ARIES-IFE Assessment of Operational Windows for IFE Power Plants

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UC San Diego

16th ANS Topical Meeting on the Technology of Fusion Energy

September 14-16, 2004
Madison, WI

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ARIES Integrated IFE Chamber Analysis and Assessment Research Is An Exploration Study

Objectives:
- Analyze & assess integrated and self-consistent IFE chamber concepts
- Understand trade-offs and identify design windows for promising concepts.
  
  *The research is not aimed at developing a point design.*

Approach:
- Six classes of target were identified. Advanced target designs from NRL (laser-driven direct drive) and LLNL (Heavy-ion-driven indirect-drive) are used as references.
- To make progress, we divided the activity based on three classes of chambers:
  - Dry wall chambers;
  - Solid wall chambers protected with a “sacrificial zone” (e.g., liquid films);
  - Thick liquid walls.

ARIES-IFE study was completed in September 2003.
Target Design

Target emission spectra and energy and particle loads on the chamber wall

Thermo-mechanical response of the chamber wall

Target survival during injection

Driver propagation and focusing in the chamber

Operational Windows
Reference Direct and Indirect Target Designs

NRL Advanced Direct-Drive Targets

- **CH Foam + DT**
  - CH Foam: \( \rho = 20 \text{ mg/cc} \)
  - DT Vapor: 0.3 mg/cc

- **1 \( \mu \)m CH + 300 Å Au**

- Dimensions:
  - 0.195 cm
  - 0.169 cm
  - 0.150 cm

LLNL/LBNL HIF Target

- Ion beam characteristics:
  - 3.5 GeV Pb\(^+\) ions
  - 3.3 MJ input energy
  - 1.7 mm effective radius spot

Time-of-Flight Ion Power Spread

<table>
<thead>
<tr>
<th></th>
<th>Direct-Drive Target</th>
<th>Indirect-Drive Target</th>
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</thead>
<tbody>
<tr>
<td><strong>Energy (MJ)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver Energy</td>
<td>1.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Total Yield</td>
<td>154</td>
<td>458</td>
</tr>
<tr>
<td>Neutrons</td>
<td>109</td>
<td>316</td>
</tr>
<tr>
<td>Fast Ions</td>
<td>18.1</td>
<td>8.43</td>
</tr>
<tr>
<td>Debris Ions</td>
<td>24.9</td>
<td>18.1</td>
</tr>
<tr>
<td>X-rays</td>
<td>2.14</td>
<td>115</td>
</tr>
<tr>
<td>% of yield</td>
<td>71 %</td>
<td>69 %</td>
</tr>
<tr>
<td>% of yield</td>
<td>12 %</td>
<td>1.8 %</td>
</tr>
<tr>
<td>% of yield</td>
<td>16 %</td>
<td>4.0 %</td>
</tr>
<tr>
<td>% of yield</td>
<td>1.4 %</td>
<td>25 %</td>
</tr>
</tbody>
</table>
Dry-wall chamber can handle direct-drive target emissions

- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1-0.2 mm of surface.
- Beyond the first 0.1-0.2 mm of the surface. First wall experiences a much more uniform q” and quasi steady-state temperature (heat fluxes similar to MFE).

- **Use an Armor**
  - Armor optimized to handle particle & heat flux.
  - First wall is optimized for efficient heat removal.

- Critical Issue is the lifetime of the armor:
  - He retention and exfoliation
  - Cyclic Fatigue
  - De-bounding of the armor
Aerosol Generation and Transport is the Key Issue for Thin-Liquid Wall Concepts

A renewable thin-liquid protection resolve several issues:

- It can handle a much higher heat fluxes compared to solid surfaces;
- It will eliminate damage to the armor/first wall due to high-energy ions.

A renewable thin-liquid protection, however, introduces its own critical issues:

- Fluid-dynamics aspects (establishment and maintenance of the film)
  - “Wetted wall:” Low-speed normal injection through a porous surface
  - “Forced film:” High-speed tangential injection along a solid surface
- Chamber clearing (recondensation of evaporated liquid)
  - “Source term:” both vapor and liquid (e.g., explosive boiling) are ejected
  - Super-saturated state of the chamber leads to aerosol generation
  - Target injection and laser beam propagation lead to sever constraints on the acceptable amount and size of aerosol in the chamber.
Two Methods for Establishment of Thin-Liquid Walls Have Been Proposed

- X-rays and Ions
- Forced Film
- Injection Point
- Wetted Film
- Detachment Distance $x_d$
- First Wall
A Thin-Liquid Protected Film can be Established and Maintained

- Developed general non-dimensional charts for film stability
- Model predictions are closely matched with experimental data.

Radial injection scheme appear to be feasible and does not impose major constraints. Attractiveness of this concept depends on:

- Details on the chamber and power plant design
- Impact of the required pumping power on the recirculating power & overall economics

For the forced-flow scheme, behavior of the film near major obstacles is a major concern.
Most of Ablated Material Would Be in The Form of Aerosol

- FLiBe aerosol and vapor mass history in a 6.5-m radius chamber (ablated thickness of 5.5 mm)
- Only homogeneous nucleation and growth from the vapor phase.

**Diagram:**

- Most of ablated material remains in the chamber in aerosol form;
- Similar analysis for a 3-m chamber radius leads to 1.8 kg aerosol mass but higher $n_r^3 = 8 \times 10^{-6}$
There Are Many Mechanism of Aerosol Generation in an IFE Chamber

- Homogeneous nucleation and growth from the vapor phase
  - Supersaturated vapor
  - Ion seeded vapor
- Phase decomposition from the liquid phase
  - Thermally driven phase explosion
  - Pressure driven fracture
- Hydrodynamic droplet formation (May be critical in Thick-liquid Wall concepts)
Aerosol Generation and Transport is also the Key Issue for Thick-Liquid Wall Concepts

- Studies of structural materials choices and limits
  - If a 300 series SS is required as a near-term base line for the design, then Ti-modified 316SS (PCA) should be used. Chamber vessel would not be a life-time components.
  - However, it was strongly recommended to consider alternate structural material candidates (ferritic steels and SiC/SiC composites) offering the possibility of higher operating temperature & performance. In this case, chamber vessel may be a life-time component.

- Aerosol concerns (similar to thin liquids) were highlighted.
  - Hydrodynamic droplet formation is a key issue. Flow conditioning and careful nozzle design are needed to control the hydrodynamic source.
Direct-drive targets (initial $T=18K$) are heated during their travel in the chamber by:

- Friction with the chamber gas (mainly through condensation heat flux) requiring
  - Lower gas pressure
  - Slower injection velocity
- Radiation heat flux from hot first wall, requiring
  - Lower equilibrium temperature
  - Faster injection velocity
- Addition of a thin (~70 µm) foam improves the thermal response considerably.

Direct-drive target injection imposes the toughest constraint on chamber gas pressure.

Impact of aerosol is unknown

No constraint for indirect-drive targets.
Studies of Ion Transport Modes Indicate Several Options are Feasible

<table>
<thead>
<tr>
<th>Transport Mode</th>
<th>Ballistic Transport</th>
<th>Pinch Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>chamber holes ~ 5 cm radius</td>
<td>chamber holes ~ 0.5 cm radius</td>
</tr>
<tr>
<td></td>
<td>most studied</td>
<td>higher risk, higher payoff</td>
</tr>
<tr>
<td>Chamber Concept</td>
<td>Vacuum-ballistic vacuum</td>
<td>Neutralized-ballistic plasma generators</td>
</tr>
<tr>
<td>Dry-wall ~6 meters to wall</td>
<td>Not considered now: requires ~500 or more beams</td>
<td>ARIES-IFE (2002) Possible option: but tighter constraints on vacuum and beam emittance</td>
</tr>
<tr>
<td>Wetted-wall ~4-5 meters to wall</td>
<td>HIBALL (1981) Not considered: needs ≤ 0.1 mTorr</td>
<td>OSIRIS-HIB (1992) ARIES-IFE (2002) Possible option: but tighter constraints on vacuum and beam emittance</td>
</tr>
<tr>
<td>Thick-liquid wall ~3 meters to wall</td>
<td>Not considered: needs ≤ 0.1 mTorr</td>
<td>HYLIFE II (1992-now) ARIES-IFE (2002) Main-line approach: uses pre-formed plasma and 1 mTorr for 3 m ~50-200 beams</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Preformed channel (“assisted pinch”) laser + z-discharge</th>
<th>Self-pinned only gas</th>
</tr>
</thead>
</table>

\[ \text{nr}^3 \leq 10^{-9} \text{ (aerosol)} \text{ or } \sim 1 \text{ mTorr (gas)} \]
\[ \text{nr}^3 \leq 10^{-6} \text{ (aerosol)} \text{ or } \sim 1 \text{ Torr (gas)} \]
\[ \text{nr}^3 \leq 10^{-7} \text{ (aerosol)} \text{ or } \sim 100 \text{ mTorr (gas)} \]
Summary

Dry wall chambers

- Laser and direct-drive targets:
  - Sever constraint on chamber gas pressure (from target injection).
  - Wall can survive without any gas protection
  - The major issue is the lifetime of the armor

- Laser or heavy-ions and indirect-drive targets:
  - Required protection gas pressure may be too high for laser and/or heavy-ion propagation
  - Recycling of hohlraum material is a major issue.

Wetted-wall and Thick-liquid wall chambers

- Heavy-ion and indirect-drive targets:
  - Requires assisted pinch propagation
  - Aerosol generation and transport is a major issue.
Extra Slides
Details of Target Spectra Has A Strong Impact on the Thermal Response of the Wall

- Photon and ion energy deposition falls by 1-2 orders of magnitude within 0.1 mm of surface.

- Heat fluxes are much lower than predicted in previous studies:
  - A much smaller portion of target yield is in X-rays.
  - Time of flight of ions spread the temporal profile of energy flux on the wall over several μs.

- A cover gas may not be necessary for protecting the chamber wall.

Energy Deposition (J/m²) in C and W Slabs (NRL 154MJ Direct Drive Target)
Thermal Response of a W Flat Wall

- NRL direct-drive target in 6.5-m chamber with no gas protection:
  - 3-mm thick W Chamber Wall
  - Coolant at 500°C
  - Convection B.C. at coolant wall: $h = 10\ kW/m^2-K$

- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Similar margin for C slab.
IFE Armor Conditions are similar to those for MFE PFCs (ELM, VDE, Disruption)

<table>
<thead>
<tr>
<th></th>
<th>ITER Type-I ELM’s</th>
<th>ITER VDE’s</th>
<th>ITER Disruptions</th>
<th>Typical IFE Operation (direct-drive NRL target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>&lt;1 MJ/m²</td>
<td>~ 50 MJ/m²</td>
<td>~ 10 MJ/m²</td>
<td>~ 0.1 MJ/m²</td>
</tr>
<tr>
<td>Location</td>
<td>Surface near div. strike points</td>
<td>surface</td>
<td>surface</td>
<td>bulk (~µm’s)</td>
</tr>
<tr>
<td>Time</td>
<td>100-1000 µs</td>
<td>~ 0.3 s</td>
<td>~ 1 ms</td>
<td>~ 1-3 µs</td>
</tr>
<tr>
<td>Max. Temperature</td>
<td>melting/sublimation points</td>
<td>melting/sublimation points</td>
<td>melting/sublimation points</td>
<td>~ 1500-2000 °C (for dry wall)</td>
</tr>
<tr>
<td>Frequency</td>
<td>Few Hz</td>
<td>~ 1 per 100 cycles</td>
<td>~ 1 per 10 cycles</td>
<td>~ 10 Hz</td>
</tr>
<tr>
<td>Base Temperature</td>
<td>200-1000 °C</td>
<td>~ 100 °C</td>
<td>~ 100 °C</td>
<td>~ &gt;500 °C</td>
</tr>
</tbody>
</table>

- There is a considerable synergy between MFE plasma facing components and IFE chamber armor.
Design Windows for Direct-Drive Dry-wall Chambers

**Thermal design window**
- Detailed target emissions
- Transport in the chamber including time-of-flight spreading
- Transient thermal analysis of chamber wall
- No gas is necessary

**Target injection design window**
- Heating of target by radiation and friction
- Constraints:
  - Limited rise in temperature
  - Acceptable stresses in DT ice

**Laser propagation design window(?)**
- Experiments on NIKE
We Have Developed Design Widows for The Forced-Wall Concepts

- Developed non-dimensional design widows for longitudinal spacing of injection/coolant/removal slots to maintain attached protective film;

![Graph showing the relationship between We and x_d for different values of δ and θ.](image)

- For δ = 1 mm
- For δ = 1.5 mm
- For δ = 2 mm

- θ = 0°

- Plexiglas
  - Flat
  - Curved

1 mm nozzle
8 GPM
10.1 m/s
10° inclination
Re = 9200
Selected Results from ARIES-IFE Study:
Wetted Wall Concepts
Selected Results from ARIES-IFE Study:
Thick Liquid Wall Concepts