

## Overview of IFE Chamber and Target Technologies R&D in the U.S.

W.R. Meier 1), M.A. Abdou 2), G.L. Kulcinski 3), R.W. Moir 1), A. Nobile 4),  
P.F. Peterson 5), D.A. Petti 6), K.R. Schultz 7), M.S. Tillack 8), M. Yoda 9)

- 1) Lawrence Livermore National Laboratory, Livermore, CA USA
- 2) University of California, Los Angeles, CA USA
- 3) University of Wisconsin, Madison, WI USA
- 4) Los Alamos National Laboratory, Los Alamos, NM USA
- 5) University of California, Berkeley, CA USA
- 6) Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID USA
- 7) General Atomics, San Diego, CA USA
- 8) University of California, San Diego, CA USA
- 9) Georgia Institute of Technology, Atlanta, GA USA

e-mail contact of main author: meier5@llnl.gov

**Abstract.** The U.S. Department of Energy, Office of Fusion Energy Science (OFES) formed the Virtual Laboratory for Technology (VLT) to develop the technologies needed to support near term fusion experiments and to provide the basis for future magnetic and inertial fusion energy power plants. The scope of the inertial fusion energy (IFE) element of the VLT includes the fusion chamber, driver/chamber interface, target fabrication and injection, and safety and environmental assessment for IFE. Lawrence Livermore National Laboratory, in conjunction with other laboratories, universities and industry, has written an R&D plan to address the critical issues in these areas over the next 5 years in a coordinated manner. This paper provides an overview of the U.S. research activities addressing these critical issues.

### 1. Introduction

Previous IFE power plant conceptual design studies identified many different driver/chamber/target options and the critical technical issues associated with them [1,2,3]. Since it is not possible to consider all these options, current R&D in the U.S. is primarily focused on two options. One is the renewable thick-liquid-wall chamber (e.g., HYLIFE-II [1]) with heavy ion driven, indirect-drive targets, and the other is the gas-protected, dry-wall chamber (e.g., Sombrero [2]) with laser driven (KrF or diode-pumped, solid-state laser) direct-drive targets. The top-level critical issues for these two approaches are summarized here.

The key issues for liquid-wall chambers with heavy-ion driven, indirect-drive targets are:

- a) Chamber Clearing: Can the liquid pocket and beam port protection jets be made repetitively without interfering with beams? Will vapor condensation, droplet clearing and flow recovery occur fast enough to allow pulse rates of ~ 6 Hz?
- b) Final Focus Magnet Interface: Can superconducting final focusing magnet arrays be designed consistent with chamber and target solid angle limits for the required number of beams, standoff distance to the target, magnet dimensions and neutron shielding thickness?
- c) Target Fabrication and Injection: Can hohlraum targets with internally mounted cryogenic fuel capsules be mass produced with the required target precision at a cost less than ~ 0.3 U.S. dollars each? Can these targets withstand the acceleration force of injection? Can they be injected, tracked and shot with sufficient accuracy and reliability?
- d) Safety and Environment: Can a level of safety be demonstrated so that a public evacuation plan is not needed (<10 mSv (1 rem) site boundary dose) for credible accident scenarios? Can radioactive hohlraum materials be recovered from the flibe and recycled in new targets?

The key issues for dry-wall chambers with laser driven, direct-drive targets are:

- a) Chamber Lifetime: Can the first wall be protected from x-ray and debris damage? Can first wall and blanket structures tolerate the effects of neutron damage for an acceptably long time and be designed for economical replacement? Can graphite channels last long enough against erosion due to  $\text{Li}_2\text{O}$  granule abrasion?
- b) Final Optics Protection: Can final optics be adequately protected from laser, neutron, x-ray and debris damage sufficient to survive for more than one year before replacement? Will final optics have sufficient mechanical stability under pulsed operation to maintain the required pointing accuracy for target tracking?
- c) Target Fabrication and Injection: Can direct-drive targets be manufactured at low cost and survive injection into a hot chamber? Can injection, tracking and triggering be sufficiently predictable with turbulence in the chamber gas?
- d) Safety and Environment: Can a level of safety be achieved so that a public evacuation plan is not needed for credible accident scenarios? Can replaced chamber materials be recycled to minimize annual waste volumes?

During Phase-I (~ next 5 years) the R&D will be focused on these issues [4]. While all these issues will not be resolved during Phase-I R&D, the objective is to make significant progress and show that credible pathways to resolution exist. Phase-I research will include assessment studies, small-scale experiments, and simulations. Later research will demonstrate more integrated but still non-nuclear tests at scales closer to full size. Information developed in Phase-I on chamber and target technologies, advances in driver designs and technology, and evolving target physics requirements for high gain, will be explored with integrated systems analysis in order to assess the overall feasibility and attractiveness of IFE. The small-scale experiments and integrated systems analyses may suggest alternative solutions to the indirect-drive and direct-drive approaches to IFE discussed above.

## 2. Chamber Technologies

### 2.1 Thick Liquid Wall Chambers

Current work in this area is based on the HYLIFE-II chamber concept. Formation of the protective liquid blanket and chamber clearing between pulses (i.e., vapor condensation, droplet clearing and flow recovery) are the critical feasibility issues. The near term (~5 year) goal for research in this area is to develop convincing evidence from scaled experiments and modeling that the protective liquid pocket can be formed and that the chamber can be cleared between shots.

Several small-scale experiments on the characteristics of liquid jets are being conducted at UC Berkeley [5], UCLA [6], and Georgia Institute of Technology [7]. Two basic types of jet flow are required: 1) oscillating jets to form the thick liquid pocket around the target every pulse, and 2) steady-flow jets that are arranged to form an array of ports for beam entry. The primary goals of these experiments are to 1) demonstrate that the liquid jet configurations required for the HYLIFE-II chamber can be established, 2) improve the quality (low surface ripple) of steady-flow jets, and 3) demonstrate that the jet configuration can be re-established between pulses.

### 2.2 Dry-Wall Chambers

Currently planned R&D for dry-wall chambers is guided by the Sombrero, gas-protected chamber that uses a carbon-carbon composite first wall and blanket structures cooled by

flowing  $\text{Li}_2\text{O}$  granules (this is also the breeding material). The key issues for this design, and any other dry-wall concept for that matter, relate to protection of the first wall and the lifetime of chamber structures. Several threats must be dwelt with: x-ray and debris damage to first wall must be prevented; the neutron damage life of the first wall and blanket structures must be acceptably long, probably at least one year depending on replacement time; and possible erosion of the coolant channels by flowing granular coolant/breeder must be manageable or prevented. There is uncertainty in the data and analyses used to predict these effects, so one of the goals is to develop a design that is tolerant of the range of uncertainties of surface ablation rates, thermal conductivity loss and swelling due to damage from neutrons, and heating from x-rays and target debris. The near term objective for work on dry-wall chambers is to conduct experiments and analyses to provide evidence supporting a wall life greater than one year. The University of Wisconsin is taking the lead in assessments of dry-wall chambers. Their initial effort will focus on a reassessment of these issues based on information developed since the completion of the Sombrero study (1993).

### **3. Chamber / Driver Interface**

#### **3.1 Ion-Driver / Chamber Interface**

Although the final focus magnets for a heavy ion driver are not in the direct line-of-sight of the fusion energy pulse, their interface with the fusion chamber is one of the key technology issues that need to be addressed. The interface of the driver beams with the chamber presents several challenges, particularly with current driver designs that have 100 beams or more. This integration requires meeting constraints imposed by the target design (e.g., the acceptance angle of the beam relative to the target axis), the liquid wall shielding configuration, and heating and activation of the final focus magnets. The better the quality of the crossed shielding jets, the closer they can be positioned to the beam path, the more effective the radiation shielding will be. LLNL is leading efforts to integrate these and other power plant subsystems as new information on target and driver requirements become available. Protecting the final focus magnets from radiation damage and heating is another important issue that is being addressed by LLNL [8].

#### **3.2 Laser-Driver / Chamber Interface**

While the final focus elements for a laser driver can be much farther from the chamber center than the final focus magnets for an ion driver, the laser final optics will be in direct line-of-sight of the target emissions. The key issue is survivability of the final optics. Concepts for protecting final optics and making them more damage tolerant have been proposed, but experimental data and development are needed. One idea is to use fused silica that runs hot enough that radiation damage is expected to anneal. Additional radiation damage studies of hot-fused silica and other optical materials (e.g., calcium fluoride) have been proposed, but current funding is inadequate to complete these. Analysis of grazing incidence metal and liquid-metal mirrors (GIMMs and GILMMs) shows that these are possible solutions. The University of California at San Diego now has a 2 J laser facility to test the laser damage threshold for GIMMS and also schemes for protecting the mirrors. The University of Wisconsin has proposed using a shock tube to address the issue of gas shocks on final optics. Detailed 3D neutronics analyses have been completed for the Sombrero power plant using a direct-drive target and a diode-pumped solid-state laser to determine neutron and gamma fluences and doses in the final and next-to-final optics [9]. Data is needed, however, to estimate the lifetime of these components.

#### **4. Target Fabrication and Injection**

The key issues here are high precision production of targets at low cost, and the ability to inject them without damage to the cold, fragile fuel capsule. R&D on target fabrication and injection must address several key questions, including target materials development, mass production, accurate injection and tracking, and target protection and survival. The two principal institutions working in this area are General Atomics (focusing on injection) and Los Alamos National Laboratory (focusing on target materials and fabrication techniques). Preliminary room temperature experiments with a gas gun injector had encouraging results showing that the target could be tracked and its final position predicted within the requirements for indirect drive targets. Direct drive targets require an order of magnitude better tracking precision and are much more thermally sensitive. Thus, a new injector is being designed and will be built at General Atomics to test both direct and indirect drive targets and eventually to inject cryogenic targets into a simulated high temperature target chamber [10]. Current work on target fabrication leverages off the target fabrication work conducted for the Inertial Confinement Fusion (ICF) target physics program. Techniques and materials suitable for low-cost mass production are being investigated and developed by Los Alamos and General Atomics. The target technology work is being closely integrated with the chamber design and S&E work.

#### **5. Safety and Environment**

Favorably resolving safety and environmental (S&E) issues will be a key factor in the success of fusion energy. In order for fusion to achieve its full potential for S&E advantages over competing energy sources, it is essential that analyses are performed early in the design of any facility so that wise choices can be made and lessons learned from previous designs incorporated. One key issue is plant safety during normal operation and in the event of possible accidents. The objective is to design plants that have a level of safety consistent with no-public-evacuation-plan requirement for credible accident scenarios and resultant radioactivity releases. Tritium inventory and confinement are issues that require special attention in the design. There are important environmental issues related to end-of-life materials processing. The degree to which materials can be recycled and the trade-offs between radioactive waste volume and hazard level are important factors in this area.

Currently two national labs, INEEL and LLNL, and the University of Wisconsin lead the S&E work for IFE. Over the past year the codes that were developed to carry out safety analyses for magnetic fusion energy (MFE) power plants have been adapted to study IFE. The first safety analysis of HYLIFE-II using these adapted models was recently completed [11]. The results of the safety analysis are encouraging, giving a site boundary dose below 5 mSv (0.5 rem) for a severe accident scenario. Preliminary results for Sombrero indicate that with minor design modifications it too can meet the < 10 mSv (1 rem) site boundary dose goal.

#### **6. Conclusions**

An R&D plan for IFE chamber and target technologies has been developed to help coordinate efforts in this area. Current activities are focused on addressing key feasibility issues. Work includes both small-scale experiments and modeling by national laboratories, universities and industry. This work, in combination with success in target physics and driver performance, will set the stage for proceeding with the next steps in the development of IFE.

## Acknowledgements

This work of W.R. Meier and R.W. Moir was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

## References

- [1] MOIR, R.W., et al., "HYLIFE-II: A Molten Salt Inertial Fusion Energy Power Plant Design-Final Report," *Fusion Technology* **25** (1994) 5.
- [2] MEIER, W.R., et al., "Osiris and Sombrero Inertial Fusion Power Plant Designs – Summary, Conclusions, and Recommendations," *Fusion Engineering and Design*, **25**, (1994) 145.
- [3] Badger, B., et al., "HIBALL-II – An Improved Heavy Ion Beam Driven Fusion Reactor Study," University of Wisconsin Fusion Technology Institute Report UWFD-625 (Dec. 1984).
- [4] MEIER, W.R., et al., "Chamber and Target Technology Development for Inertial Fusion Energy," LLNL report UCRL-ID-133629 (April 1999).
- [5] BAUMAN, C., PEMBERTON, S., PETERSON, P.F., "Single-Jet Experiments for HIF Thick-Liquid Chambers," (Proc. 13th International Symposium on Heavy Ion Fusion, March 13-17, 2000, San Diego, California) to appear in *NIMA*
- [6] KONKACHBAEV, A.I., MORLEY, N.B., GULEC, K., SKETCHLEY, T., "Stability and Contraction of a Rectangular Liquid Metal Jet in a Vacuum Environment," (Proc. 5<sup>th</sup> International Symposium on Fusion Nuclear Technology, September 19-24, 1999, Rome, Italy) to appear.
- [7] ELWELL, L.C., COLLINS, J.A., YODA, M., ABDEL-KHALIK, S. I., "Dynamics of Obliquely Oscillated Turbulent Free Rectangular Jets," American Physical Society Division of Fluid Dynamics Annual Meeting, New Orleans, LA (1999). *Bulletin of the American Physical Society* **44** (8), 154-155.
- [8] LATKOWSKI, J.F., MEIER, W.R., "Improved Final Focus Shielding Designs for Modern Heavy-Ion Fusion Power Plant Designs," (Proc. 13th International Symposium on Heavy Ion Fusion, March 13-17, 2000, San Diego, California) to appear in *NIMA*.
- [9] REYES, S., LATKOWSKI, J.F., MEIER, W.R., "Radiation Damage and Waste Management Options for the SOMBRERO Final Focus System and Neutron Dumps," Proc. of the First International Conference on Inertial Fusion Sciences and Applications, Bordeaux, France (Apr. 2000) 819.
- [10] GOODIN, D., et al., "Developing the Basis for Target Injection and Tracking in Inertial Fusion Energy Power Plants," (Proc. IEAE TCM on Physics and Technology of Inertial Fusion Energy Targets and Chambers, June 7-10, 2000, Madrid, Spain) to appear in *Fusion Engineering and Design*.
- [11] REYES, S., LATKOWSKI, J.F., GOMEZ DEL RIO, J., SANZ, J., "Accident Consequences Analysis of the HYLIFE-II Inertial Fusion Energy Power Plant Design," (Proc. 13th International Symposium on Heavy Ion Fusion, March 13-17, 2000, San Diego, California) to appear in *NIMA*.