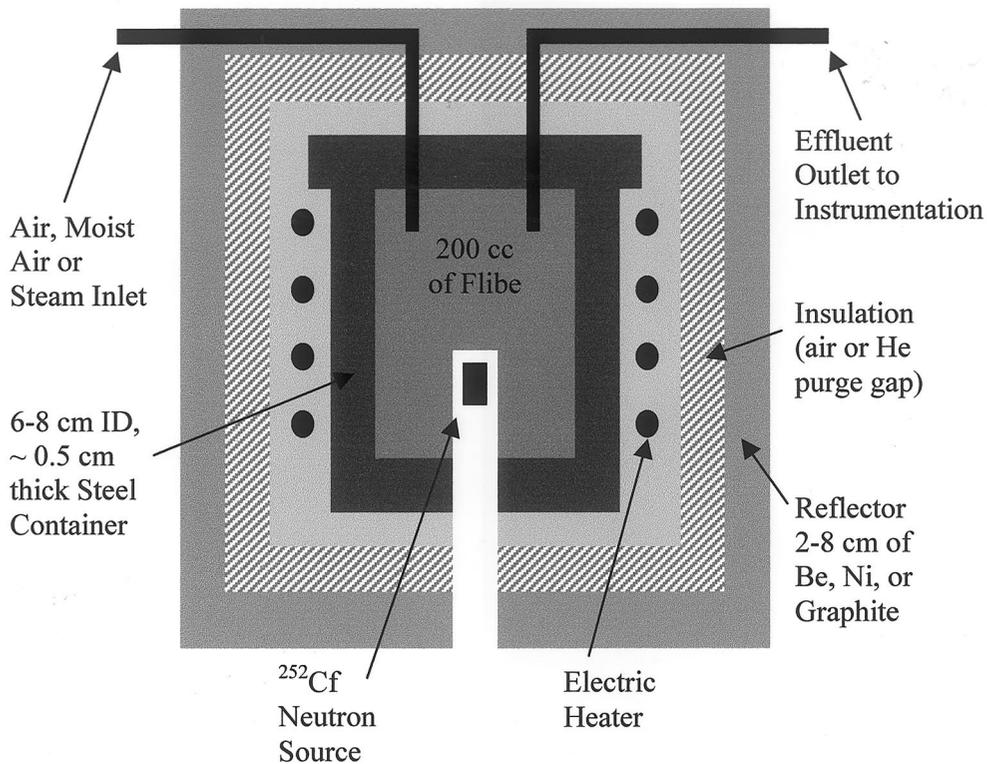


Fig. 5. The Idaho National Energy Environmental Laboratory (INEEL) is designing the FLIQUIRE experiment to study radionuclide mobilization from liquids such as the molten salt Flibe shown here. Data from this experiment can be important to both MFE and IFE fusion energy concepts.

shell inside the capsule. These fragile targets must be injected and precisely tracked at a rate of ~ 5 Hz to the center of the high temperature target chamber without damage. An integrated effort on target technologies has also begun and plans for an expanded effort have been completed. General Atomics and Los Alamos National Laboratory are taking the lead in this area. For both heavy ion and laser drivers, the near term objectives are to identify methods for low cost manufacture and rapid injection of direct- and indirect-drive targets. Fig. 4 shows an experiment used to test the accuracy of injecting and tracking indirect drive hohlraum targets using a gas gun at LBNL.

4.5. Environmental and safety characteristics

Attractive environmental and safety (E&S) characteristics are essential to the eventual accep-

tance of fusion as a future energy source. An integrated effort on E&S is planned to develop the tools and carry out analyses for both laser and heavy ion IFE. Issues specific to each chamber approach will be addressed, for example, activation, recovery and recycle of hohlraum materials in indirect drive targets and dust transport in dry-wall chambers. Experiments are needed to quantify release fraction for key in-chamber materials, which will allow more detailed accident consequence assessments. Fig. 5 depicts a planned experiment at the Idaho National Energy and Environmental Laboratory (INEEL) designed to measure the mobility of activated components in Flibe that relates to the release fractions at various temperatures which may occur in accidental spills of such liquids. A key goal is to develop power plant designs that can avoid the need for a

public evacuation plan. Meeting low-level waste criteria and recycling radioactive materials to minimize waste streams are also goals of this work. INEEL, LLNL, and UW are the primary groups involved in this R&D.

4.6. Integrated systems analysis

During the course of the above described IFE research on chambers and targets over the next 4 years (phase I), it is likely that there will be findings that call to question the compatibility of the chamber approaches chosen for direct and indirect-drive with the evolving IFE target design, fabrication, injection, and tracking requirements. It is also likely that new driver-chamber interface issues and impacts of new driver optimizations (e.g. number of beams and the illumination geometry of such beams onto the target) from ongoing heavy-ion and laser-IFE driver design and development will be found. This new information will require integrated systems analysis to insure overall compatibility and optimization of heavy-ion and laser IFE, and where necessary, develop alternative approaches.

5. Summary

Several new research and development activities on critical issues in the area of IFE chamber and target technology have just begun as a part of the VLT, which will require several years to complete. The feasibility of IFE depends on solving the critical issues in this area just as much as IFE

depends on the development of high gain targets and efficient, high-pulse-rate drivers. Many of these areas of research could benefit from international cooperation as is presently the case for magnetic fusion research.

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References

- [1] W.R. Meier, Osiris and sombrero inertial fusion power plant designs-summary, conclusions and recommendations, *Fusion Eng. Des.* 25 (1994) 145–157.
- [2] R.W. Moir, R.L. Bieri, X.M. Chen, T.J. Dolan, M.A. Hoffman, P.A. House, et al., HYLIFE-II: a molten-salt inertial fusion energy power plant design — final report, *Fusion Technol.* 25 (1994) 5–25.
- [3] L.M. Waganer (Ed.), Inertial Fusion Energy Reactor Design Studies-Prometheus-L and Prometheus-H, McDonnell Douglas Report MDC 92E0008 and DOE Report DOE/ER-54101 (March 1992), also see L.M. Waganer, *Fusion Eng. Des.* 25 (1994) 125–143.
- [4] C.D. Orth, S.A. Payne, W.F. Krupke, A diode-pumped solid-state laser driver for inertial fusion energy, *Nucl. Fusion* 36 (1996) 75.
- [5] G.L. Kulcinski, R.L. Engelstad, J.J. Lovell, E.A. MacFarlane, G.A. Mogahed, R.R. Moses, et al., LIBRA-LITE: a 1000 MWe reactor, *J. Fusion Energy* 10 (1991) 339.
- [6] S. Zinkle, Oak Ridge National Laboratory, private communication, 1999.