ARIES INERTIAL FUSION CHAMBER ASSESSMENT

M. S. Tillack, F. Najmabadi
Center for Energy Research
UC San Diego
La Jolla, CA 92093-0417

L. A. El-Guebaly, R. R. Peterson
Fusion Technology Institute
University of Wisconsin Madison
Madison, WI 53706-1687

D. T. Goodin, K. R. Schultz
General Atomics
P.O. Box 85608
San Diego, CA 92186-5608

W. R. Meier, J. Perkins
Lawrence Livermore
National Laboratory
P.O. Box 808, L-481
Livermore, CA 94551

D. A. Petti
Idaho National Engineering
& Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415

J. D. Sethian
Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375

L. M. Waganer
Boeing Company
P.O. Box 516
St Louis, MO 63166-0516

and the ARIES Team

ABSTRACT

A critical assessment of the feasibility of IFE chambers has been initiated. This work seeks to define design windows and explore in detail the tradeoffs for various chamber concepts. The work is performed in an integrated and self-consistent manner by including all key elements of IFE chambers, including target physics, target injection and tracking, final optics interface, chamber engineering, safety and environment. Chamber concepts are being considered in a sequential fashion; initial studies reported here have concentrated on dry wall options. The goals and approach of the program are described and some preliminary results reported.

I. INTRODUCTION

Nearly 10 years have passed since the US DOE commissioned two large, multi-institutional IFE power plant design studies: Prometheus[1] and OSIRIS/ SOMBRERO[2]. Since that time, several major factors – both scientific and programmatic – have improved the opportunities for IFE research. Increased confidence in the physics feasibility of inertial fusion has led to the construction of NIF, with its expected demonstration of ignition and gain. Declassification and increased international effort on unclassified target physics has enabled target design to be included in system optimizations. In addition, significant achievements in key enabling technologies have been made over the past decade, such as improved understanding of ion beam propagation and ion-material interactions, increased efficiency of high-power lasers, demonstration of effective laser beam smoothing techniques for direct drive targets, and advances in target physics, including innovative concepts such as close-coupled indirect drive and fast ignition.. Inertial fusion looks significantly more credible and more attractive than it did only ten years ago.

The ARIES team recently initiated a new activity to assess the current state of inertial fusion energy research and to help motivate and guide R&D programs. The team includes participation from several of the major national laboratories and universities engaged in IFE research. The first phase of the program is focused on a broad-based assessment of chamber options and related technologies relevant for both laser and heavy ion drivers. Utilizing the progress in the past decade, detailed analyses of more traditional IFE chamber concepts as well as newer concepts are being performed. This analysis highlights shortcomings in the present data base and helps identify high-leverage areas for R&D. Key issues and design trade-offs are discussed for the major technologies, including target injection, tracking and transport; driver/ chamber interface components (*i.e.*, final optics, final focus magnets); chamber physics (particle and radiation transport, gasdynamics); and chamber materials response. These technologies are assessed using an integrated system-wide approach with economics, safety and environmental attributes, and credibility as principal metrics.

II. DESIGN CONCEPTS

Chamber design concepts are classified into three primary categories: dry chambers, solid wall chambers protected with a "sacrificial zone" (such as liquid films), and neutronically thick liquid walls. Each class of chamber embodies a different characteristic set of issues and constraints. In order to maintain focus, each of these chamber classes will be examined sequentially. At present, the primary emphasis of the ARIES activity is dry walls coupled with either direct or indirect drive targets and both laser and heavy ion drivers.

During the past 25 years, numerous IFE power plant conceptual design studies have introduced a wide variety of chamber materials and configurations. While recognizing that various chamber concepts can be used with either laser or heavy ion drivers, the US IFE technology program[3] has focused on addressing critical issues for chamber concepts based on SOMBRERO[2] and HYLIFE-II[4], matched to laser and heavy ion drivers respectively. The intent of the ARIES IFE chamber assessment is not to produce a new power plant "point design", but rather to better understand fundamental tradeoffs, characterize design windows and offer additional guidance to R&D programs.

To provide a framework for this study, baseline target designs have been defined. One of these is the NRL high-gain direct drive target[5] (see Fig. 1). This target consists of a DT gas core surrounded by solid DT ice and an ablator consisting of a low-density plastic foam impregnated with DT. A very thin (300Å) gold outer coating improves the gain by preheating the ablator, and also helps to reflect heat from the chamber walls. An alternate design omits the gold and includes a thicker CH coating.

The reference indirect-drive target uses a "close coupled" geometry for higher gain[6] (see Figure 1). Alternate hohlraum designs are being considered, including the distributed radiator, "clamshell" and "tuna can" configurations. In addition, direct drive targets compatible with HI drivers are under examination. More advanced designs, including fast-ignition and advanced fuel targets, are being explored for both laser and HI drivers.

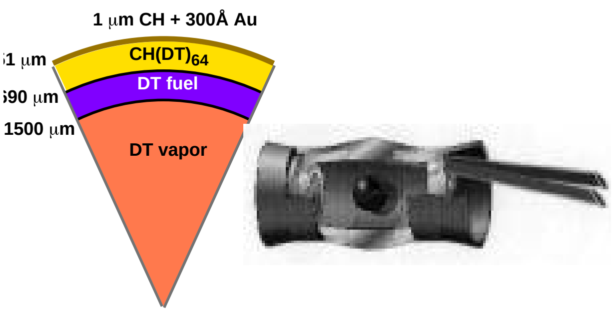

Fig. 1. Baseline direct and indirect drive target designs[5, 6] (not to scale)

The primary driver options are adopted from ongoing research programs. These include a KrF excimer laser[7], diode-pumped solid state laser (DPSSL)[8] and heavy ion accelerator[9]. Efforts on ARIES are focused on the driver/chamber interface rather than the drivers themselves.

III. TARGET EMISSIONS

Detailed knowledge of the energy spectrum and yield of neutrons, photon and debris ions is essential in order to analyze and improve the performance of the chamber. Table 1 summarizes the energy partitioning 100 ns after burn time for both the direct and indirect drive targets. The most notable distinction between the two cases is the higher x-ray output for indirect drive targets.

Table 1. Energy partitioning at 100 ns

	NRL direct drive laser target (MJ)		HI indirect drive target (MJ)	
X-rays	2.14	1%	115	25%
Neutrons	109	71%	316	69%
Gammas	0.0046	0.003%	0.36	0.1%
Burn products	18.1	12%	8.43	2%
Debris ions	24.9	16%	18.1	4%
Total yield	**154**		**458**	

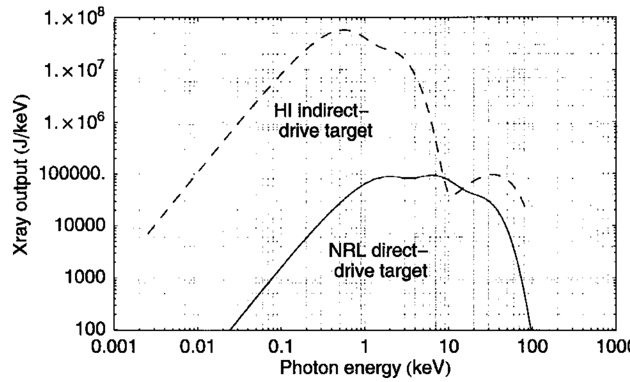

Fig. 2. Photon spectra.

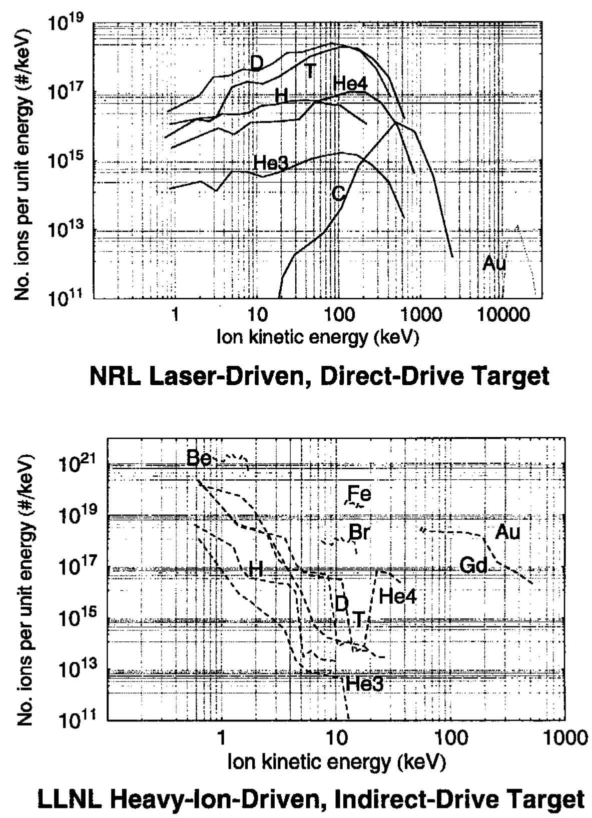

Fig. 3. Debris spectra

Photons and high-energy particles can deposit their energy very differently in the chamber materials. In some ways, debris are a more serious concern due to their high stopping power and capability of sputtering wall atoms. Figure 2 shows the x-ray spectra for both baseline targets. The difference in energy partitioning is apparent. In addition, the peak in the spectrum for the direct drive target is shifted to higher energies as a result of the much higher average temperature of the target materials. Fig. 3 shows the energy spectra from ionic debris, excluding the prompt burn products. The spectral differences between direct and indirect drive targets again are very apparent.

IV. TARGET INJECTION AND TRACKING

One of the most difficult challenges of inertial fusion energy is the requirement to inject cryogenic targets accurately, reliably and repetitively at a frequency of several times per second. Direct drive targets are particularly challenging due to their lower mass, more stringent illumination requirements and absence of a hohlraum to protect against interactions with the chamber materials. Therefore, more attention has been given to the issues related to direct drive capsule injection in this stage of the project.

The current goal of target injection is to place targets in the center of the chamber with ±5 mm accuracy at a rate of 5–10 Hz. It is assumed that multiple driver beams can be steered with the precision required to ignite targets – a maximum deviation in the range of 20–200 μm, depending on target design. In order to achieve the 20–200 μm accuracy, the target trajectory must be predictable to the same degree. This requires both accurate tracking and minimization of random perturbations in the flight path.

Surface finish requirements place additional constraints on target injection. Heat-up of the target surface may degrade the surface finish beyond acceptable limits (500Å roughness, 1% out-of-round). Parametric studies of target heating have been performed under a variety of scenarios for a range of wall temperatures and chamber gas pressures. The key concerns are cracking of the DT ice surface from thermal stresses and exceeding the triple point temperature. This constraint is particularly challenging due to the additional requirement to maintain the DT temperature relatively close to the triple point to maintain proper layering.

Figure 4 summarizes the results of a transient thermal analysis. In these simulations, the spectrum and angle-averaged reflectivity from the 300Å gold coating is assumed to be 98%. At high wall temperature, a bare target is at risk regardless of the injection velocity or chamber gas pressure. With lower wall temperatures, successful injection requires chamber pressures of 10 mtorr or less. Higher injection velocities improve the chances of success but are not seen as a major factor. More detailed studies are underway to determine whether targets can withstand these heat loads for short periods of time (targets reside in the chamber for only ~20 ms).

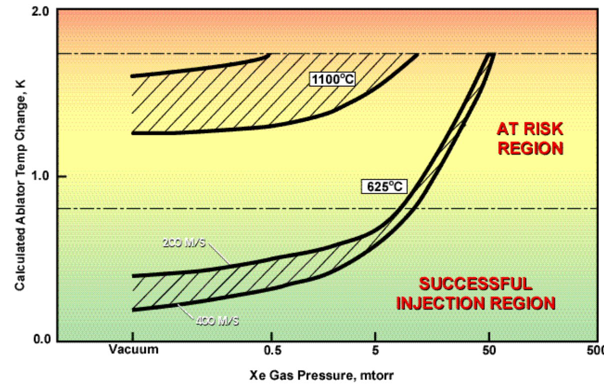

Fig. 4. Successful injection of direct drive targets requires control of heating from the chamber walls and gas.

Gasdynamic effects on target trajectory have been assessed using direct Monte Carlo simulations of fluid flow around a sphere at low gas pressures. The change in axial location of the target due to drag in 0.5 torr Xe is about 20 cm. This base level of displacement is predictable, but random fluctuations in the background gas density or velocity will deflect the target from its predited trajectory. If the exact trajectory-averaged displacements cannot be predicted within the 20-200 μm position requirement, then target ignition can not be assured.

Figure 5 summarizes some initial results. An average density variation of 1% at a chamber pressure of 0.5 torr will cause a change in predicted position of 1 mm. Even at 50 mtorr, density variations must be less than 0.01%. In order to achieve the necessary accuracy of target position, in-chamber tracking may be needed for any gas-protected chamber. Techniques to track targets deep into the chamber are under investigation.

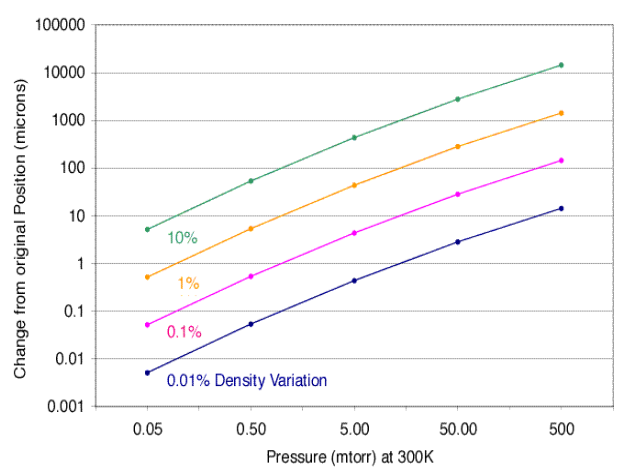

Fig. 5. Uncertainties in chamber gas pressure will lead to significant perturbations in target trajectory.

Possible solutions to these issues are being pursued. Further reductions in the chamber gas pressure and reduced wall temperature will help expand the design window. Other chamber protection schemes also need to be assessed. Target-based solutions under consideration include a sabot or wake shield far into the flight path, or frost coatings directly on the surface.

V. CHAMBER PHYSICS

Chamber physics refers to the short time-scale interaction of target emissions with chamber materials, and includes the physics of photon and particle interactions, radiation transport, atomic processes and gas hydrodynamics. Chamber physics uses the prompt target emissions as input and provides a description of the various energy sources that impact chamber materials, including final optics. Here we discuss only one aspect of chamber physics related to the tradeoff between gas pressure, chamber radius and ablation of the first surface in a dry chamber. For this analysis, a carbon first wall and xenon chamber gas are assumed and the baseline direct drive laser target spectra are used.

Table 2 summarizes the results of a parametric study of the vaporized surface mass as a function of the background gas pressure using the NRL direct drive target output. These results were obtained from a full 1D simulation of the chamber dynamic response using the BUCKY code[10]. Graphite sublimation is a threshold effect, quickly becoming unacceptably large as the gas pressure is reduced below a certain value. According to Table 2, the threshold occurs somewhere between 100-150 mtorr for a 6.5 m wall initially at 1500˚C. Increasing the chamber radius and reducing the wall temperature should help avoid vaporization with gas pressures in the range of 50–100 mtorr. These conditions are being investigated.

Table 2. Wall sublimation *vs.* Xe pressure (6.5 m radius)

Xe density (mtorr)	**Ion energy deposited in the wall, MJ**	**X-ray energy deposited in the wall, MJ**	**Vaporized wall mass, g**
50	4.2	1.7	300
100	2.0	1.5	10
150	1.5	1.3	0
300	0.95	1.2	0

VI. CHAMBER ENGINEERING

One of the most important design considerations for an IFE chamber is the choice of wall materials and configurations for the first surface facing the blast. Protection of the wall against blast effects is a central issue for dry walls. The interaction of target energy and debris products with the wall is a key factor in safety and environmental concerns, and the wall and its surrounding structures remove the heat which is used to generate electricity. The work presented below focuses only upon issues of pulsed damage resistance and temperature window constraints.

Short pulse energy deposition on surfaces strongly suggests a separation of spatial scales, and perhaps functions. For unirradiated carbon, the thermal diffusion characteristic depth is about 1 μm for energy pulses of the order of 10 ns and 100 μm for pulses of the order of 100 μs ($\alpha = k/\rho C_p = 94x10^{-6}$). This is roughly the same order of magnitude as the photon penetration depth at the peak of the spectrum (1–10 keV).

Micro-engineered surfaces with spatial scales of the order of 1–100 μm might offer advantages with respect to pulsed heat removal and erosion lifetime. For example, the novel "fiber-flocked" carbon surface shown in Figure 6 has been examined as a candidate wall construction (A similar "carbon carpet" wall was previously proposed for the first wall of a single-shot ICF chamber[11].) These materials exhibit good heat transfer parallel to the fiber direction and are compliant to thermal shock. Fibers can be tailored in geometry and composition. Typical fiber values are 5-10 mm fiber, 1-2 mm length and 1-2% packing fraction. Fibers of thickness similar to the x-ray attenuation length will lead to semi-transparency of the surface.

Another useful aspect of this material is its extended surface area. If the area that intercepts the target emissions is larger than the underlying flat substrate, then the adiabatic temperature rise will decrease. The ratio of fiber surface area (assuming one-sided illumination) to substrate area (A_f/A) depends on the fiber length to diameter ratio, L/d:

$$A_f/A = 4/\pi\,(1-\varepsilon)\,L/d$$

where ε is the porosity. For L/d=100 and ε =0.95, the maximum surface area enhancement factor is A_f/A~5.

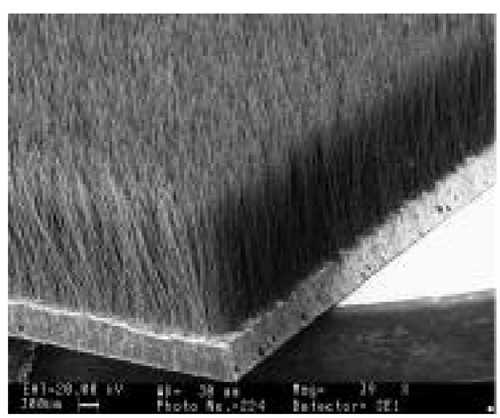

Fig. 6. Fibrous wall material (photo courtesy of Energy Science Laboratories, Inc (San Diego, CA) www.esli.com

Combined with the fast thermal diffusion of narrow fibers, the transient temperature rise due to individual target explosions could be substantially decreased. Analysis of this and similar micro-engineered surfaces is underway.

The wall temperature prior to the target blast determines the baseline from which the transient excursion takes place. Maintaining a low time-averaged wall temperature not only helps reduce the peak temperature following the blast, but also determines thermal radiation heat transfer to the target prior to the blast. As shown in Section IV, this temperature should be minimized to allow successful target injection.

The primary factors leading to higher wall temperature are the desire for maximum thermal conversion efficiency and the need to maintain materials within acceptable operating ranges. (Metals such as tungsten suffer from radiation-induced embrittlement effects which may require a minimum operating temperature to maintain adequate ductility.)

Several techniques have been developed in recent years to allow high coolant bulk outlet temperature while maintaining the first wall within its required operating range[12,13]. One well-known way to minimize the first wall temperature is to exploit the fact that most of the fusion power is in deeply-penetrating neutrons. Power can be removed from the first wall at the lowest coolant inlet temperature while maintaining high thermal conversion efficiency, which depends primarily on the blanket outlet temperature. Techniques for internal thermal isolation can be used to enhance this effect. Small penalties in net efficiency resulting from the rejection of some of the power absorbed in the first wall may be desirable if the net effect is higher utilization of the neutron power. Application of techniques such as these to the conditions of an IFE chamber are under detailed examination.

VII. FINAL LASER OPTIC

Whereas heavy ions can be deflected using magnets that are shielded against radiation and blast effects, the final laser optic necessarily resides in direct line-of-sight with the target. The chamber design choices and operating regimes therefore affect this important interface with a laser driver.

Two principal damage concerns are those which increase absorption or those which modify the wavefront in such a way that the spot size, position or spatial uniformity can not be assured. Damage threats and nominal goals for absorption and wavefront degradation are summarized in Table 2. The absorption limit is based upon both an increased susceptibility to laser-induced damage as well as the requirement to maintain spatial uniformity across the beam. The wavefront goal is approximate, and depends on the cumulative distortions throughout the entire optical train. The limit of $\lambda/3$ is based on a doubling of the diffraction-limited spot [8]; tighter tolerances may be required.

Table 3. Summary of damage threats

Final Optic Threat	Nominal Goal or Limit
Optical damage by laser	>5 J/cm^2 threshold (normal to beam)
Nonuniform ablation by x-rays and sputtering by ions	Wavefront distortion $<\lambda/3$
Defects & swelling induced by neutrons and γ-rays	Absorption loss of <1% Wavefront distortion $<\lambda/3$
Contamination by condens able material (aerosol, dust)	Absorption loss of <1% >5 J/cm^2 threshold

Two options which previously have been proposed for a damage-resistant final optic are grazing-incidence metal mirrors (GIMM's)[14] and refractive wedges[8]. Figure 7 shows the layout expected for both – a standoff of 20-30 m from chamber center helps reduce the flux of target emissions as well as providing space for protective measures. The next optic upstream should be shielded adequately to allow for more flexibility in the selection of optics.

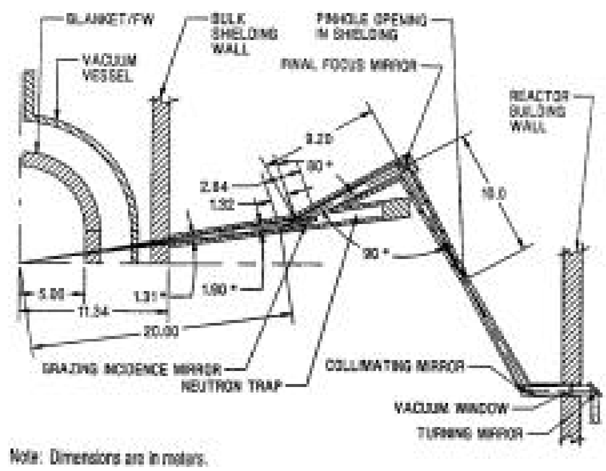

Fig. 7. Layout of final optic[1]

Calculations have been performed on grazing incidence mirrors to characterize their reflective properties with either protective coatings or contaminant films. Conventional high-performance UV mirrors normally utilize dielectric materials in multiple layers instead of metals. These rely upon interference effects requiring precise dimensions, and are not expected to withstand exposure to ionizing radiation. Most metal mirrors exhibit relatively poor reflectivity for UV wavelengths.

However, by operating at a grazing angle of incidence, the absorption of s-polarized light decreases by over an order of magnitude as compared with normal incidence.

Aluminum will be difficult to maintain chemically pure in the chamber environment, and so two scenarios have been examined: allow a dense oxide layer to form naturally, or overcoat the aluminum surface with a protective material such as CaF_2. Figure 8 shows an important phenomenon in a GIMM with a transparent Al_2O_3 overcoat. Because pure dielectrics and insulators also exhibit high reflectivity at grazing angles, interference of reflections at the coating surface with reflections at the metal surface can create serious loss of reflectivity. Coatings (or contaminants) with thickness below ~50 nm should avoid this problem.

Additional concerns with metal mirrors include absorption due to imperfections as well as unstable growth of surface defects. Operation at grazing angles with intensities far beyond the normal-incidence damage threshold may lead to unstable growth of small defects. Experiments are planned to demonstrate acceptable laser damage limits under long-term exposure both with and without surface defects and contamination to simulate conditions in a fusion chamber.

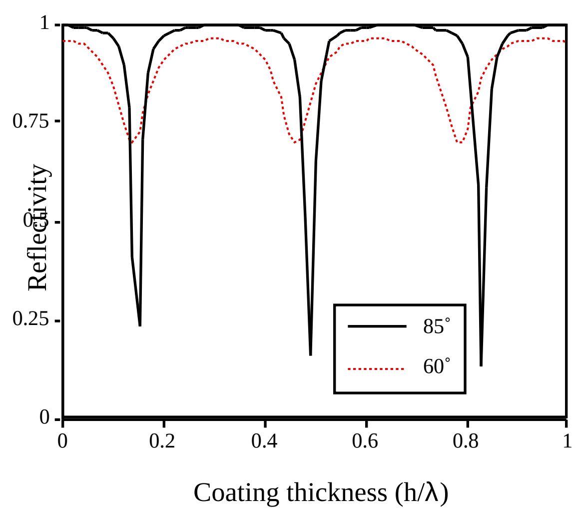

Fig. 8. Effect of surface oxide on Al reflectivity

VIII. SAFETY AND ENVIRONMENT

Safety and environmental constraints are used to provide guidance on the design and operating parameters for chambers. ARIES designs customarily have used two primary requirements: (1) no evacuation should be needed at the site boundary in the worst case accident scenario (1 rem dose to the most exposed individual) and (2) no deep geological disposal of waste should be required. Additional guidance on waste volume minimization and the possibility of recycling is under review.

Safety work for the IFE chamber assessment centers upon four major activities:

- Minimization of radiological inventories in the chamber (e.g. tritium, activation products, debris/dust) and in the tritium pellet factory (where preliminary estimates of tritium inventory are quite large) through smart materials selection and careful design
- Implementation of radiological confinement in IFE systems recognizing the large number of penetrations in the chamber (*e.g.*, number and location of the confinement boundaries)
- Identification of accident scenarios in IFE systems focusing on events that might bypass the confinement system, ex-vessel events that could propagate into the chamber, and events involving imperfect target fusion (e.g., shrapnel, partial burn) as well as the traditional loss of coolant and loss of flow events
- Safety analysis of some of these events based on existing designs (e.g. SOMBRERO, HYLIFE-II)

In the environmental area, waste management assessments of different configurations will be performed, focusing on both volume and hazard of waste.

IX. SUMMARY

A national team has been assembled to investigate design windows and tradeoffs for IFE chamber concepts. The work is being performed in an integrated and self-consistent manner by including all key elements of IFE chambers: target physics, target injection and tracking, final optics interface, chamber engineering and safety.

Initial efforts have focused on establishing a dry-wall chamber operating window that is consistent with adequate first wall protection and target injection/tracking requirements. Some key elements of a strategy to enable dry walls are beginning to emerge:

1) Reduced target x-ray yield. Direct drive targets have been designed with only 2 MJ of x-ray yield (as compared with 22 MJ for the SOMBRERO[2] direct drive target). In addition, the harder photon spectrum has a longer range of energy deposition. In this regime, x-rays are not considered a critical problem. Experiments are currently underway to validate target calculations.

2) Reduced gas pressure. Chamber gas can be used to buffer the debris energy release, absorbing the prompt flux and then re-radiating over a longer time scale. However, the use of a chamber gas poses a difficult problem for target heating and trajectory control. More recent analyses suggest the target debris can be adequately stopped with as little as 50 mTorr.

3) Debris diversion. With the x-ray yield reduced to such an extent, the primary concern regarding wall protection comes from energetic debris ions. Alternative

methods to divert debris, such as the use of magnetic fields, offers an alternative to absorption in gas.

4) Lower chamber wall temperature. Thermal radiation from hot chamber walls can significantly heat unprotected direct drive targets in the chamber. Stresses induced by rapid heat-up can fracture the outer surface or elevate the fuel above the triple point. Design innovation and trade-offs with cycle efficiency can help reduce the target heat loads.

5) Increased chamber wall radius. Chambers are a relatively small fraction of the total plant cost, and could be made even cheaper with advanced manufacturing techniques. The size of laser-driven chambers could be increased substantially in order to reduce the flux of particles and energy to the walls.

6) Damage resistant materials. Modern materials and fabrication techniques can help expand the design window for dry wall chambers. Pulsed energy deposition validation experiments are needed.

7) Target protection schemes. The exact response of cryogenic targets to the hot chamber environment requires additional analysis of the consequences (experiments are planned to examine this issue). If acceptable performance is not possible, then alternative target protection schemes (such as in-chamber sabots) may be needed.

REFERENCES

1. L. M. Waganer, *et al.*, "Inertial Fusion Energy Reactor Design Studies: Prometheus Final Report," MDC 92E0008 (DOE/ER-54101) March 1992.

2. W. R. Meier, *et al.*, "OSIRIS and SOMBRERO Inertial Fusion Power Plant Designs: Final Report," WJSA-92-01 (DOE/ER/54100-1) March 1992.

3. W. Meier, M. Abdou, G. Kulcinski, R. Moir, A. Nobile, P. Peterson, D. Petti, K. Schultz, M. S. Tillack and M. Yoda, "Overview of IFE Chamber and Target Technologies R&D in the U.S.," proceedings of the 18th IAEA Fusion Energy Conference, Sorrento Italy, Sept. 2000.

4. R. W. Moir, *et al*., "HYLIFE-II: A Molten-Salt Inertial Fusion Energy Power Plant Design," Fusion Technology 25 (1994) 5-25.

5. S. E. Bodner, D. G. Colombant, A. J. Schmitt, and M. Klapisch, "High-Gain Direct-Drive Target Design for Laser Fusion," Physics of Plasmas 7(6), June 2000, pp. 2298-2301.

6. D. A. Callahan-Miller and M. Tabak, "Progress in Heavy Ion Fusion Targets," 13th Int. Symp. on Heavy Ion Inertial Fusion, San Diego, March 2000.

7. J. D. Sethian, S. P. Obenschain, R. H. Lehmberg, and M. W. McGeoch, "KrF Lasers for Inertial Fusion Energy," Proc. 17th IEEE/NPSS Symp. on Fusion Energy, San Diego CA, October 1997.

8. C. D. Orth, S. A. Payne, and W. F. Krupke, "A Diode Pumped Solid State Laser Driver for Inertial Fusion Energy," Nuclear Fusion 36 (1996) 75-116.

9. R. O. Bangerter, "The Heavy Ion Fusion Program in the U.S.," Proc. 13th Int. Symp. on Heavy Ion Inertial Fusion, San Diego CA, March 2000.

10. J. J. MacFarlane, G. A. Moses, and R. R. Peterson, "BUCKY-1 – A 1-D Radiation Hydrodynamics Code for Simulating Inertial Confinement Fusion High Energy Density Plasmas," UWFDM-984, August 1995.

11. M. J. Monsler and W. R Meier, "A Carbon-Carpet First Wall for the Laboratory Microfusion Facility," Fusion Tech. 15, 595-602 (1989).

12. M. S. Tillack, X. R. Wang, J. Pulsifer, S. Malang, D. K. Sze, and the ARIES Team, "ARIES-ST Breeding Blanket Design and Analysis," *(to be published in Fusion Engineering and Design*).

13. A. R. Raffray, L. El-Guebaly, S. Gordeev, S. Malang, E. Mogahed, F. Najmabadi, I. Sviatoslavsky, D. K. Sze, M. S. Tillack, X. R. Wang, and the ARIES Team, "High Performance Blanket for ARIES-AT Power Plant," 21st Symposium on Fusion Technology, Madrid, September 2000.

14. R. L. Bieri and M. W. Guinan, "Grazing Incidence Metal Mirrors as the Final Elements in a Laser Driver for Inertial Confinement Fusion," Fusion Technology 19, May 1991, 673-678.