# Technology and Power Plant Issues For Inertial Fusion

Presented by
Mohamed Abdou
On Behalf of the FESAC/IFE
Review Panel

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# Outline

- General Charateristics of IFE Power Plants
- Potential of IFE
- Charaterization of Issues
- Research Priorities

# Power Plants
# Conceptual Design & System Studies

- 49 Studies since 1971
- Eleven were driven by Heavy Ions
- The most recent, and most comprehensive studies were carried out by two teams of industry and universities and completed in March 1992:

**PROMETHEUS - H (HI), PROMETHEUS - L (Laser)**

McDonnell Douglas
Ebasco
TRW
CFFTP
KMS Fusion
SPAR
UCLA

**OSIRIS (HI), SOMBRERO (Laser)**

W.J. Schafer
Bechtel
Textron
GA
University of Wisconsin

- *These studies*
- did excellent work
- developed many innovative concepts
- helped evaluate the potential of IFE
- helped identify the key R&D Issues

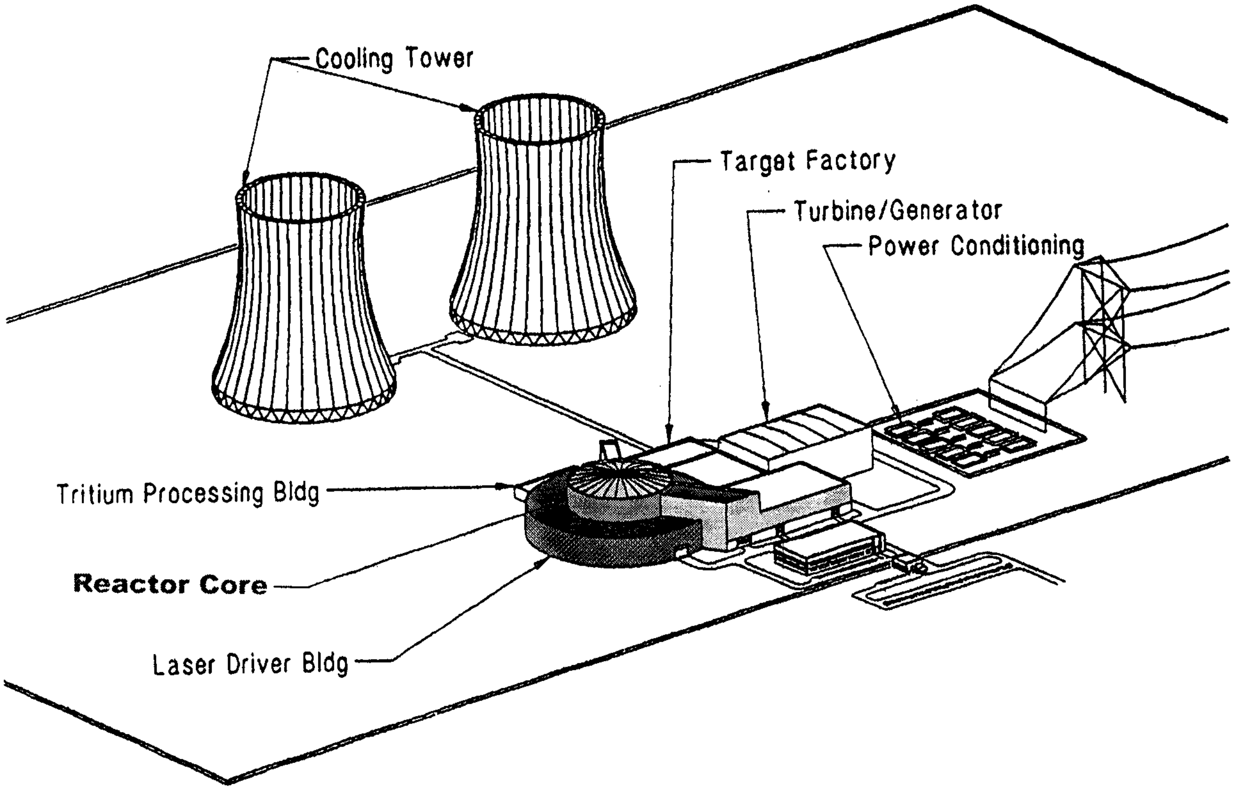


Figure ES-1. Prometheus-L Plant Site Trimetric View

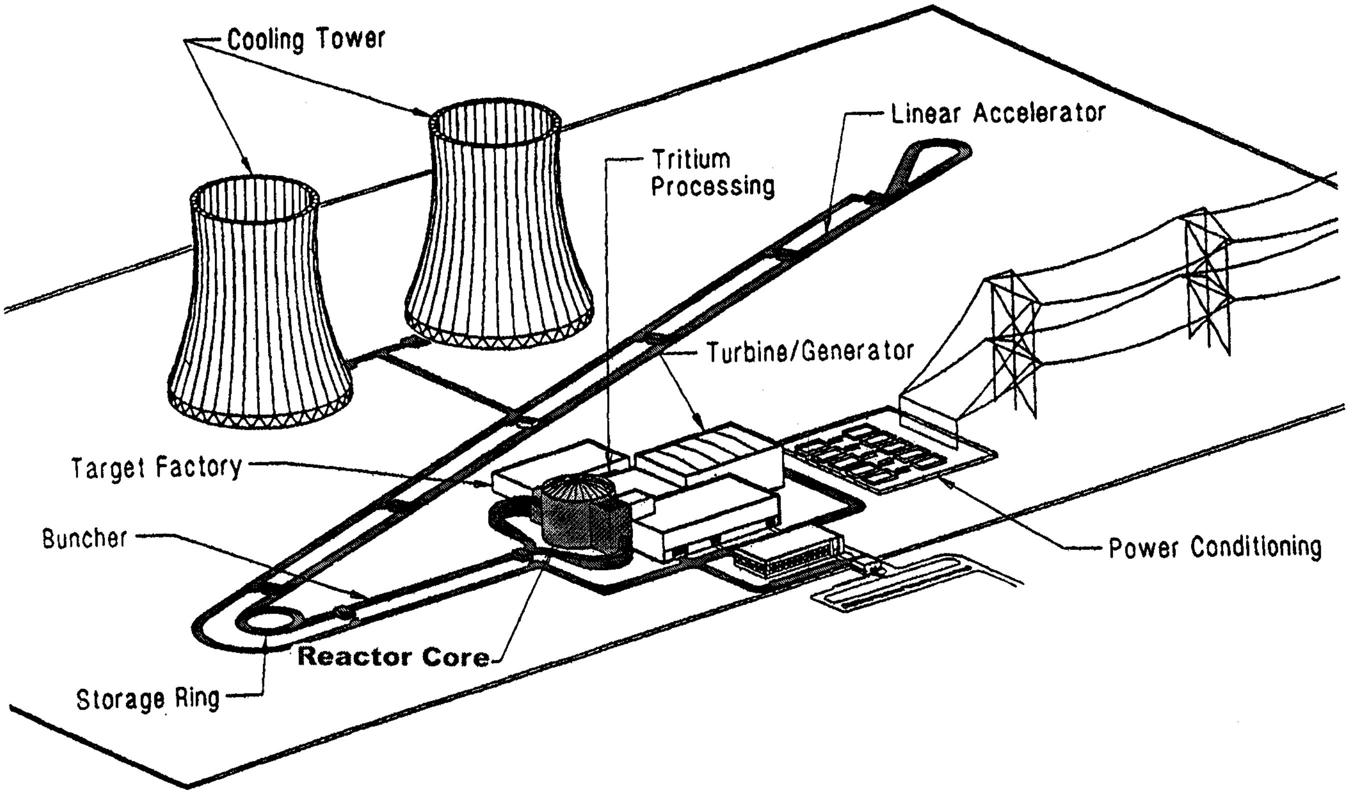
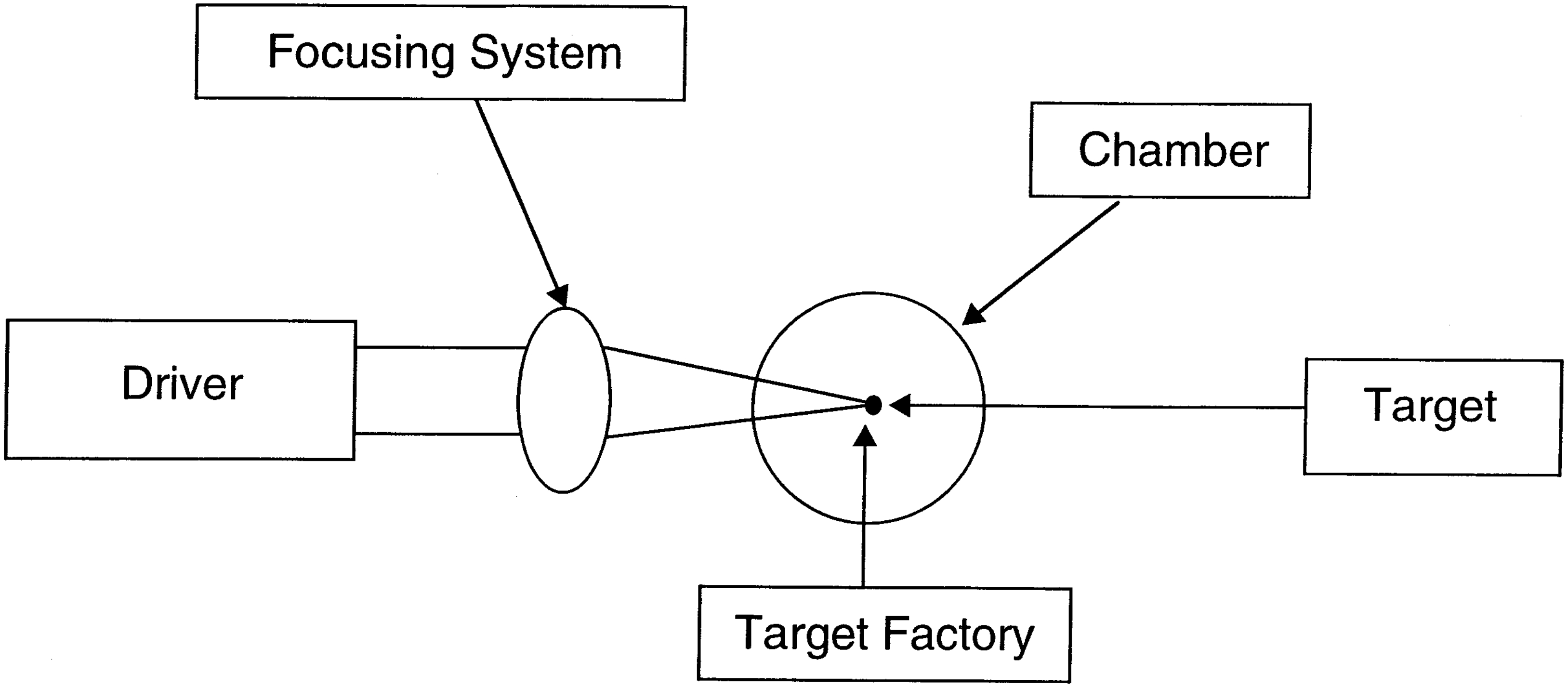


Figure ES-2. Prometheus-H Plant Site Trimetric View

# The core of an inertial fusion power plant has five main parts



Focusing System

Chamber

Driver

Target

Target Factory

- All five parts are essential.
- While interrelated, the parts are sufficiently independent to allow great flexibility in plant optimization and design.

# Top - Level Issues For Inertial Fusion Energy

1. Target Gain and Driver Energy.
    a). Power Plants:
    High Gain at Moderate Driver Energy.
    b) Development Steps
    Moderate Gain at Low Driver Energy.
2. Driver Cost, Efficiency, Reliability and Lifetime.
3. Fusion Chamber.
    a) Feasibility and Performance of a Viable WALL PROTECTION scheme.
    b) Cavity Clearing at IFE Pulse Repetition Rate.
    c) Tritium Self Sufficiency in a practical IFE system.
    d) Adequate radiation shielding of all components.
    e) Pulsed radiation damage and thermomechanical response of first wall/blankets, particularly for concepts without thick liquid protection.
4. Sufficiently low cost, high volume TARGET production system.

# Major Parameters of Several IFE Reactor Studies

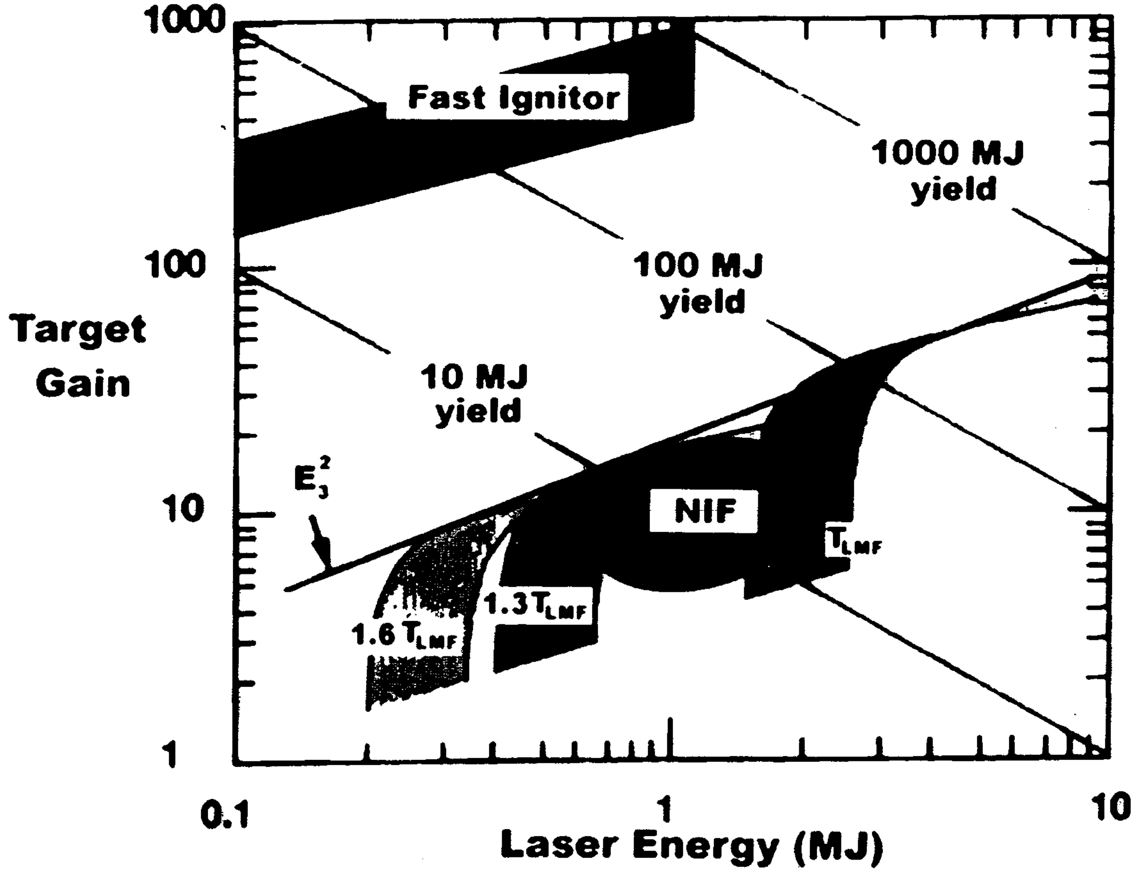
| Parameter | Prometheus-H | Prometheus-L | Osiris | Sombrero |
|---|---|---|---|---|
| Driver Concept | Heavy Ion | Laser | Heavy Ion | Laser |
| Accelerator/Driver type | Induct. Linac | KrF | Induct. Linac | KrF |
| Driver Energy, MJ | 7 | 4 | 5 | 3.4 |
| Number of Beams | 18 | 60 | 12 | 60 |
| Target Type | Indirect | Direct | Indirect | Direct |
| Target Gain | 103 | 124 | 87 | 118 |
| Yield, MJ | 720 | 497 | 430 | 400 |
| Rep-Rate, Hz | 3.5 | 5.65 | 4.6 | 6.7 |
| Gross Th. Eff., % | 43 | 42.3 | 45 | 47 |
| Driver Eff., % | 20 | 6.5 | 28 | 7.3 |
| Net Power, MWe | 1000 | 972 | 1000 | 1000 |

- Major Difference between Laser and Heavy Ion Drivers: Driver Efficiency
- Studies Compensate for this difference by:
  - Higher Gain with direct drive laser at lower driver energy
  - Recycling waste heat from laser driver
  - Higher repetition rate with laser

# Power Plants Require High Gain at Moderate Driver Energy

Typical Requirements:

Gain > 70 (at 5-7 MJ) for driver efficiency > 20% (Typical HI ID designs)
Gain > 120 (at 3-4 MJ) for driver efficiency ~7% (Typical Laser DD designs)



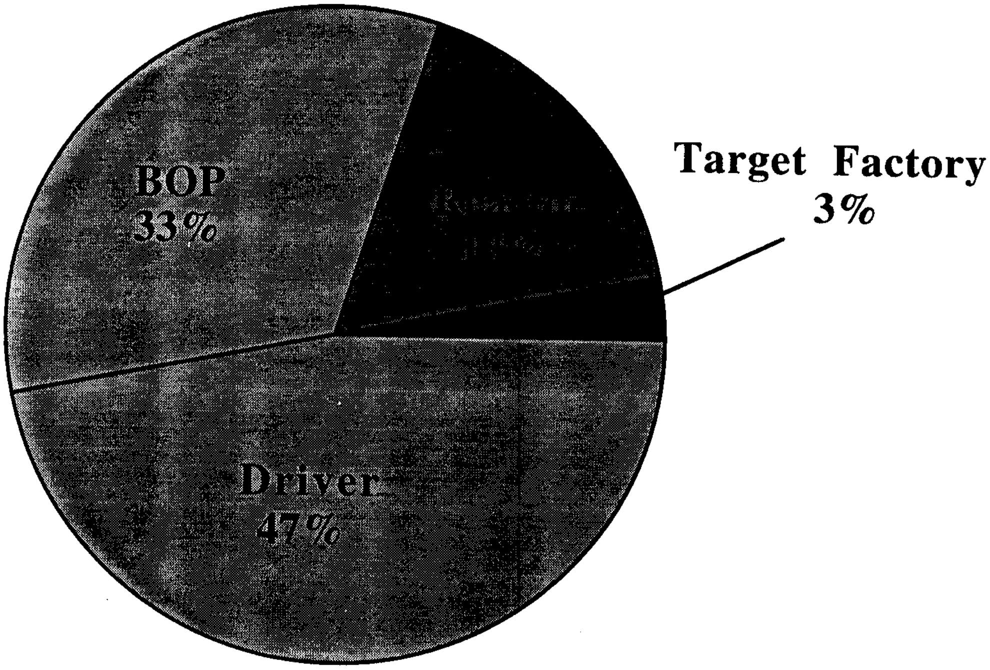
"Identification of an affordable development path is as important as identifying concept improvements" (Public Comment)

Development steps with affordable costs (< 100 MW units) favor moderate gain (20-50) at low driver energy (1-2 MJ)

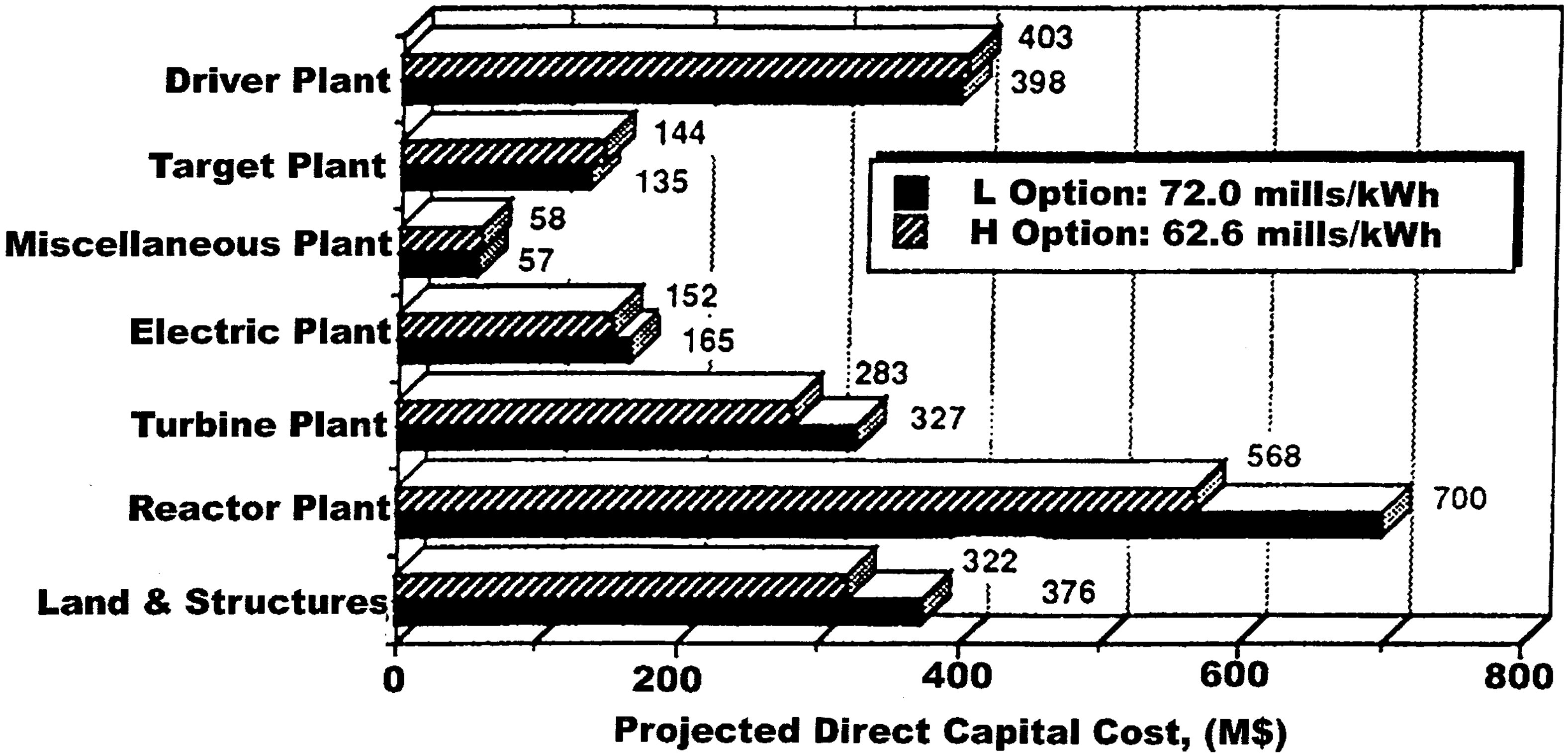
# Typical Elements of Cost for a Heavy Ion Power Plant (1000MWe)

Costs (in $M)

| | |
|---|---|
| Total Direct Cost | 1934 |
| - Driver | 909 |
| - Target Factory | 59 |
| - Reactor | 330 |
| - BOP | 636 |



- The Cost of the Driver is the largest component (~ 50%) of the cost of an IFE Power Plant
- Cost Reduction Strategy is an important R&D Issue for the Heavy Ion Driver



**Capital Cost Comparison Between the Laser and Heavy Ion Plant Designs [Prometheus]**

# Availability
# (Maintainability and Reliability)

$$\text{COE} \sim \frac{1}{\text{availability}}$$

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

Mean-Time-To Replace (MTTR)

IFE Power Plants will have advantages of enhanced Maintainability.

- "Compartmentalization", i.e. the driver, target factory being physically outside the chamber reduces "physical" intersections.
- Easy access and replacement.

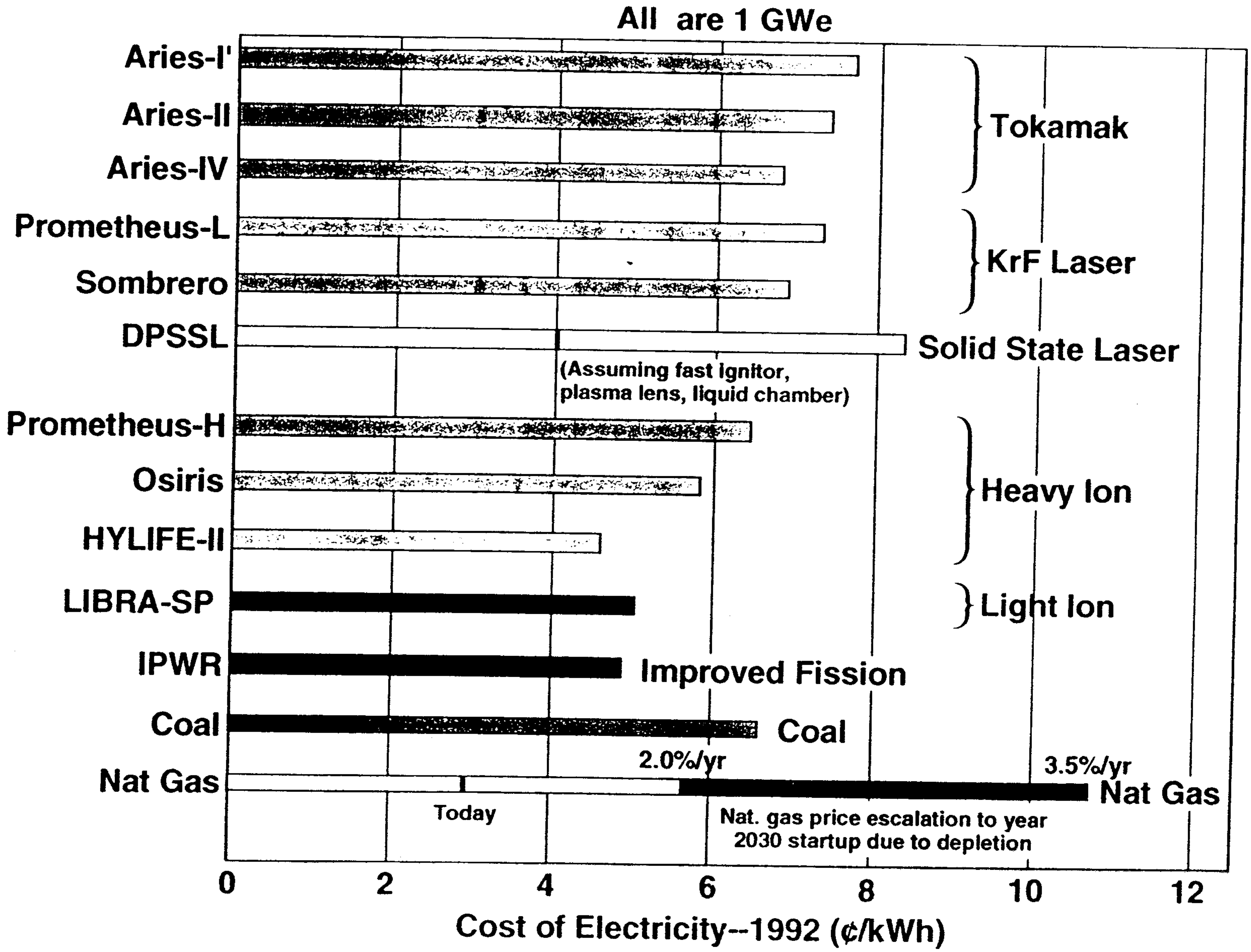
Mean-Time-To-Failure (MTBF)

"Assumed Numbers" (as in MFE).

But, Some Observations

1. MTBF will critically depend on successful development of a WALL PROTECTION scheme.
2. Heavy Ion Driver has advantages over laser (MTBF for final laser optics is a serious issue).

# Our economic projections for IFE encourage us to proceed with R&D

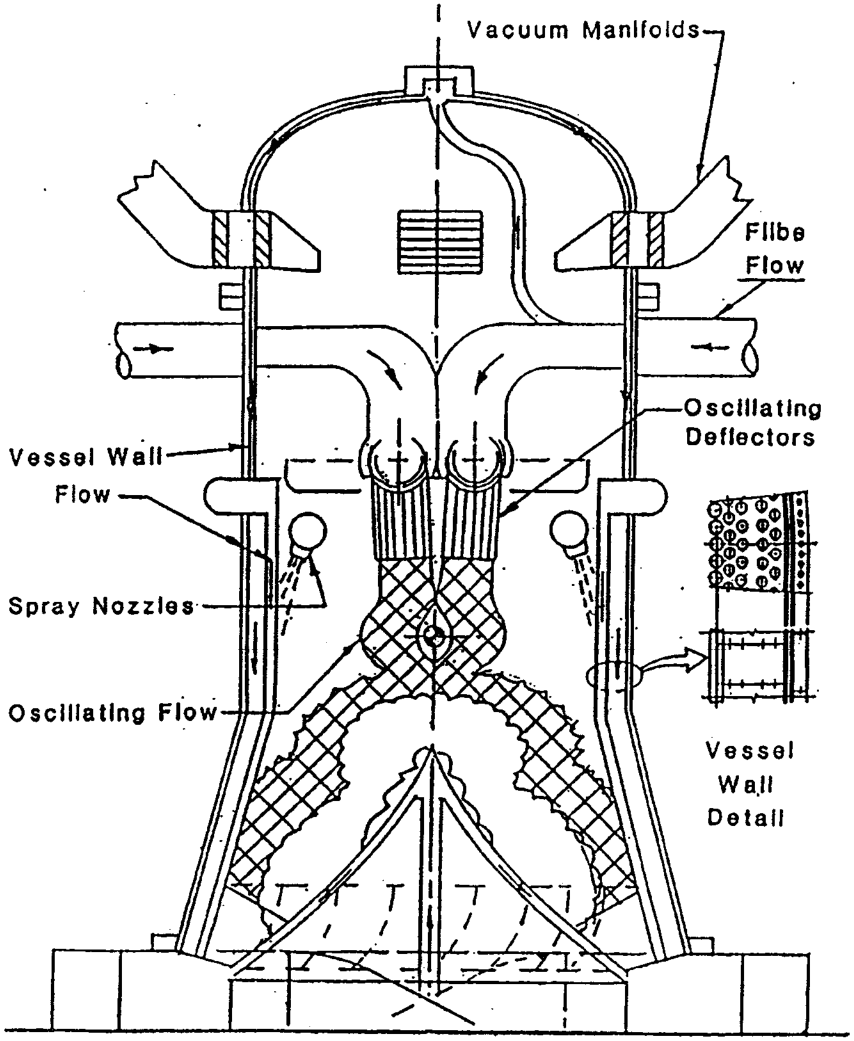


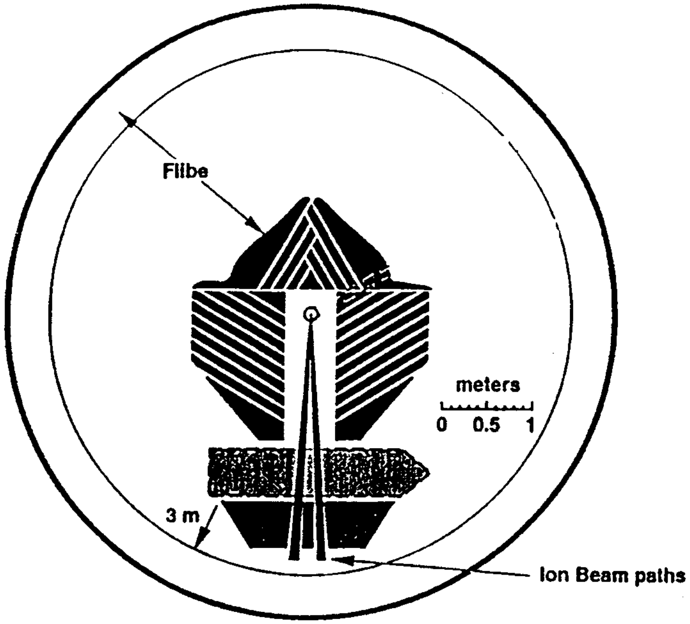
# CHAMBER WALL PROTECTION

- Next to Ignition, Chamber Wall Protection is likely to be the most serious challenge to IFE.
- Very high instantaneous loads of x-rays, target debris and neutrons can lead to serious ablation of surfaces and severe damage of structures surrounding the microexplosion:
  - Fatigue would also be a serious issue ($> 10^8$ cycles per year).

But, this is an excellent example of how a very serious technical Problem has been turned into a Potential Opportunity through Innovative Design Solutions that Promise to give IFE unique advantages and Radically eliminate long-term activation of conventional structural materials.

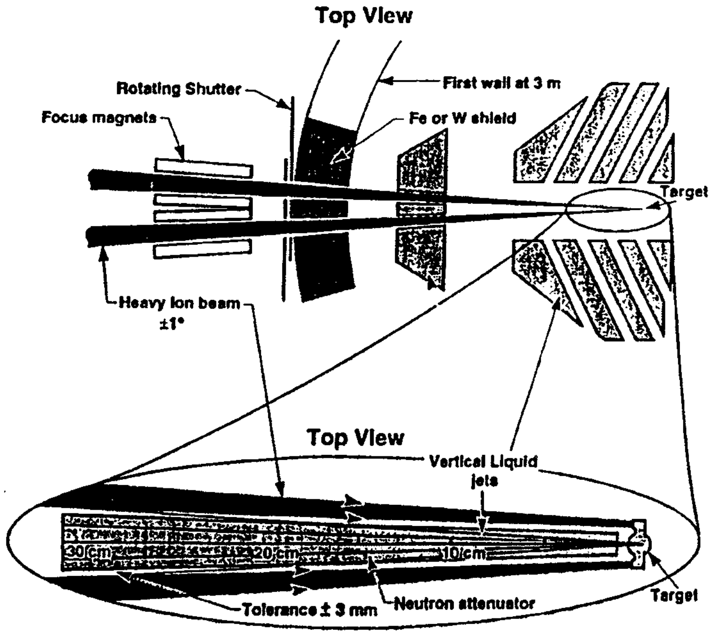
# Thick Liquid Protection of Chamber Wall



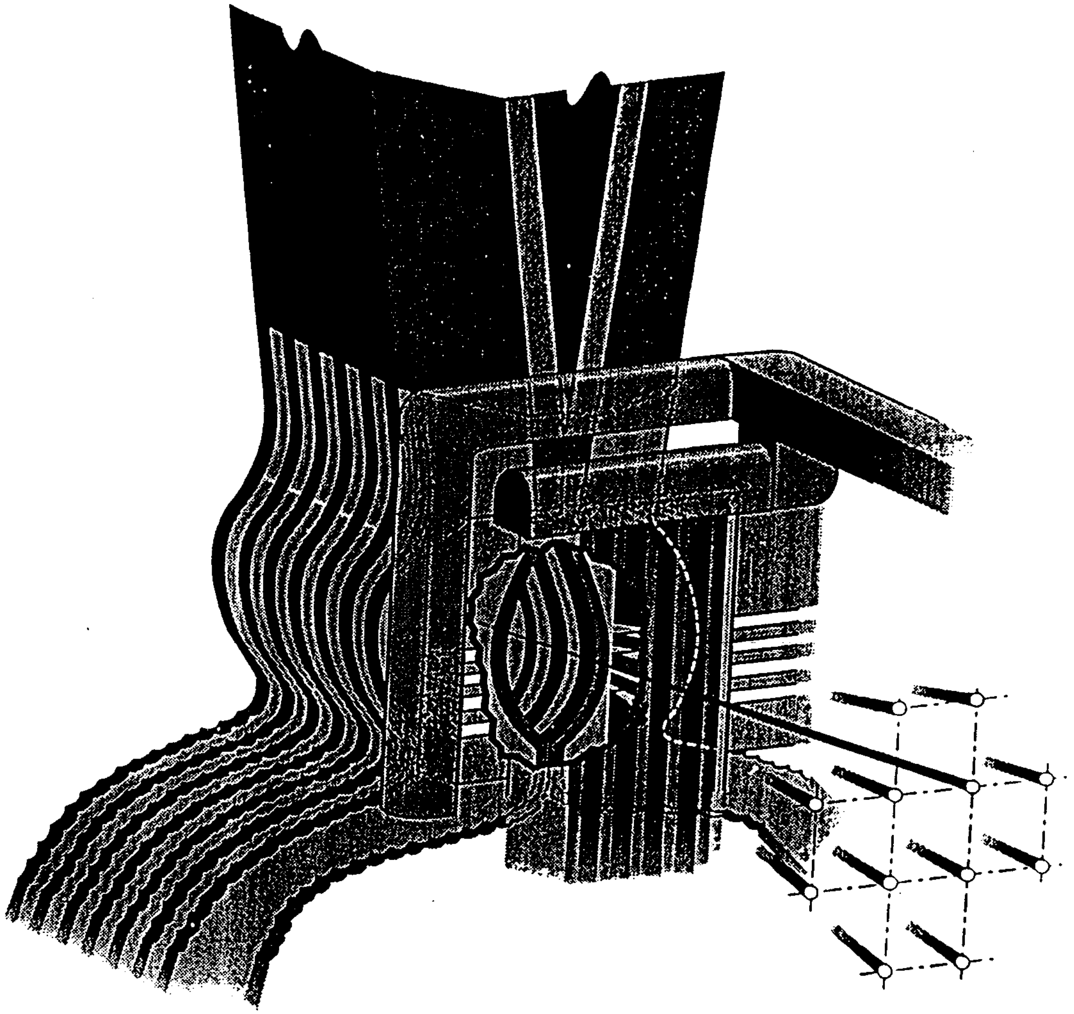


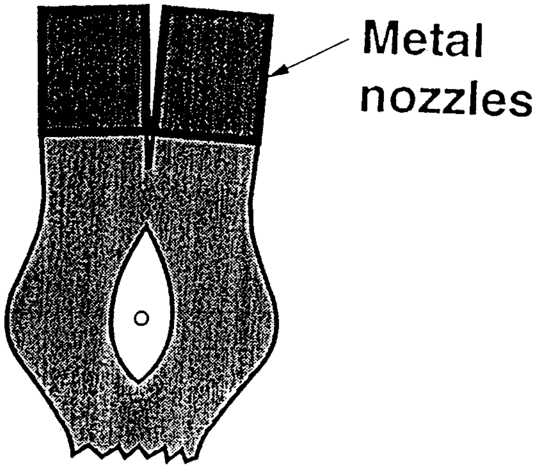
Cross Section through liquid

**Top View**



# A liquid "pocket" surrounds the microexplosion and protects the walls from neutron damage

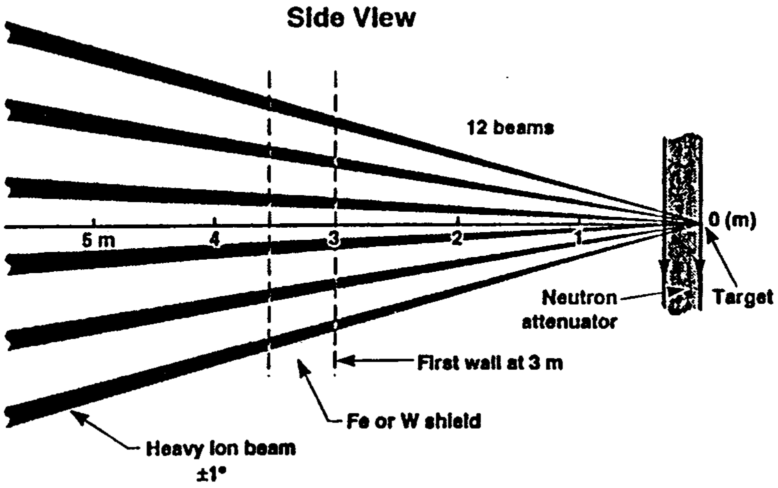


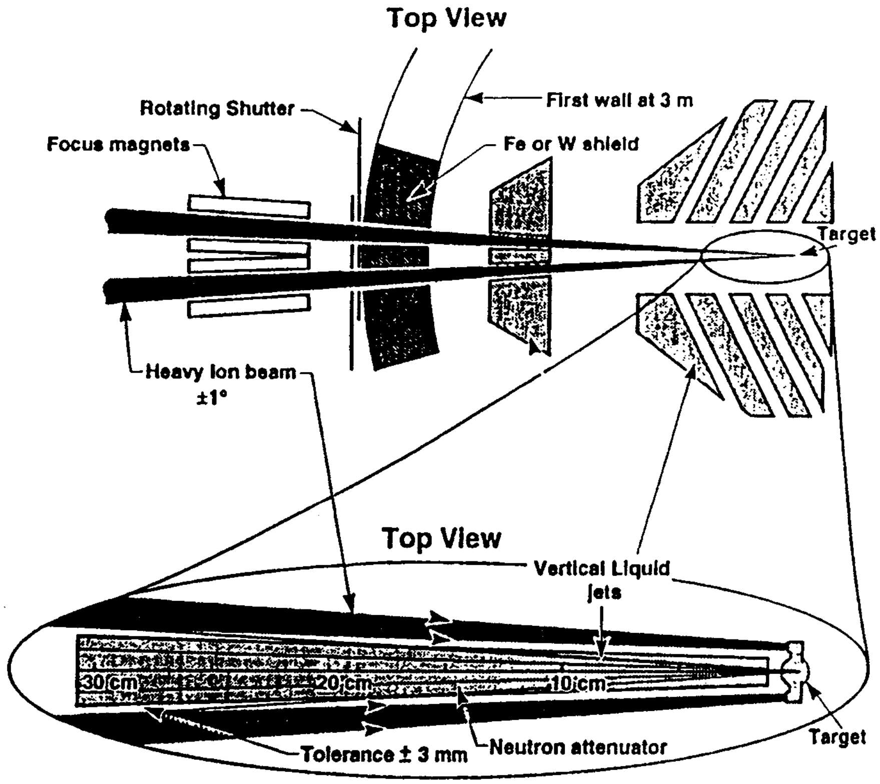


**Jets removed**

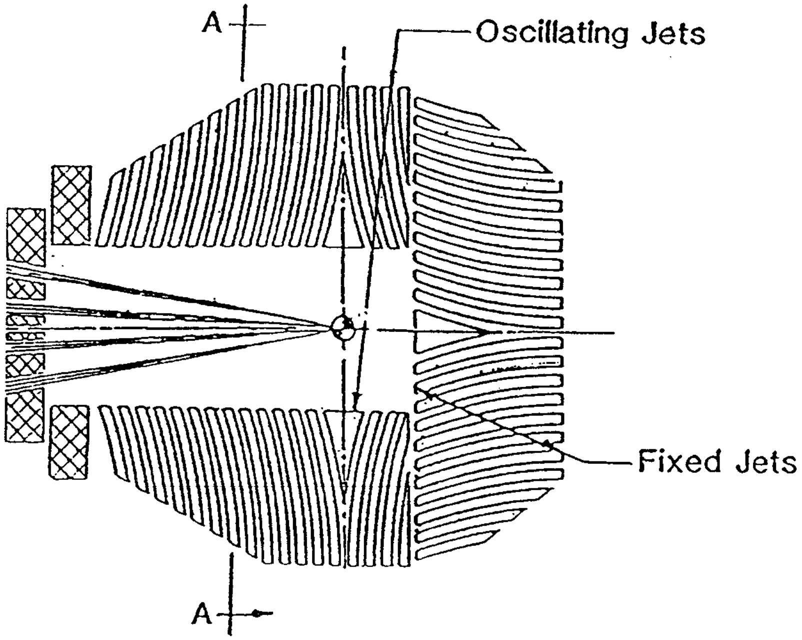
**Front View**

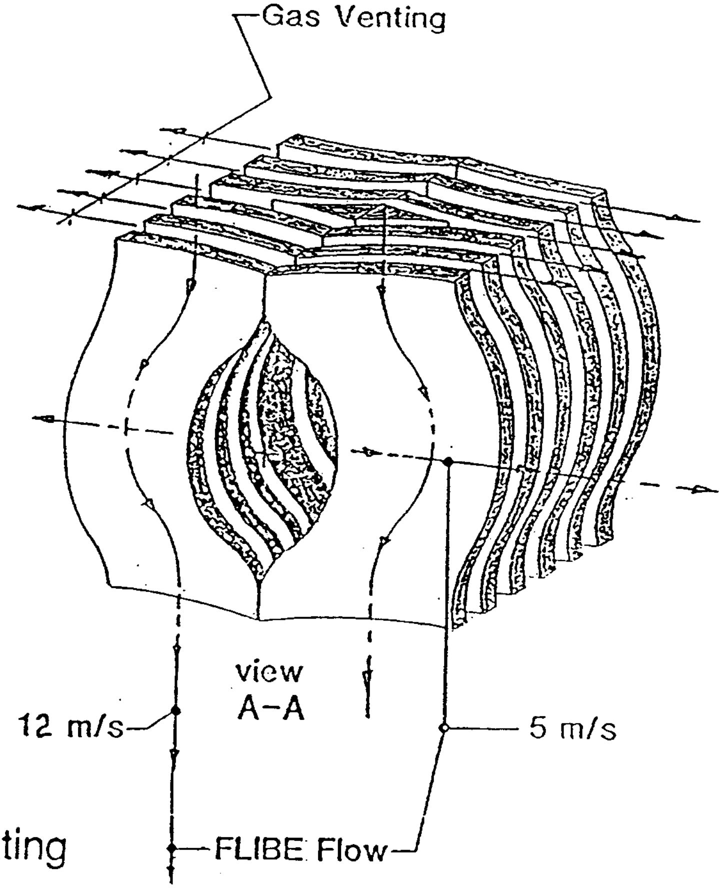
# The beam ports are protected from neutron damage





# The jets from a pocket that attenuates neutrons but vents vapor rapidly

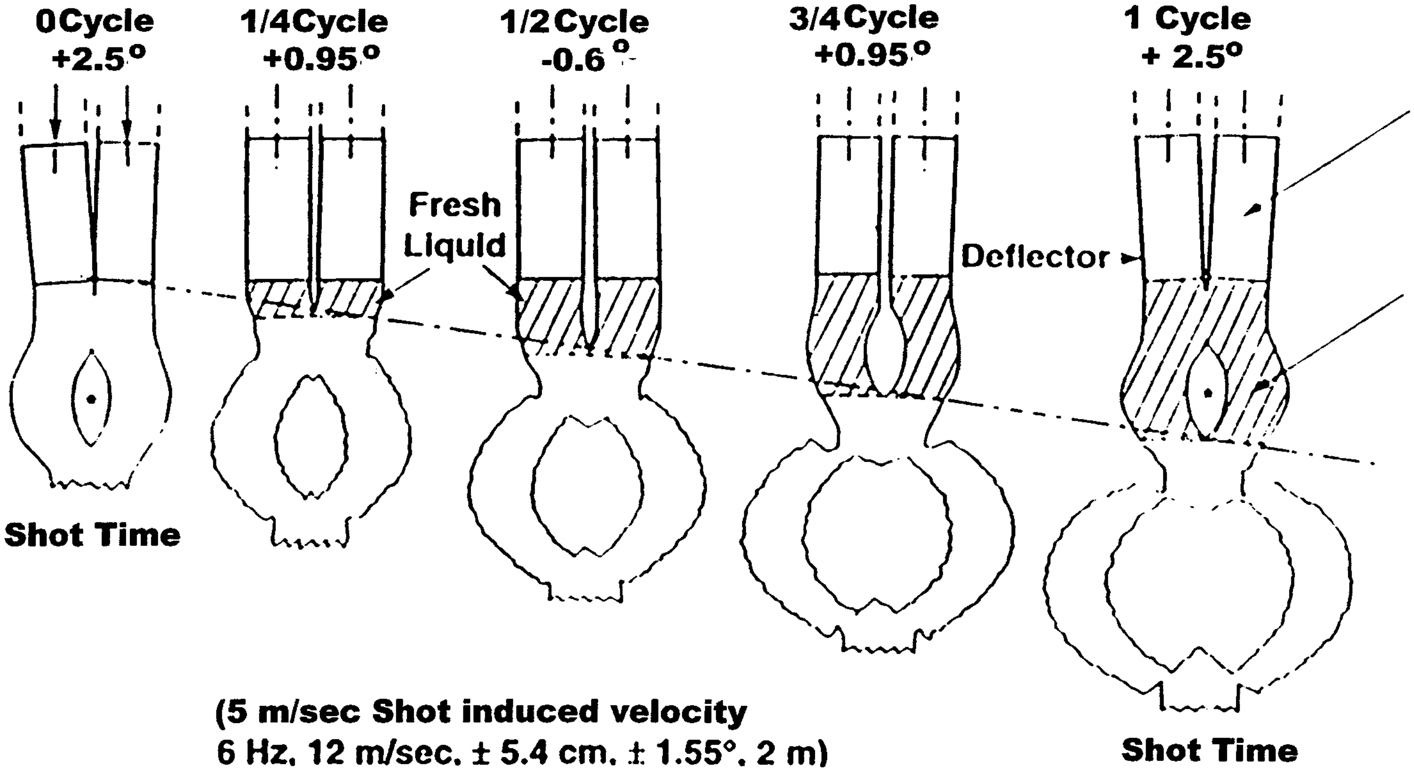




Estimated radial impulse

| | |
|---|---|
| 0.5 m/s | X-ray Ablation impulse |
| 0.5 m/s | From gas pressure during venting |
| 4.0 m/s | Impulse from isochoric neutron heating |
| 5.0 m/s | Total shot induced outward velocity |

# The Sequence Shows the Effect of Sweeping the Chamber Clear of Droplets

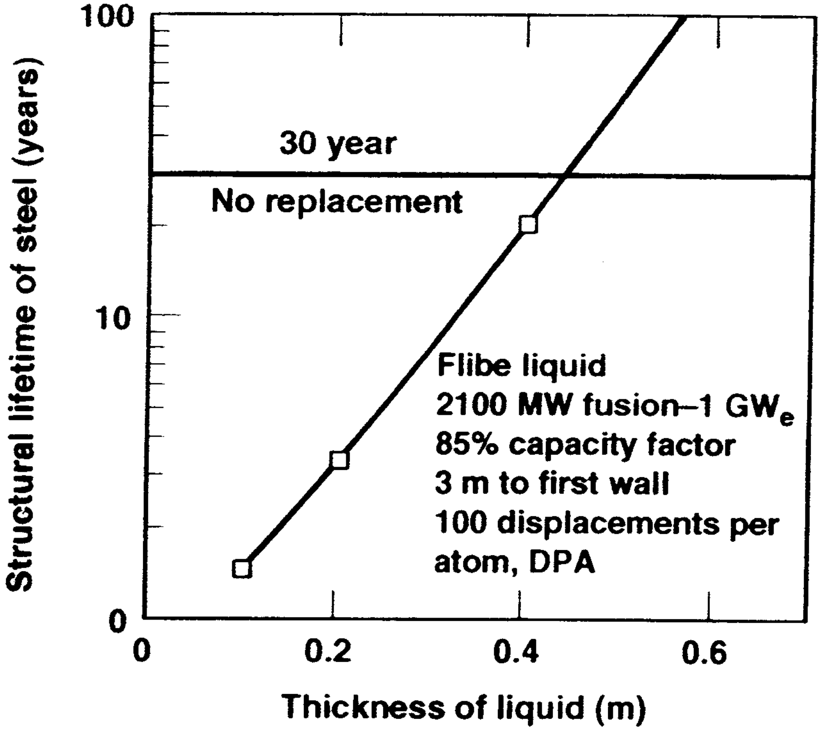


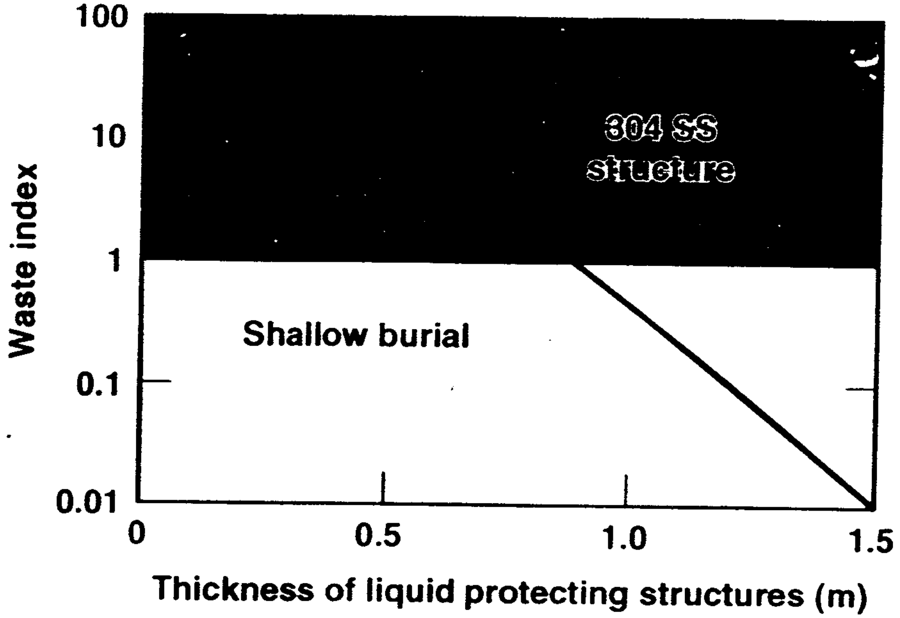
**The 2-m-long deflectors move through + 1.55 or ±54mm**

**The liquid protects the ends of the deflectors from neutrons at shot time**

**(5 m/sec Shot induced velocity**
6 Hz, 12 m/sec, ± 5.4 cm, ± 1.55°, 2 m)

# Inertial fusion power plants can use renewable liquid-protected walls to achieve long life, low activation and low maintenance costs





# Profound Implications of Thick Liquid Metal Protection for IFE Development

1. Conventional Stainless Steel would become “low activation material” in IFE solid first wall. It would qualify for shallow land burial.
    - (There is presently no other technically credible approach to achieve this goal in any DT fusion concept).

2. The solid first wall and the remainder of the blanket would have much reduced loading conditions. It would become a “simple technology” that could be built with essentially the current data base.

3. Life-of-the-plant structure even with current structural material.

4. It would almost eliminate the cost, time, and the very large uncertainties associated with new material development.

# The Liquid Wall Protection Offers Opportunity for Challenging "Science"Research

The thick liquid metal protection design uses a curtain of oscillating and stationary molten salt (flibe) sheet jets to protect the reactor chamber solid wall and beam ports. The design concept relies on:

- Generating controlled and precise liquid geometries.
- And condensing ablated vapor on spray droplets, which also sweeps away the droplets rapidly to provide a clean path for target injection and beam transmission.

The current literature is inadequate for predicting the stability of such high velocity (high Reynolds and Weber numbers) jets in vacuum, exposed to turbulent fluctuations and large-scale secondary jets (Re = inertia/viscous, We = inertia/surface tension).

Characteristics of Liquid JET Protection (HYLIFE-II)

| Quantity | Flibe | Quantity | Flibe |
|---|---|---|---|
| Jet Reynolds number | $2.43 \times 10^5$ | Nozzle oscillation frequency [Hz] | 6.0 |
| Jet Weber number | $1.03 \times 10^5$ | Nozzle oscillation amplitude [cm] | 9.0 |
| Jet thickness [cm] | 7.0 | Ambient pressure [atm] | ~0 |
| Jet width [cm] | 100 | Fluid temperature [°C] | 660 |
| Jet aspect ratio | 14.3 | Fluid density [$kg/m^3$] | 1963 |
| Jet fall distance [m] | 2.0 | Fluid viscosity [$kg/m \cdot s$] | $6.78 \times 10^{-3}$ |
| Jet velocity [m/s] | 12.0 | Fluid surface tension [N/m] | 0.193 |
| Jet volumetric flow rate [$m^3/s$] | 0.84 | | |
| Jet dynamic pressure ($pU_j^2$) [Pa] | $2.83 \times 10^5$ | | |

# Isochoric Heating and Outward Forces

- The thick liquid wall protection has to also serve as the blanket (partial) with heat removal and tritium breeding.

- The liquid blanket is subjected to forces associated with X-ray ablation, gas pressure (from drag), and shear (skin drag) that impart an outward radial motion toward the vessel wall.

- These contributions may be augmented further by the net effect of break up (fracture of the liquid) following neutron-induced isochoric heating of the blanket [Isochoric, 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].

- One estimate is that the liquid blanket will receive an average velocity of ~7m/s, which would result in impacting the bottom of the wall with low pressure. But many complex phenomena are involved and can not now be predicted with confidence.

# Issues To Resolve For Thick Liquid Metal Protection

1. Hydrodynamic Stability of high Reynolds number jets in vacuum exposed to turbulent fluctuations and large scale secondary flows

2 To show that the condensation of the evaporated liquid is quick enough to permit the required pulse (repetition) rate without interfering with the passage of the beams to the target

3. To show that the incoming liquid clears the splashed liquid from a prior micro-explosion to not interfere with the target injection and ion beam propagation for the next shot

4. Show that the liquid jet configurations can be made to meet the required conditions (including protection of beam ports, particularly focusing magnets)

5. Reliability of metal nozzles and mechanical moving parts, including fatigue and vibration

6. Understand Isochoric Heating and Gas Venting to predict net outward momentum

7. Show that tritium self sufficiency can still be satisfied in a system that uses this concept

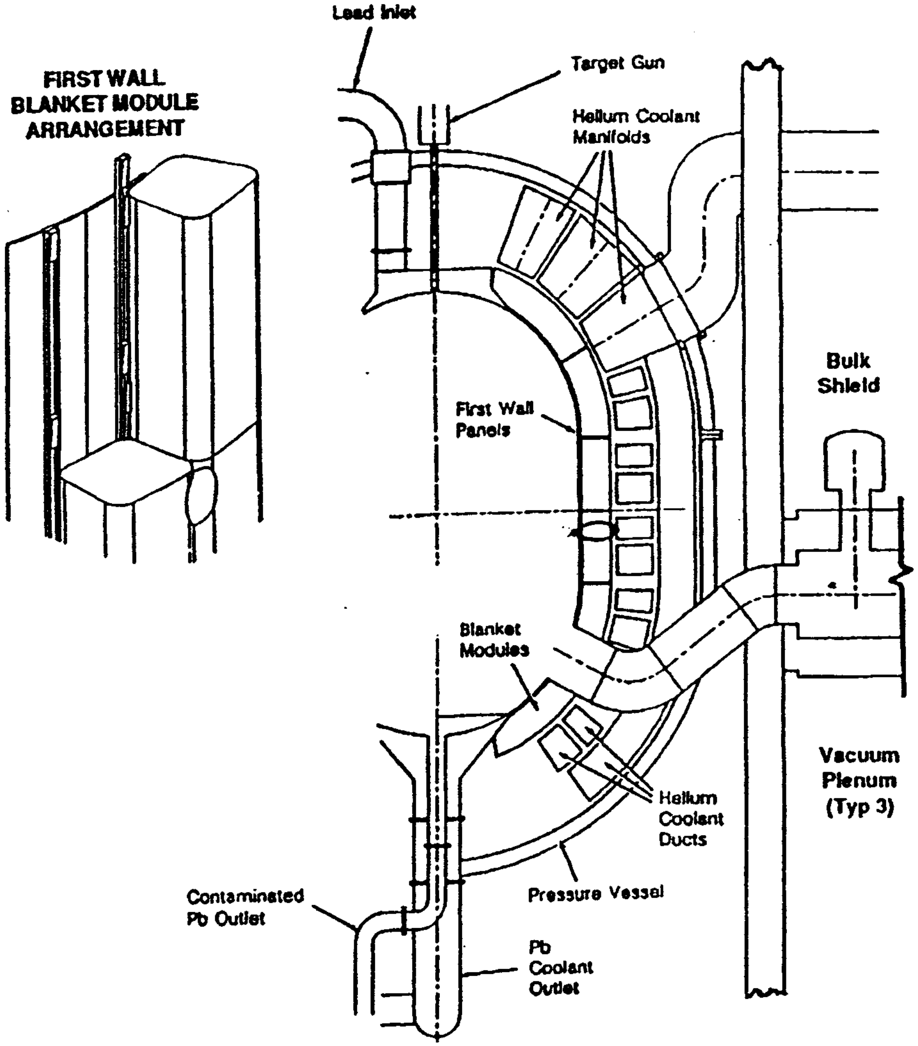
# Conceptual Design Studies
# Commercial Reactor
# Proposed Different Approaches to Wall Protection

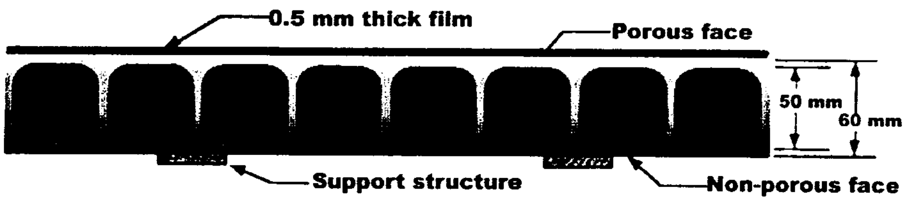
| Reactor | Cavity Design Features |
|---|---|
| SOLASE | Gas protection of first wall, flowing $Li_2O$ breeder |
| SIRIUS | Gas protection |
| HIBALL | LiPb INPORT modules, porous SiC sleeves |
| LIBRA | also used INPORT modules |
| CASCADE | Granular protection, rotating cavity |
| HYLIFE-I | Thick, gravity-driven Li jets |
| HYLIFE-II | FLiBe thick, oscillating, gravity-driven jets |
| SENRI | Magnetically-guided thick jets |
| Prometheus | Pb-wetted FW systems, separate blanket |
| Osiris | Carbon fabric FW and blanket, Flibe protection |
| SOMBRERO | C/C structure, Xe gas protection, flowing $Li_2O$ |

# Major Features of Several IFE Reactor Studies

| Parameter | Prometheus-H | Prometheus-L | Osiris | Sombrero | HYLIFE-II |
|---|---|---|---|---|---|
| Driver Concept | Heavy Ion | Laser | Heavy Ion | Laser | Heavy Ion |
| First Surface | Pb | Pb | FLiBe | C/C | FLibe |
| 1st Surf. Radius, m | 4.5 | 4.5 | 3.5 | 6.5 | 0.5 |
| Breeding Blanket | Li2O in SiC structure | Li2O in SiC structure | FLiBe in porus C cloth | Flowing $Li_2O$ | FLiBe jet array |
| Primary Coolant | Pb & He | Pb & He | FLiBe | $Li_2O$ | FLiBe |
| Vacuum Vesel | Ferritic St. | Ferritic St. | C/C compos. | C/C compos | Stainless St. |

# Thin Liquid Protection of Chamber Wall





**First Wall Panel**

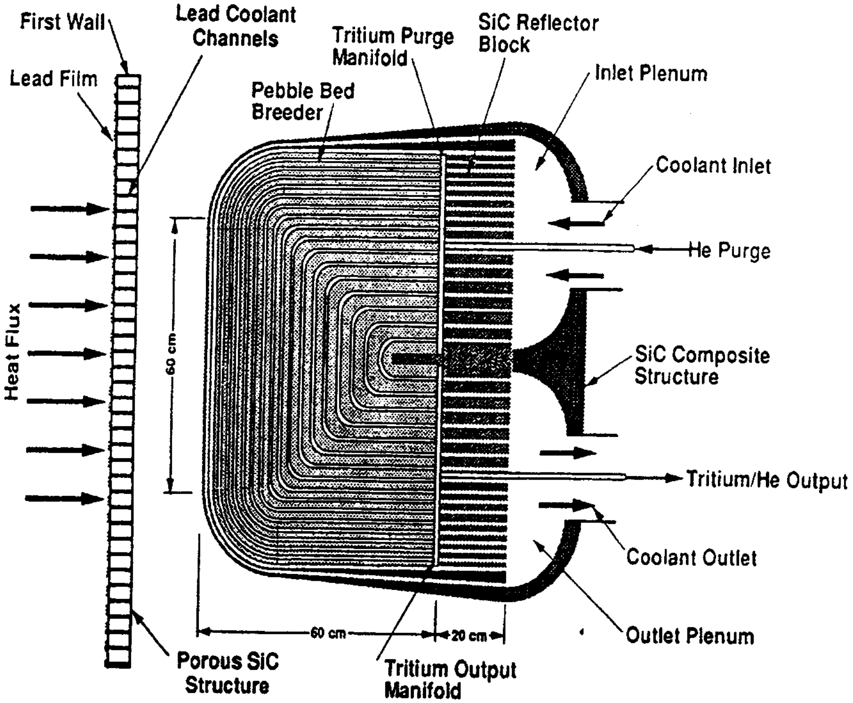
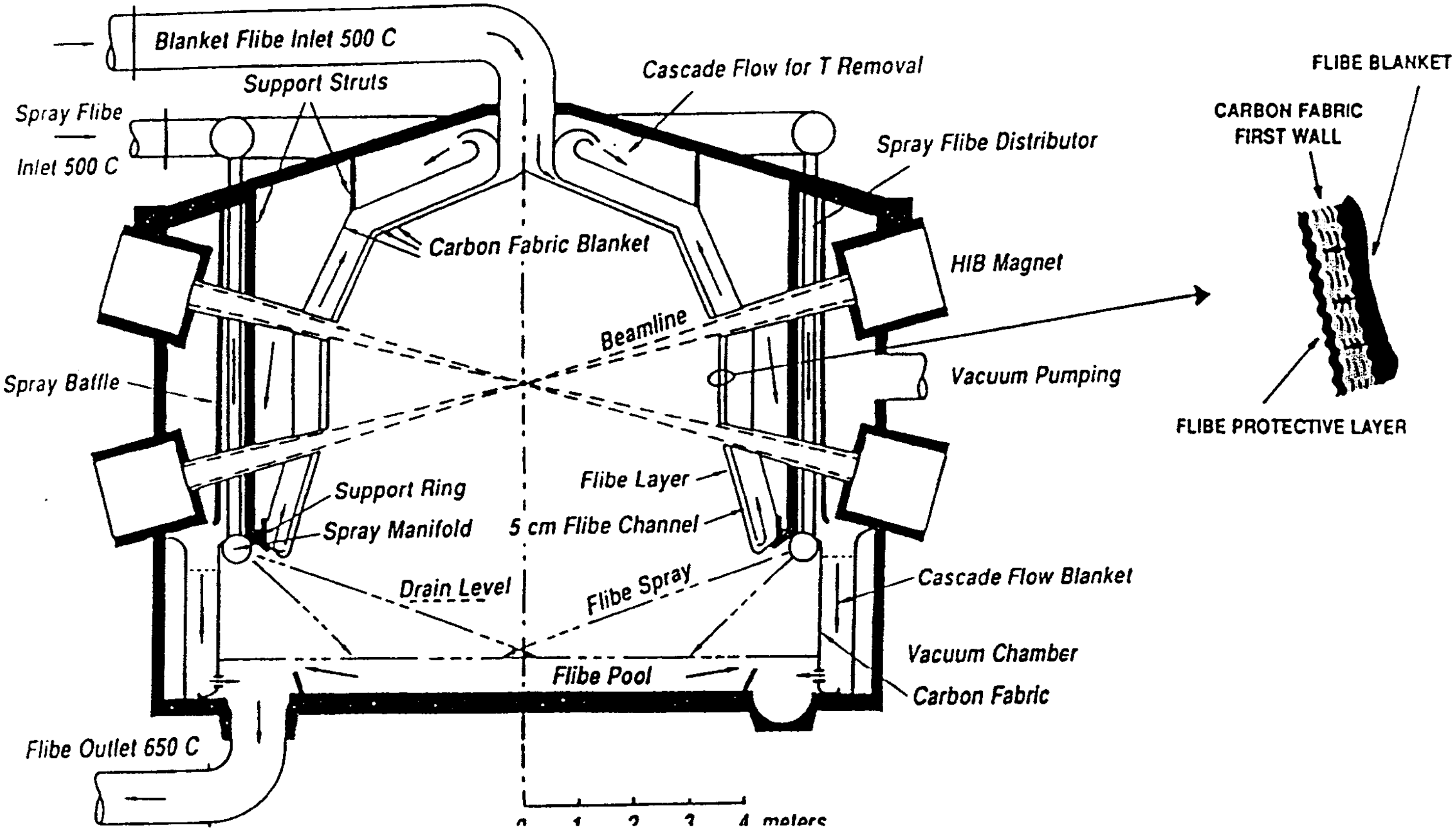
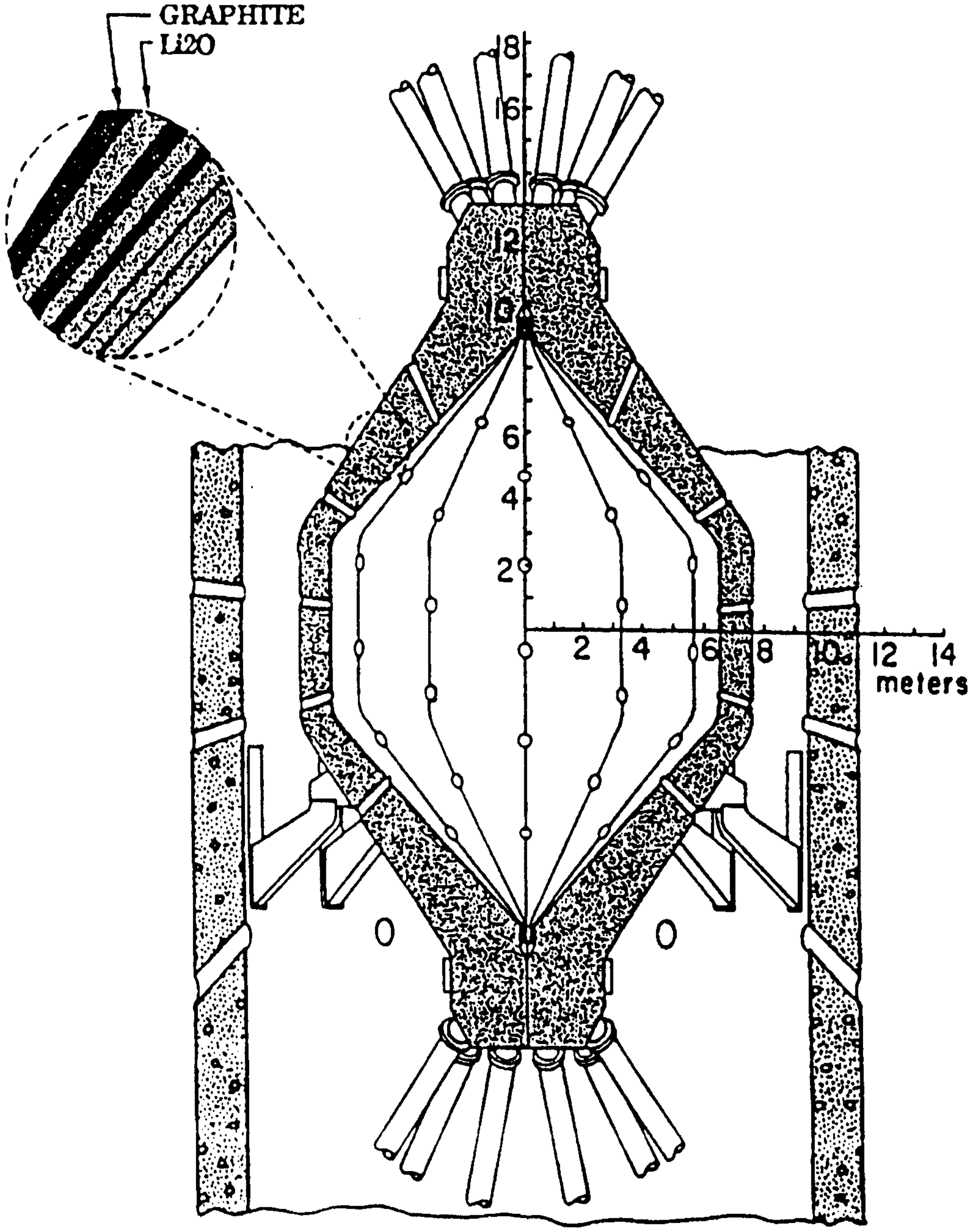


Figure 2.4-9 Schematic of a Blanket Module

# Osiris - Thin Liquid Film Protection of Chamber Wall



# SOMBRERO (Laser Driven)



# Chamber Clearing at IFE Repetition Rate

- IFE Power Plants require a repetition rate:
  ~ 3 - 10 pulses per second.

- Following each pellet explosion the chamber fills with target debris and material evaporated, or otherwise ejected from the cavity surfaces.

- This material must be removed from the cavity before the next target/beam are injected.

  - Recondense Condensable Gases into cavity surfaces.
  - Pump non-condensable gases through large ducts.

- Issues

  A) Evacuation Requirements (base pressure).
    - depend on propagation limits for both target and driver energy

  B) Ability to clear the chamber to the required base pressure during the time available between shots.
    - Highly Dependent on the Specific Wall Protection Scheme.

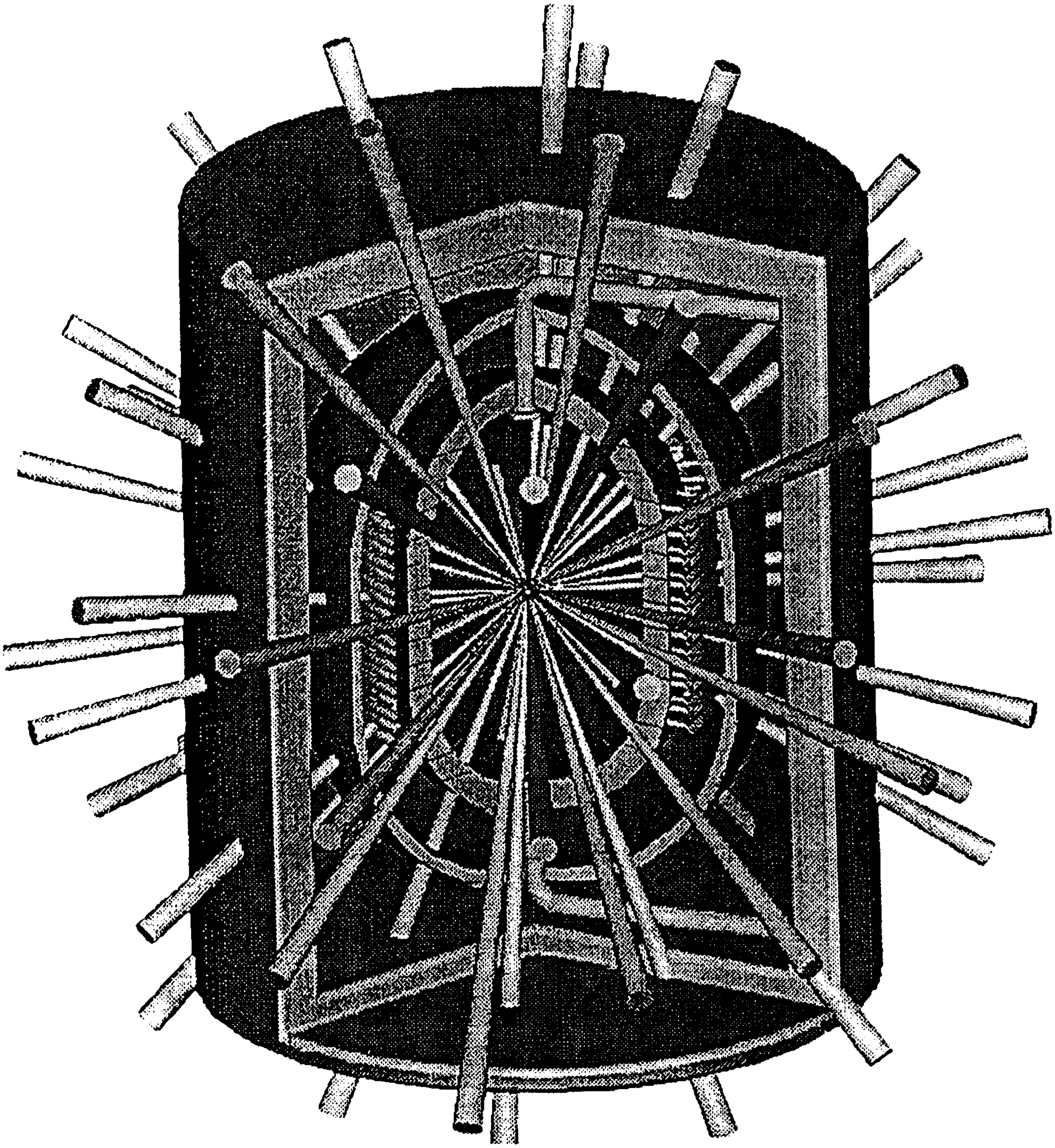
# Other Chamber Issues (In addition to Wall Protection and Chamber Clearing)

- Tritium Self Sufficiency in a Practical IFE System.
- Adequate Radiation Shielding of All Components.
- Pulsed Radiation Damage and Thermomechanical Response of first wall/blankets, particularly for concepts without thick liquid metal protection.

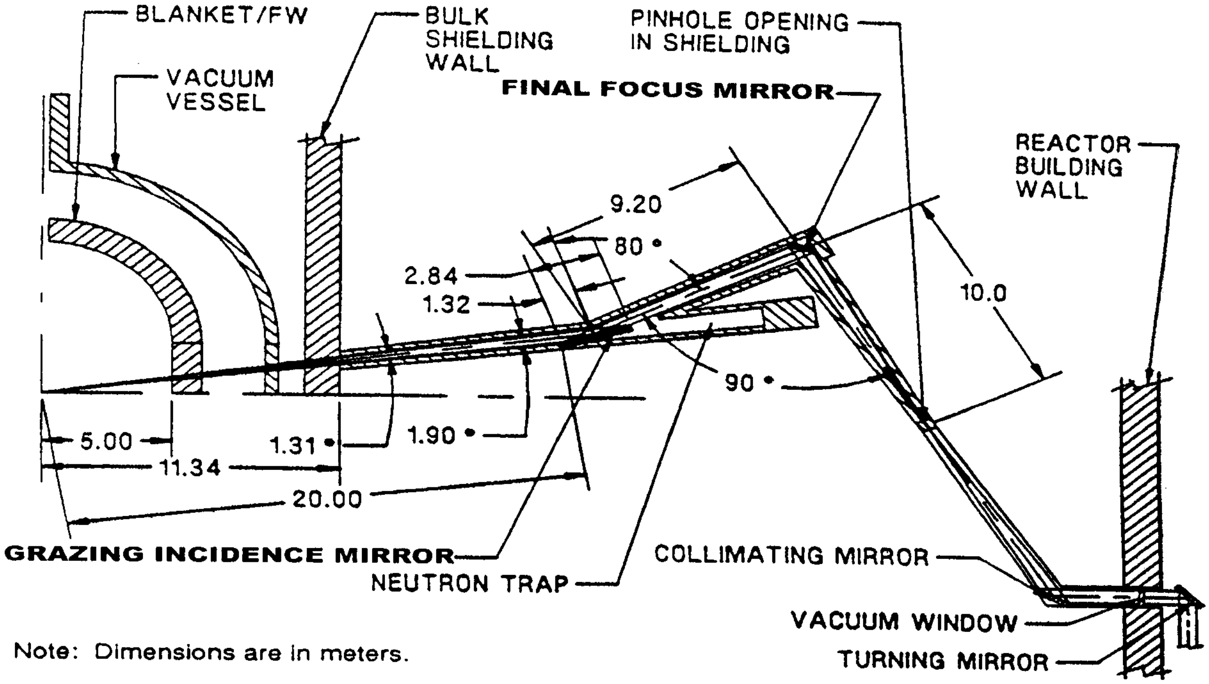
## Observations

- These issues are important and could be critical.
- Some aspects will have to be addressed as part of Wall Protection Research.
- The severity and specifics of these issues will greatly depend on the selected wall protection scheme.

# Perspective View of the Cavity with Laser Beams (Prometheus-L)

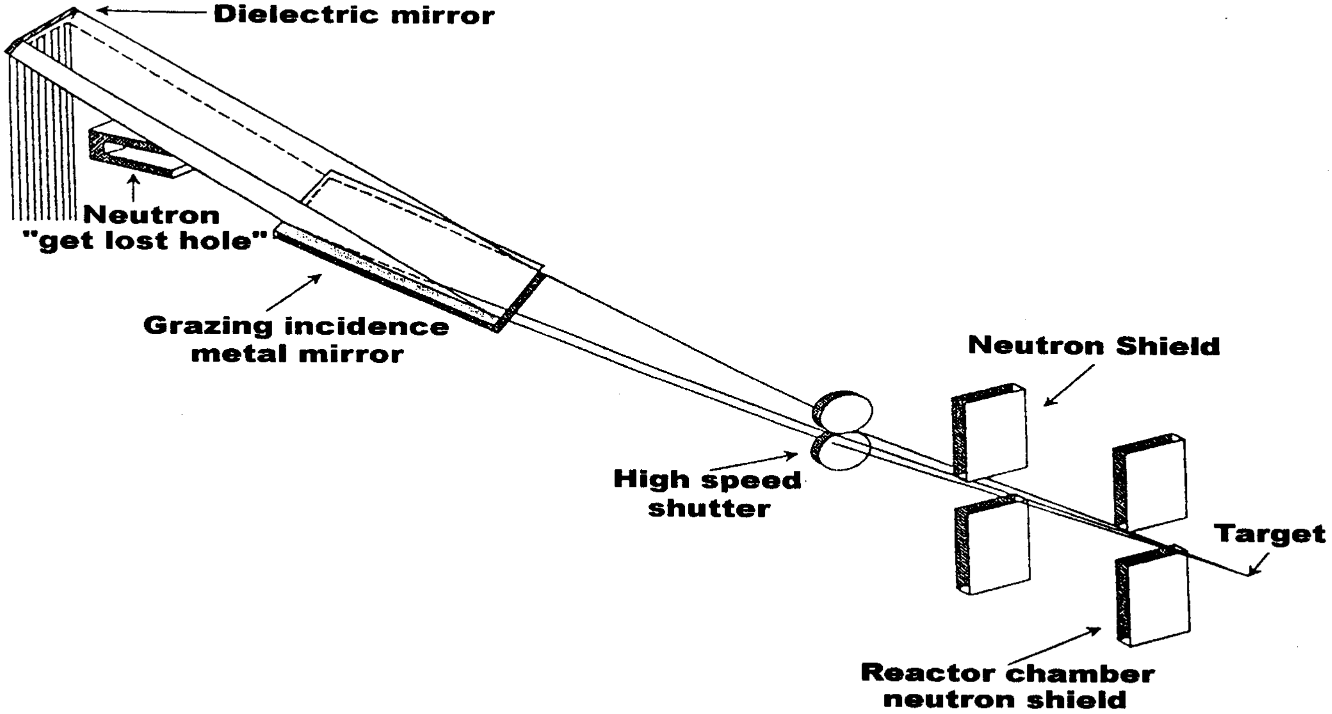


# The Key Issue of Final Laser Optics Received Attention in Design Studies



Note: Dimensions are in meters.

PROMETHEUS-L FINAL OPTICS CONFIGURATION

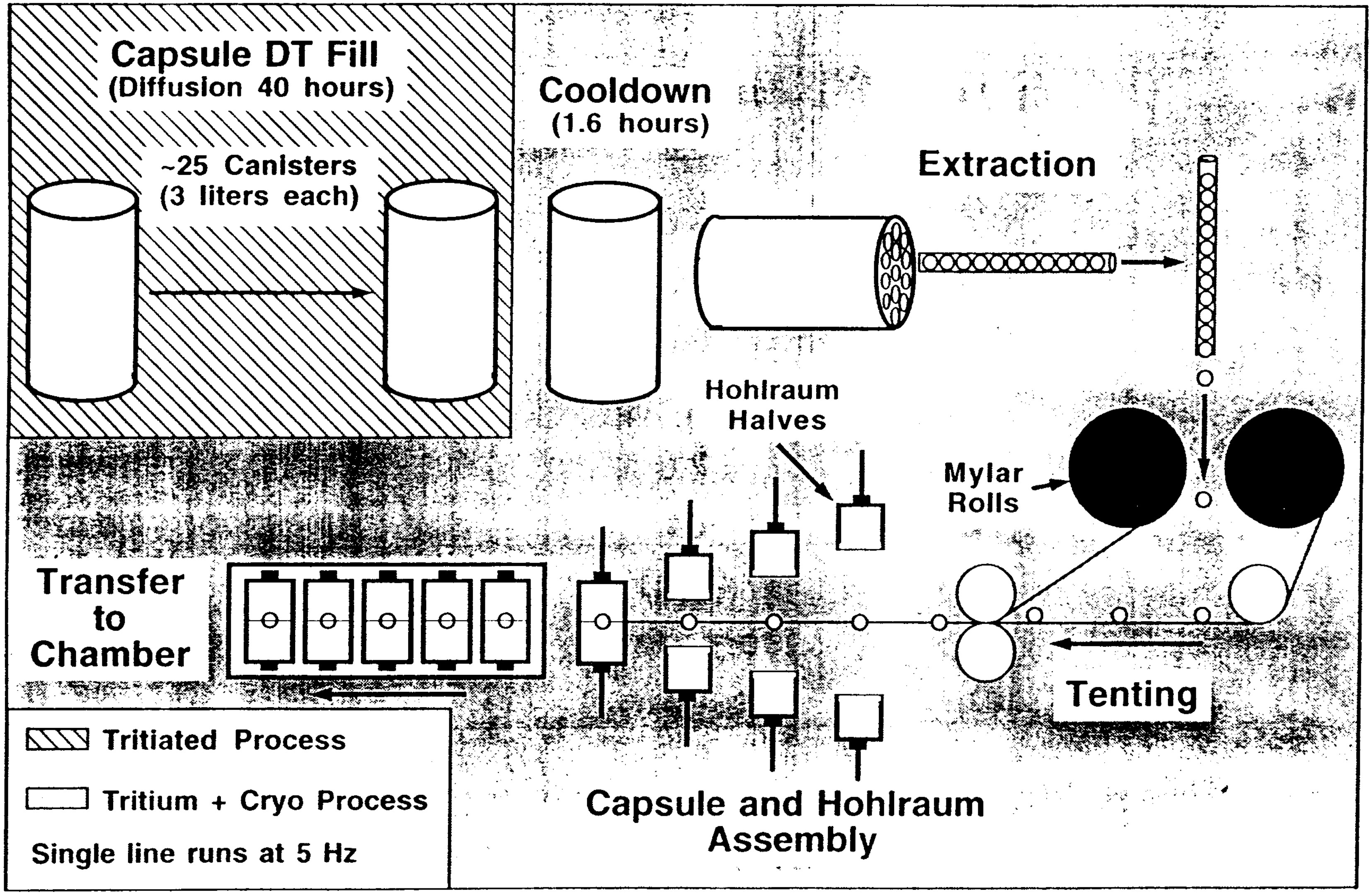


SOMBRERO FOCUSING SCHEME USING GRAZING INCIDENT METAL MIRRORS

# Cost of Targets is an Issue

- Current targets are developmental, “Few-Of-A-Kind“ and thoroughly characterized
  - They cost from \$500 to \$2500 each
- Power plants will need ~ $10^8$ per year
  - Could only pay ~ 25¢ each
- Design studies have shown that improved fabrication methods, economies of scale, use of designs and characterization only for QA offer significant cost savings
- **Target cost** remains an issue that requires future R&D

# A target factory study identified capsule smoothness and rapid DT fill as critical issues



**Capsule DT Fill**
(Diffusion 40 hours)

~25 Canisters
(3 liters each)

**Cooldown**
(1.6 hours)

**Extraction**

Hohlraum
Halves

Mylar
Rolls

**Transfer to Chamber**

**Tenting**

**Capsule and Hohlraum Assembly**

▨ Tritiated Process

☐ Tritium + Cryo Process

Single line runs at 5 Hz

from J.G. Woodworth and W.R. Meier, "Target Production for Inertial Fusion Energy," LLNL report UCRL-ID-117396 (1995). Submitted to Fusion Technology (1995).

# IFE Target Injection Is A Challenge

- Current experiments use Stalk-Mounted targets
- IFE will require injection
  - Direct Drive: $t_{survival}$ ~ 1-10 ms - sabot needed
  - Indirect Drive: $t_{survival}$ ~ 0.1-1 s - direct insertion
  - Accuracy Required: ~± 10s µm - 100 s µm
- Studies point promising directions
- Actual development is needed

Experiments planned at LBNL in 1997 to being addressing target injection

# IFE - Relevant Experiements on NIF

- NIF will provide critical data for IFE on target ignition, energy gain and system integration information

- Although NIF lacks a meaningful pulse repetition rate, the significant yield per shot (up to 20 MJ) and other features of the facility allow very useful experiments specifically aimed at energy applications. Examples are:

  - Experiments on Wall Protection Scheme
  - Experiments on final optics
  - Data on High-Dose-Rate neutron effects on materials
  - Data on neutron heating, tritium breeding, activation, and shielding

- Near-Term R&D, e.g. on Wall Protection should provide the data needed to construct energy-relevant experiments on NIF

- These experiments can be part of the DP-ER coordination

# Program Needs Derived from Power Plant Studies

- Several comprehensive, conceptual design and systems studies have been completed. They show the potential for and requirements for IFE to provide competitive power plants. Other than development of the driver, the key issues are:
  - Demonstration of high gain at moderate driver energy.
  - Development of chamber technology, including wall protection and cavity clearing schemes at power plant rep.-rates.
  - Development of power plant technologies to provide tritium self-sufficiency, radiation shielding, radiation resistant materials, and low-cost target production.
- The IFE program within OFES must have sufficient BREADTH beyond driver development, to cover those other areas which are critical to its feasibility and competitiveness.

Progress in these areas will influence driver research priorities and should provide the data needed in the near term to perform meaningful experiments on NIF that are important to IFE.

# Priorities Beyond Heavy Ion Accelerator Development

The panel suggests the following priorities for the broader program:

First priority:

- Wall protection scheme evaluations and development.
- Confirmatory simulations of heavy ion driver target performance.

Second Priority:

- Cavity clearing technologies at IFE repetition rates.
- Development of the final focusing optics for laser systems. (It is assumed that final focusing and transport studies for heavy ion beams are undertaken as a part of the accelerator development program.)

Third priority:

- Target factory studies.
- Work on rep-rated laser systems. This is an important area but until IFE funding increases substantially, development of only the presently most promising driver can be afforded.
- Shielding, blanket and tritium studies.
- Detailed power plant conceptual design studies. The extensive studies made in recent years have identified the principal issues for IFE. It is time now to concentrate on scientific and technological studies on these specific issues.