ELSEVIER

Fusion Engineering and Design 42 (1998) 537–548

Fusion Engineering and Design

Chamber technology concepts for inertial fusion energy—three recent examples

Wayne R. Meier [a,*], Ralph W. Moir [a], Mohamed A. Abdou [b]

[a] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[b] *University of California, Los Angeles, CA 90095, USA*

Abstract

The most serious challenges in the design of chambers for inertial fusion energy (IFE) are: (1) protecting the first wall from fusion energy pulses on the order of several hundred megajoules released in the form of X-rays, target debris, and high energy neutrons; and (2) operating the chamber at a pulse repetition rate of 5–10 Hz (i.e. re-establishing the wall protection and chamber conditions needed for beam propagation to the target between pulses). In meeting these challenges, designers have capitalized on the ability to separate the fusion burn physics from the geometry and environment of the fusion chamber. Most recent conceptual designs use gases or flowing liquids inside the chamber. Thin liquid layers of molten salt or metal and low pressure, high-Z gases can protect the first wall from X-rays and target debris, while thick liquid layers have the added benefit of protecting structures from fusion neutrons thereby significantly reducing the radiation damage and activation. The use of thick liquid walls is predicted to: (1) reduce the cost of electricity by avoiding the cost and down time of changing damaged structures; and (2) reduce the cost of development by avoiding the cost of developing a new, low-activation material. Various schemes have been proposed to assure chamber clearing and renewal of the protective features at the required pulse rate. Representative chamber concepts are described, and key technical feasibility issues are identified for each class of chamber. Experimental activities (past, current and proposed) to address these issues and technology research and development needs are discussed. Published by Elsevier Science S.A. All rights reserved.

1. Introduction

The ability to separate the burn physics from the design of the inertial fusion chamber (both in geometric configuration and choice of materials) has led to a large variety of chamber design concepts for inertial fusion energy (IFE). Refs. [1–8] provide an excellent review of many of the past designs. Chamber designs are typically characterized by the approach taken to dealing with the potentially damaging effects of the pulsed energy release, especially the ~30% of the fusion yield that is in the form of X-rays and target debris. The general classes of chamber design include:

- Concepts that use low pressure gas in the chamber to protect the first wall (FW) from X-rays and debris;
- Designs that use a thin liquid film or sprays of liquid mist to protect structures from X-rays and debris; and

* Corresponding author.

0920-3796/98/$19.00 Published by Elsevier Science S.A. All rights reserved.
PII S0920-3796(97)00132-4

- Chambers that use thick flowing blankets (liquid or granular) to protect structures from X-rays, debris and neutrons.

In this paper we describe three recent concepts to illustrate the design features and issues for each class of chamber. These include:

- Sombrero [9,10], a laser-driven design that uses xenon gas to protect a carbon/carbon composite FW;
- Prometheus-H [11–13], a heavy-ion-driven design that uses a thin film of liquid lead to protect a porous SiC FW; and
- HYLIFE-II [14], a heavy-ion-driven design that used an array of molten salt jets to absorb X-rays, debris and moderate neutrons and protect a 304 stainless steel (SS) FW.

Table 1 summarizes key design and operating parameters for these three IFE chamber concepts. The design characteristics, attractive features and key technical issues, experiments and technology development needs for these three examples are described in the sections that follow.

Table 2 summarizes the key issues and development needs for IFE reactors. As used here, the 'reactor' includes the chamber (first wall, blanket, vacuum vessel), shield, chamber/driver interface, and the balance of plant including energy transport and conversion systems. While some of the

Table 1
Comparison of key design parameters for three IFE chamber concepts

Parameters	Sombrero	Prometheus-H	HYLIFE-II
Driver			
Type	KrF laser	HI induction linac	HI induction linac
Number of beams	60	14	12
Driver energy (MJ)	3.4	7.0	5
Pulse rate (Hz)	6.7	3.54	6.4
Driver efficiency (%)	7.3	18[a]	33
Target			
Type	Direct drive	Indirect drive	Indirect drive
Target gain	118	103	70
Yield (MJ)	400	719	353
Chamber			
First wall material	C/C composite	Porous SiC	304 Stainless
First wall protection	Xenon gas	Liquid Pb film	Flibe jet array[b]
First wall radius (m)	6.5	4.5	3.3
First wall coolant	Li_2O granules	Liquid Pb	Flibe
Blanket structure	C/C composite	SiC	Stainless steel
Blanket coolant	Flowing Li_2O + 0.2 MPa He	He (1.5 MPa)	Flibe jet array
Breeding material	Li_2O granules	Li_2O pebbles	Flibe
T breeding ratio	1.25	1.20	1.17
Vacuum vessel	C/C composite	Ferritic steel	Stainless steel
Power balance			
Gross efficiency (%)	47	43	43
Fusion power (MW)	2677	2543	2245
Total thermal (MW)	2891	2780	2675
Gross electric (MW)	1359	1189	1150
Driver power (MW)	304	137	97
Auxiliary power (MW)	55	53	52
Net electric (MW)	1000	1000	1000
Net system eff. (%)	35	36	37

[a] Based on energy to target.
[b] Inner radius of jet array is 0.5 m.

Table 2
Key issues and development needs for IFE reactors

Basic concept issues
Fabricability of first wall (FW), blanket, vacuum vessel (VV)
Establishing first wall protection mechanism
Chamber issues
X-ray and debris induced impulse to FW/blanket
Chamber clearing time
Vaporization and condensation rate
Dissociation and recombination rate (for Flibe, PbLi, Li_2O)
Droplet formation and control (for liquid walls)
Neutron induced pressure pulse due to isochoric heating
Effects FW protection
Effects on flowing blankets
Tritium breeding and recovery
Lifetime and maintenance issues
Radiation damage life of FW, blanket, and VV structures
Activation of FW, blanket, VV, and shield materials
FW/blanket replacement approach and required time
Corrosion and/or erosion of FW and blanket structures
Reliability of reactor systems
Chamber/driver interface issues
Ion driver
Vacuum interface
Shielding of focusing magnets and neutron streaming
Migration of radioactive material up beam line
Isolation mechanism for routine and emergency shut-down
Laser driver
Radiation damage to final optics
Contamination of final optics by target debris
Contamination of final optics by chamber materials
Chamber/target interface issues
Standoff, trajectory and tracking constraints set by chamber
Isolation of injector from radiation damage/contamination
Effect of chamber conditions on target positioning
Balance of plant issues
Pumps and piping for primary and intermediate coolants
Heat exchangers and steam generators if non-standard coolants
Power conversion systems if non-conventional
Environmental and safety issues
Radiation doses due to normal and accidental releases
Tritium/radioactive material confinement and recovery
Activation of FW, blanket, VV, and shield materials

listed issues are generic to all IFE reactor designs, some are specific to the particular chamber configuration, materials used, operating conditions, etc. In the specific examples discussed in the following sections we primarily focus on the issues related to chamber designs.

2. Sombrero

2.1. Description of Sombrero concept

Sombrero is a 1000 MW, KrF-laser-driven power plant design [9,10]. It features a carbon/carbon (C/C) first wall (FW) and blanket structure with a granular Li_2O breeding blanket. The FW is protected from X-rays and ions by 0.5 Torr of xenon gas. The Li_2O granules flow through the blanket region of the chamber and are circulated as the primary coolant. The Sombrero chamber is shown in Fig. 1 and key design parameters are listed in Table 1.

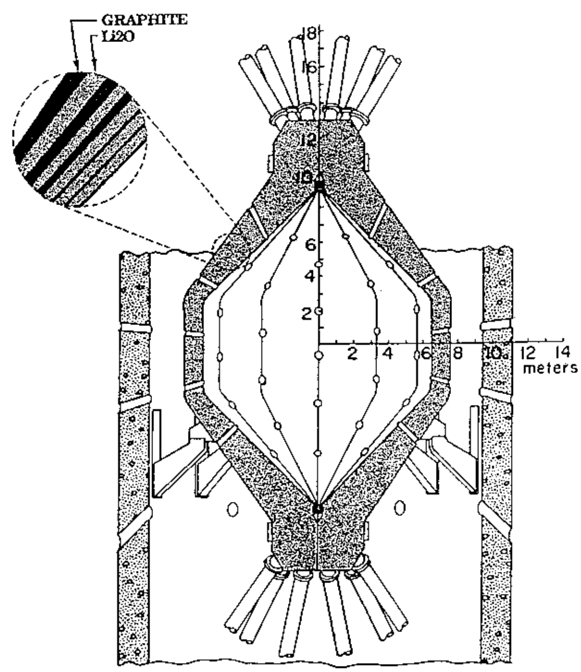

Fig. 1. The Sombrero chamber features carbon–carbon composite first wall and blanket structures. Flowing Li_2O is the breeder and coolant.

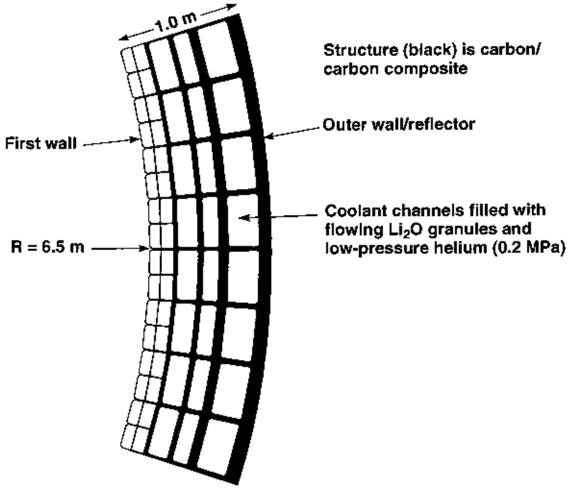

Fig. 2. Cross-section of the Sombrero blanket showing the channels for the flowing Li_2O breeder–coolant (open regions) and the carbon–carbon composite structure (dark regions).

The chamber is assembled from 12 wedge-shaped, C/C composite modules that are totally independent with separate Li_2O inlet and outlet tubes. The chamber has a cylindrical central section with conical ends, a radius of 6.5 m at the midplane, and an overall height of 18 m. Each module is subdivided both radially and circumferentially into coolant channels as shown in Fig. 2. The carbon structure fraction increases from 3% at the front to 50% at the rear of the blanket, thus providing an internal reflector which does not require separate cooling. The FW thickness is 1.0 cm. The thickness of the coolant channel behind the FW varies from 7 cm at the midplane to 37 cm at the upper and lower extremities, making the flow area constant along the entire FW from top to bottom. This is done to ensure a constant velocity at the FW where a high heat transfer coefficient is needed.

The Li_2O particles, with a size range of 0.3–0.5 mm, have a void fraction of 40% in the moving bed, and the grains are 90% of theoretical density. The Li_2O particles enter the top of the chamber from a manifold that doubles as a cyclone separator to remove the particles from the He gas that is used to transport Li_2O through the intermediate heat exchanger (IHX). After the particles enter the chamber, they flow under the force of gravity through the chamber and exit at the bottom. The Li_2O velocity at the FW is 1.15 m s^{-1}, and each succeeding radial zone has progressively lower velocity toward the rear of the blanket. Low pressure (0.2 MPa) helium gas flows counter-current to the particles in the chamber coolant channels; this helps maintain a steady movement of particles and prevents the formation of clustering or compaction. The He flow also sweeps tritium from the Li_2O breeding particles. A thin coating of SiC on the inner surface of the coolant channels aids in sealing the C/C composite structure against He gas leakage into the chamber. The Li_2O inlet temperature to all the zones is 550°C, but the outlet temperature is 700°C for the FW coolant channel and 800°C for the rear zones. The total mass flow rate of 2×10^7 kg h^{-1} has an equilibrated outlet temperature of 740°C. Flow in the different channels is controlled with baffles located at the bottom of the chamber to ensure that there will not be voids in the blanket. After going through the chamber, the particles are transported around the loop and through the IHX in a fluidized or entrained state by He gas.

The 0.5 Torr of xenon gas that fills the Sombrero chamber absorbs the target X-rays and debris ions and re-radiates the energy to the FW over a long enough time that thermal conduction in the wall can keep the surface temperatures low enough to avoid damage (i.e. ablation and vaporization) of the graphite. The peak surface temperature for the 400 MJ yield target is calculated to be $\sim$2100°C, well below the sublimation temperature for graphite of 4100°C. The peak pressure on the wall of 0.013 MPa and impulse of 2.1 Pa s should not cause any major mechanical response in the first wall.

Sombrero also has very good neutronic performance. The tritium breeding ratio is 1.25 with 0.91 coming from ^6Li. The energy multiplication factor is 1.08, which increases the 2677 MW of fusion power to 2891 MW of total thermal power. The peak displacement damage rate in the carbon first wall is about 15 displacements-per-atom (dpa) per full-power-year (fpy), and the helium production rate is about 3800 atom-part-per-million per fpy. The lifetime limit for radiation damage is uncertain. If a material program can develop a C/C composite with a damage limit of 75 dpa, a first wall lifetime of ~ 5 fpy would be possible.

Sombrero has several attractive features, including:

(i) Uniform beam illumination required for direct drive targets is most easily accommodated in a dry wall chamber such as Sombrero. It is difficult to design wetted wall (thick or thin) chambers that can assure droplets will not fall on the optics of those beams that enter from the bottom of the chamber.

(ii) Compared to some solid breeder blanket design, the Sombrero blanket structures are very simple and should be easily maintained. The flowing breeder retains the advantages of solid breeders without the need for high pressure helium coolant. The low pressure (0.2 MPa) helium sweep gas is effective for tritium recovery.

(iii) The use of low activation materials for the first wall, breeder and blanket structures results in good environmental and safety characteristics for the power plant.

2.2. Critical chamber issues and development needs for Sombrero

To realize the potential advantages listed above, significant research and development (R and D) will be required for the Sombrero chamber. Critical chamber issues are listed in Table 3. To address these issues R and D in the following areas is needed:

2.2.1. First wall

Experimental verification of the effectiveness of the first wall protection scheme is needed. The ability to re-establish proper xenon gas protection between shots to allow beam propagation but prevent first wall vaporization must be demonstrated.

2.2.2. Chamber structures

The development of the capability to manufacture larger C/C composite structures is essential to the design concept. Radiation damage tests with composite materials to determine material lifetime and the effects on thermal conductivity are needed. A materials development program for this class of materials is needed for both IFE and magnetic fusion energy (MFE).

2.2.3. Laser propagation

If the xenon gas density is too high, breakdown can occur which would reduce the amount of energy delivered to the target. Experiments to quantify the limits on the density of the gas are needed at the correct wavelength and intensity. The implications on target performance if breakdown occurs near the target also need additional study. Gradients in the xenon gas density can increase the focal spot size.

2.2.4. Flowing blanket

Several aspects of the flowing breeding blanket would benefit from further study. Additional experiments on the heat transfer capabilities of the flowing bed examining a wider range to the operating variables and materials should be carried out. The issues of granule break-up and erosion of the blanket and heat transfer components need study.

2.2.5. Tritium control

Since tritium is present in the xenon gas that fills the reactor building, it is essential that the building walls do not absorb tritium. Verification

Table 3
Critical chamber issues for Sombrero

Basic concept issues
Fabricability of C/C composite FW and chamber
Granule flow in blanket
Fluidize transport to/from heat exchangers
Beam propagation through xenon gas
Chamber operation issues
Effectiveness of xenon gas in preventing ablation/vaporization
Re-establishing correct gas pressure after each pulse
Heat transfer/transport with granular flow blanket
Tritium recovery and control within reactor building
Lifetime and maintenance issues
Radiation damage life of FW/blanket
Time required for replacing blanket modules
Erosion of FW and blanket structures by flowing granules

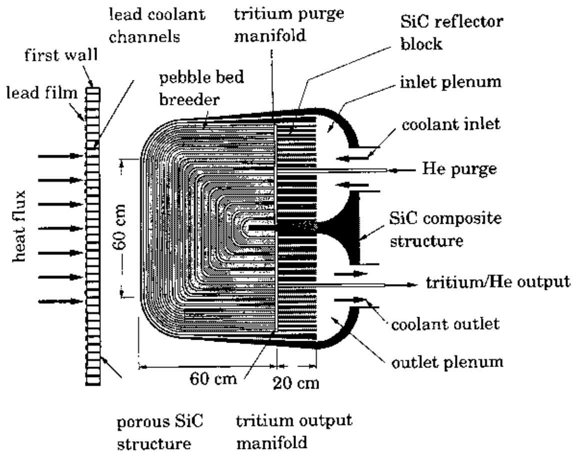

Fig. 3. Prometheus chamber features a Pb-cooled porous SiC first wall and a helium-cooled Li_2O breeding blanket with SiC structures.

of the ability of coatings to prevent absorption is needed.

3. Prometheus

3.1. Description of Prometheus-H chamber

Prometheus-H is a heavy-ion driven, 1000 MW power plant design [11–13]. The first wall and blanket are illustrated in Figs. 3 and 4 and key parameters are listed in Table 1. The first wall, blanket, shield, and coolant tubes are all constructed of the SiC structural material. SiC was chosen for the structural material because it has shown promise of a high resistance to radiation damage, good fatigue characteristics, and good environmental disposal properties (low activation). The postulated lifetime of the first wall is 5 years, whereas the blanket is longer-lived at 10 years. All other SiC reactor components are considered to be life-of-plant equipment.

The Prometheus first wall is at a radius (mid-plane) of 4.5 m and is protected by a thin (0.5 cm) film of liquid lead, which is partially evaporated by each microexplosion and is condensed between explosions. In addition to protection for the first wall, this layer of liquid lead provides vacuum pumping to maintain the proper chamber pressure for the incoming heavy ion beams and to cleanse the chamber of residual fuel and fusion by-products. The first wall panels are constructed of porous composite SiC structure that is internally cooled with the liquid lead. Behind the first wall, a Li_2O solid breeder is cooled with a low pressure (1.5 MPa), high temperature (650°C) helium coolant. A low pressure helium purge extracts the tritium generated in the breeder. The tritium breeding ratio is 1.20. All the lead and helium coolant piping within the bulk shielding is constructed with the low-activation SiC structural material.

A cylindrical reactor cavity with hemispherical ends is used to provide the necessary maintainability of the first wall and blanket system with a reasonable ratio of peak-to-average neutron wall loading (7.1/4.7 MW m^{-2}). The upper section of the chamber is designed to be removed to gain access to the replaceable first wall and blanket systems. An overhead crane will remove the upper sections and transport them to a lay-down area within the reactor building.

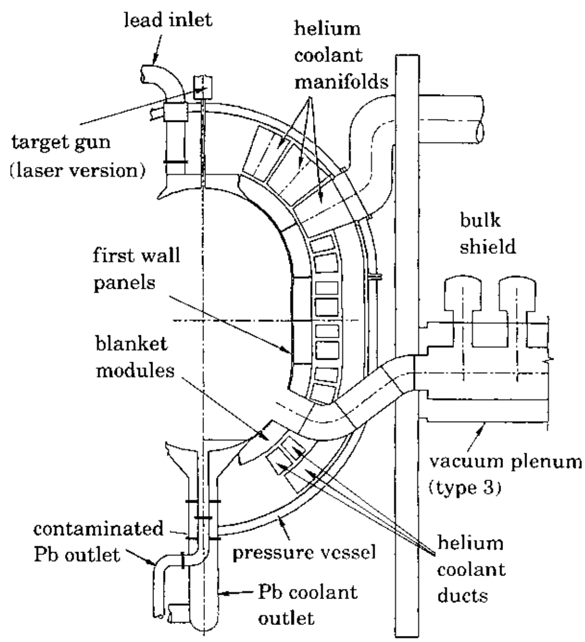

Fig. 4. A steel vacuum vessel contains the Prometheus FW and blanket modules. Inlets and outlets for the lead and helium coolants are shown as well as the vacuum port for pumping non-condensable gases.

Following each target explosion, the chamber fills with target debris and liquid lead evaporated from the protective film. This material must be removed from the chamber before the next target is injected. In the Prometheus design, the chamber is cleared by condensing the condensable gases on the surface of the first wall and by pumping non-condensable gases out through large ducts shown in Fig. 4.

The liquid lead flowing in 5-cm channels within the first wall structure also serves as a primary coolant and heat transfer medium. The inlet and outlet lead temperatures are 375 and 525°C based upon fluid flow, vapor pressure, and thermal conversion efficiency considerations. The lead coolant transports 1162 MW of power. The heat transfer medium within the blanket is low-pressure helium with inlet and outlet temperatures of 400 and 650°C which transports 1597 MW. Usable pumping waste heat of 21 MW can be recovered. The total thermal power of 2780 MW is delivered to an advanced Rankine thermal conversion cycle with an efficiency of 43%, which yields a gross electric power of 1189 MW. Recirculating power requirements for the Prometheus first wall protection system, the heavy-ion driver, and auxiliary systems require an additional 190 MW which results in a net power output of 999 MW. Steam-driven circulators are used because they are more efficient-their power requirement is accounted for in a slightly lower system efficiency.

Some of the attractive features of the Prometheus chamber design include:

- Use of a low activation material (SiC) for the first wall and blanket results in good environmental and safety characteristics.
- Use of lead for the liquid metal film to protect the FW reduces corrosion/accident hazard compared to Li.
- Use of helium coolant enhances blanket safety.
- The concept is adaptable to two-sided or uniform illumination with heavy-ion or laser drivers.

3.2. Critical chamber issues and development needs for Prometheus-H

The key issues and developmental needs associated with the Prometheus-H chamber (see Table 4) involve the liquid metal first wall surface protection, the ability to effectively clear the reactor chamber, and viability of SiC composite structures. Future R and D needs should focus on the following:

Table 4
Critical chamber issues for Prometheus-H

Basic concept issues
Fabricability of SiC FW and blanket modules
Establishing uniform Pb film on porous SiC FW
Flow around geometric perturbation (e.g. ports)
Protection of inverted surfaces
Chamber operation issues
Response of thin film to X-ray and debris pulse
Vapor flow up beam lines
Re-establishing film between shots
Condensation of Pb vapor to allow beam propagation
Tritium breeding and recovery from solid breeder
Lifetime and maintenance issues
Radiation damage life of FW/blanket
Time required for replacing FW and blanket modules
Recovery of target debris from Pb coolant

3.2.1. First wall concept

The Prometheus design team chose to use liquid lead to wet the first wall to prevent the solid first wall structures from rapidly degrading due to extremely high, instantaneous heat and particle loads. Major uncertainties include film feeding, thickness control, blast effects, flow around geometric perturbations and protection of inverted surfaces.

3.2.2. Condensation

The condensation of the evaporated lead film is calculated to result in a cavity pressure below 1 mTorr before the next explosion. However, the actual physics of energy and mass transport and vapor condensation are very complex. The cavity gases are partially ionized and subject to highly time-dependent processes such as hydrodynamic shock waves.

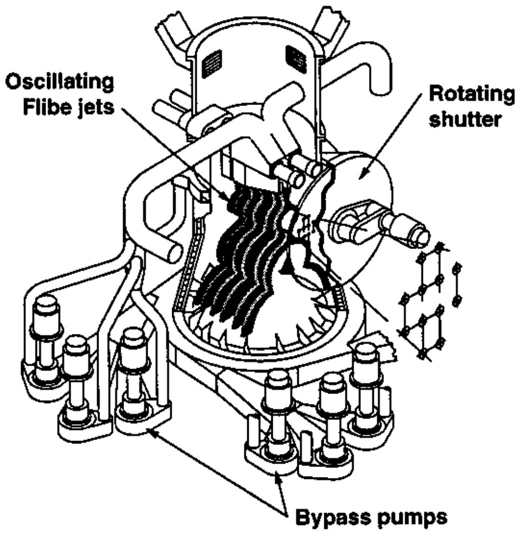

Fig. 5. The HYLIFE-II chamber uses an array of oscillating jets of liquid Flibe to form a thick protective blanket between the fusion target and the chamber structures. The pumps required to circulate the Flibe (Li_2BeF_4) are shown.

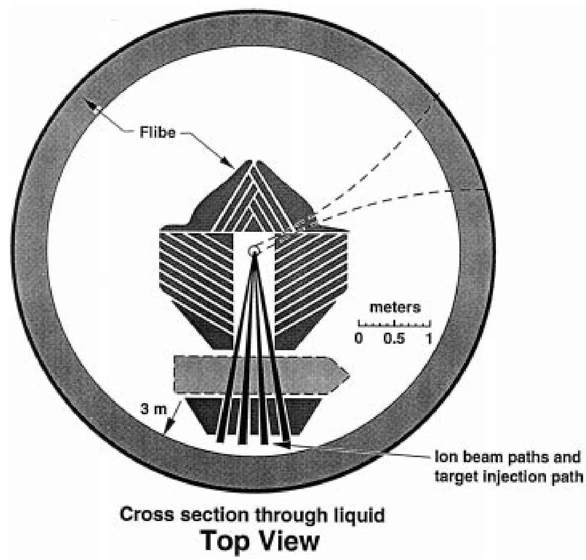

Fig. 7. Cross section of the chamber at the target elevation showing the open space for vapor venting and 0.5 m of liquid to attenuate neutrons in all directions except the beam paths. (The single-sided illumination configuration is shown, although two-sided illumination is now the preferred approach).

3.2.3. Materials development

The use of SiC as the cavity structural material is very desirable, but its viability is questionable until well proven. Areas of uncertainty involve the lifetime in a highly radioactive environment, established material databases, and development of processing methods and manufacturing techniques for large structural components with reasonable economics.

4. HYLIFE-II

4.1. Description of HYLIFE-II concept

HYLIFE-II is a 1000 MWe, heavy-ion-driven power plant design [14]. As illustrated in Figs. 5–7, oscillating and stationary nozzles and deflec-

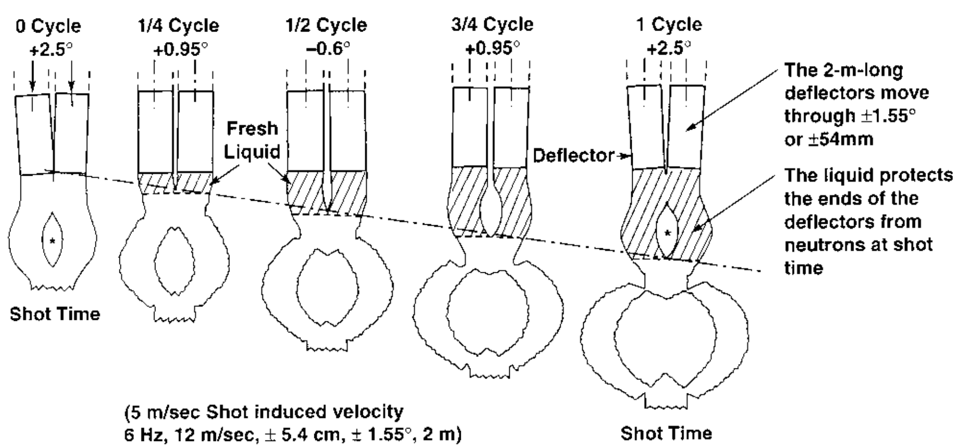

Fig. 6. Sequence showing how the liquid pocket is formed using the oscillating nozzles.

tors are used to form a 'pocket' of liquid Flibe (Li_2BeF_4) at shot time. The liquid is thick enough (~ 7 mean free paths for 14 MeV neutrons) to breed tritium and attenuate neutrons enough to reduce damage to structures located behind 0.5 m of Flibe in order to last the life of the plant. Out beyond the 0.5 m pocket of Flibe is a thin few centimetre thick steel wall containing another 0.5 m of Flibe. Over 92% of the activated 304 SS qualifies for shallow burial [15].

Because the fluid mechanical basis for HYLIFE-II (built upon the HYLIFE-I work) is reviewed extensively in [14], it is only summarized here. Several issues must be considered in the reaction chamber to allow 6-Hz operation. Flibe splash from each pulse must be cleared from the beam path prior to the next pulse, and enough vaporized Flibe must condense for both beam propagation and for target injection. One way to achieve a high pulse rate is to shorten the distance between the microexplosion and the nozzles that inject the Flibe and to oscillate the jet nozzles horizontally, as shown in Fig. 6 (see [16,17] for more details). A pocket is formed in the flow where a target is injected and the microexplosion occurs. The oscillating motion of the incoming liquid sweeps away splashed liquid left over from the previous microexplosion and clears the region inside the pocket. The slots between the liquid slabs shown in Fig. 7 permit the vapor produced by the microexplosion to vent rapidly. Mechanical moving parts allow the nozzles to oscillate at 6 Hz through a motion of $\pm 2.5°$ or ± 0.09 m at the nozzle tips. Fatigue and vibration appear manageable, but more detailed design work is required. Continuously flowing, horizontal and vertical, neutronically thick liquid jets (shown in Fig. 7) will protect the beam ports from radiation damage.

Initially about 16% of the 350-MJ microexplosion yield is deposited by X-ray absorption in a thin layer on the exposed surfaces of the Flibe blanket, causing ablation (vaporization, dissociation and ionization) of a small amount of mass. The vaporized material cools rapidly while expanding into the central cavity with high inward velocity. As it moves toward the center of the Flibe pocket, it interacts with the target debris (which carries an additional 16% of the yield) and recompresses, which increases its temperature again. After re-expansion, the vapor impinges on and vents through the blanket within about 1 ms [18]. To assure rapid condensation, cold Flibe (cooler than the bulk but still molten) is sprayed into the annular region between the Flibe blanket and the vessel wall. The flow rate of this spray is capable of condensing all the vapor to a particle density in the range 3×10^{12}–3×10^{13} cm^{-3} needed for heavy ion propagation for the next shot [19,20] within the allowed 0.167 s for 6-Hz pulse rate. Stated another way, it is assumed that the spray must absorb all the X-ray and debris energy (112 MJ). Future improvements in analysis of the central cavity pocket and venting phenomena will remove some of the assumptions in the present spray system design; experiments clearly will be needed.

Some Flibe is ablated, vaporized, dissociated, and ionized into its constituents by X-rays from the microexplosion. These constituents will reform Flibe and not other species because the chemical recombination to Flibe is strongly favored. Furthermore, on the basis of a preliminary study, it is believed that the recombination is sufficiently fast compared to time scales for the gas dynamics and condensation processes, that chemical equilibrium can be assumed for all gas dynamics and condensation processes. This permits the use of a recently developed equilibrium equation of state for Flibe vapor [21]. On the other hand, the presence of trace noncondensable species such as tritium and helium will impact condensation processes by creating a diffusional resistance. The areas of chemical kinetics and rapid condensation will require definitive experiments.

The liquid blanket is subjected to forces associated with X-ray ablation, gas pressure (form drag) and shear (skin drag) that impart an outward radial motion toward the vessel wall. These contributions may be further augmented by the net effect of breakup following neutron-induced isochoric heating of the blanket. (Isochoric, or constant volume, heating is the intense, instantaneous, volumetric heating that occurs as the fusion neutrons are absorbed in the liquid, generating internal pressures of hundreds of atmospheres).

Considering all these interactions, it is estimated that the liquid blanket of the present design injected at 12 m s^{-1} downward will receive an average outward velocity of about 7 m s^{-1}, which will result in the liquid impacting the wall near the bottom of the vessel (see Fig. 5) with an impact pressure of only 25 kPa. Given the complex nature of these phenomena, however, especially the rather unusual effect of isochoric heating, much more work needs to be done to predict the liquid motion with confidence.

We chose Flibe because it is compatible with stainless steel up to 650°C and has a low enough vapor pressure. Li and $Li_{17}Pb_{83}$ would also work but must be 1.5 m thick versus 0.5 m to attenuate neutrons [22]. Due to corrosion the temperature must be reduced or an expensive material such as vanadium alloy must be used. The reduced temperature, increased chamber radius and increased pumping power features required by use of Li or $Li_{17}Pb_{83}$ suggest Flibe might be the lowest cost choice.

The attractive features stated here can be described as having four profound implications for development of IFE due to the use of thick liquid walls:

- Life-of-plant structures mean there is no periodic downtime for first-wall/blanket replacement and no replacement costs for new first wall/blankets, equipment, and hot cells; combined these could reduce the cost of electricity by 24%.
- There is no need to develop new materials; 304 SS qualifies for shallow burial at decommission time, i.e. can be considered a low-activation material.
- High fluence and volumetric neutron sources are not needed to develop first-wall materials.
- The projected cost of electricity is competitive with future fission plants and lower than future coal-fired plants.

Another feature is that the extremely low solubility of tritium in Flibe results in a low tritium inventory. The inventory is calculated at 140 g in the steel and far less in the Flibe. As a consequence all steel will have to be double walled with purged flow to scavenge permeating tritium to keep losses acceptably low.

4.2. Critical chamber issues and development needs

The key issues and developmental needs for the HYLIFE-II chamber (see Table 5) have to do with repeated formation of the protective liquid pocket, the ability to condense and clear the chamber to pre-shot conditions and issues related to the use of Flibe. Experiments are needed to put the concept of liquid-wall protection on a firm foundation. Research and development on liquid-jet formation, gas/jet and gas/wall shock phenomena, chamber clearing, condensation, and reliability of moving jets are called for. In the near term, R and D should focus on the following:

4.2.1. Liquid pocket

Demonstrating the ability to form the protective liquid pocket using oscillating nozzles at the required pulse rate (even without the disruptive fusion blast) is a necessary first step. Some jet

Table 5
Critical chamber issues for HYLIFE-II

Basic concept issues
Formation of fluid pockets
Extraction of fluid w/o stagnation (splash back)
Oscillating flow nozzles and deflectors to generate ‘clean’ jets
Cross-flow for beam protection
Chamber operation issues
Vaporization and condensation (vapor flow, jet response)
Dissociation/recombination of Flibe
Jet pocket in high pulse rate environment (clearing of droplets, etc.)
Isochoric heating of jets
Response of cross jets
Impulse to wall (vapor and liquid)
Chamber lifetime and maintenance
Corrosion by fluorine
Fluid clean-up (chemistry, target debris recovery)
Pulsed neutron damage effects on chamber structures
Fatigue of nozzle tips
Life of mechanisms and seals

formation experiments are currently underway at the University of California, Berkeley (UCB) [23], but a small-scale oscillating jet array proof-of-concept demonstration is needed.

4.2.2. Response to fusion pulse

Computer codes (e.g. TSUNAMI [24]) have been used to simulate the response of the liquid pocket and crossing jets that protect the beam ports. Experiments such as the shock tube experiments at UCB [24] that help benchmark these codes are needed. Work on vaporization and condensation is needed.

4.2.3. Use of Flibe

Issues related to use of Flibe, such as corrosion by fluorine and removal of target debris require attention. Experiments to show chemical recombination is rapid enough to not limit condensation clearing for the next shot are needed.

Technology development needs for the longer term include:
- Pumps for Flibe capable of $\sim 5\ m^3\ s^{-1}$ flow rates,
- Tritium extraction in the vacuum disengager,
- Flibe-to-steam heat exchanger designed to avoid freeze-up, and
- Flibe chemical clean-up equipment.

5. Summary

A practical IFE system requires protection of the chamber solid first wall from rapid degradation due to the extremely high instantaneous heat and particle loads associated with the X-rays and debris from the target. While researchers agree on the need to protect the chamber solid wall, there is no consensus on the best means to achieve this since each has advantages and disadvantages. Three recent designs described in this paper illustrate the general classes of gas protected dry wall, thin liquid layer protection, and thick liquid layer protection. A common issue requiring R and D for all of these concepts is the ability to re-establish chamber conditions between pulses. This involves condensing condensable materials, pumping non-condensable gases and assuring that liquid droplets or residual vapor pressure does not impede the delivery of the next target and propagation of the ion or laser beams to the target.

The thick liquid wall design has the potential to have significant advantages. Its primary advantage is that by protecting chamber structures from neutron damage, these structures are predicted to survive for the life of the plant. A benefit of long-life components is a reduction in maintenance requirements and commensurate increase in chamber availability. If the other major subsystems of the power plant (i.e. driver, target factory, balance of plant) can also achieve high reliability, the overall plant availability factor can be higher than other fusion chamber concepts that require periodic first wall replacement, and the cost of electricity can be reduced. In addition, and perhaps more significant, is the fact that ordinary steel (304 SS in the case of HYLIFE-II) will qualify for shallow land burial at the end of life. In this way, IFE can achieve fusion's promise of low activation without the need for a materials development program to develop a new low-activation material.

Acknowledgements

Part of this work (that of W. Meier and R. Moir) was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

References

[1] M.J. Monsler, J. Hovingh, D.L. Cook, T.J. Frank, G.A. Moses, An overview of inertial fusion reactor design, Nucl. Technol./Fusion 1 (1981) 302.
[2] W.J. Hogan (Ed.), Energy from Inertial Fusion, STI/PUB/944, International Atomic Energy Agency, Vienna, Austria, 1995.
[3] R.W. Moir, Liquid wall inertial fusion energy power plants, Fusion Eng. Des. 32/33 (1996) 93–103.
[4] J.H. Pitts, Cascade: a centrifugal-action solid breeder reaction chamber, Nucl. Technol./Fusion 4 (1983) 967.
[5] Heavy ion fusion reactor—HIBLIC-I, Rep. IPPJ-663, Inst. of Plasma Physics, Nagoya, 1984.

[6] B. Badger, et al., HIBALL-II, an improved conceptual heavy ion beam driven fusion reactor study, Rep. KfK-3840, Kernforschungszung Karlsruhe; UWFDM-625, University of Wisconsin, Madison, 1985.
[7] G. Kessler, U. von Mollendorff, Studies on heavy-ion beam fusion reactors, Fusion Technol. 11 (1987) 374–399.
[8] B. Badger, et al., LIBRA-LITE: a commercial size light ion fusion power plant, Rep. UWFDM-880, University of Wisconsin, Madison, 1991.
[9] W.R. Meier, et al., Osiris and Sombrero inertial fusion power plant designs, W.J. Schafer Associates report, WJSA-92-01, DOE/ER/54100-1, 1992.
[10] W.R. Meier, Osiris and Sombrero inertial fusion power plant designs-summary, conclusion, and recommendations, Fusion Eng. Des. 25 (1994) 145–157.
[11] L.M. Waganer, et al., Inertial fusion energy reactor design studies, McDonnell Douglas Aerospace report, DOE/ER-54101, MDC 92E0008, 1992.
[12] L.M. Waganer, Innovation leads the way to attractive inertial fusion energy reactors—Prometheus-L and Prometheus-H, Fusion Eng. Des. 25 (1994) 125–143.
[13] M.A. Abdou, et al., Critical technical issues and evaluation and comparison studies for inertial fusion energy reactors, Fusion Eng. Des. 23 (1993) 251–297.
[14] R.W. Moir, Improvements to the HYLIFE-II inertial fusion power plant design, Fusion Technol. 26 (1994) 1169–1177.
[15] J.D. Lee, Waste disposal of HYLIFE-II structure-issues and assessment, Fusion Technol. 26 (1994) 74.
[16] P.A. House, HYLIFE-II reactor chamber mechanical, Fusion Technol. 21 (1992) 1487.
[17] P.A. House, HYLIFE-II reactor chamber design refinements, Fusion Technol. 26 (1994) 1178.
[18] J.C. Liu, P.F. Peterson, V.E. Schrock, Blast venting through blanket material in the HYLIFE-II reactor, Fusion Technol. 21 (1992) 1514.
[19] R.W. Moir, Heavy ion beam and reactor chamber interface design, Part. Accel. 37/38 (1992) 459.
[20] A.B. Langdon, Reactor chamber propagation of heavy ion beams, Part. Accel. 37/38 (1992) 175.
[21] X.M. Chen, V.E. Schrock, P.F. Peterson, Fitted equations of state for flibe gas, Fusion Technol. 26 (1994) 912.
[22] S. Sahin, R.W. Moir, A. Sahinaslan, H.M. Sahin, Radiation damage in liquid-protected first-wall materials for IFE-reactors, Fusion Technol. 30 (1996) 1027–1035.
[23] C.J. Cavanaugh, P.F. Peterson, Scale modeling of oscillating sheet jets for the HYLIFE-II inertial confinement fusion reactor, Fusion Technol. 26 (1994) 917–921.
[24] J. Liu, V.E. Schrock, P.F. Peterson, Experimental and numerical investigation of shock wave propagation through complex geometry, gas continuous, two-phase media, Ph.D. Dissertation, Department of Nuclear Engineering, University of California, Berkeley, 1993, Lawrence Livermore National Laboratory report UCRL-ID-116871, 1993.