Design Windows for IFE Chambers and Target Injection

Farrokh Najmabadi
for the ARIES Team

US/Japan Workshop on Target Fabrication

December 3-4, 2001
General Atomics, San Diego, CA

Electronic copy: http://aries.ucsd.edu/najmabadi/TALKS
ARIES Web Site: http://aries.ucsd.edu/ARIES
ARIES Integrated IFE Chamber Analysis and Assessment Research -- Goals

Goals:

- 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.
- We research these classes of chambers in series with the entire team focusing on each concept.
Reference Direct and Indirect Target Designs

NRL Advanced Direct-Drive Targets

- 1 μm CH + 300 Å Au
  - CH Foam + DT
  - DT Vapor 0.3 mg/cc
  - .195 cm
  - .169 cm
  - .150 cm
  - CH foam $\rho = 20$ mg/cc

- 5 μ CH
  - CH Foam + DT
  - DT Fuel
  - DT Vapor 0.3 mg/cc
  - .162 cm
  - .144 cm
  - .122 cm
  - CH foam $\rho = 75$ mg/cc

LLNL/LBNL HIF Target

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

• NRL Direct Drive Target Gain Calculations (1-D) have been corroborated by LLNL and UW.
Target injection Design Window Naturally Leads to Certain Research Directions

- Analysis of design window for successful injection of direct and indirect drive targets in a gas-filled chamber (e.g., Xe) is completed.
  - No major constraints for indirect-drive targets (Indirect-drive target is well insulated by hohlraum materials)
  - Narrow design window for direct-drive targets:
    \[ \text{Pressure} < \sim 50 \text{ mTorr, Wall temperature} < \sim 700^\circ \text{C}. \]
Variations in the Chamber Environment Affects the Target Trajectory in an Unpredictable Way

- Repeatable, high-precision placement (± 5 mm).
- Indirect/direct requires tracking and beam steering to ±200/20 µm.
- For Ex-Chamber Tracking:
  - 1% density variation in chamber gas causes a change in predicted position of 1000 mm (at 0.5 Torr)
  - For manageable effect at 50 mTorr, density variability must be <0.01%.
- Need both low gas pressure and in-chamber tracking.
X-ray and Ion Spectra from Reference Direct and Indirect-Drive Targets Are Computed

<table>
<thead>
<tr>
<th></th>
<th>NRL Direct Drive Target (MJ)</th>
<th>HI Indirect Drive Target (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays</td>
<td>2.14 (1%)</td>
<td>115 (25%)</td>
</tr>
<tr>
<td>Neutrons</td>
<td>109 (71%)</td>
<td>316 (69%)</td>
</tr>
<tr>
<td>Gammas</td>
<td>0.0046 (0.003%)</td>
<td>0.36 (0.1%)</td>
</tr>
<tr>
<td>Burn product fast ions</td>
<td>18.1 (12%)</td>
<td>8.43 (2%)</td>
</tr>
<tr>
<td>Debris ions kinetic energy</td>
<td>24.9 (16%)</td>
<td>18.1 (4%)</td>
</tr>
<tr>
<td>Residual thermal energy</td>
<td>0.013</td>
<td>0.57</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>458</td>
</tr>
</tbody>
</table>

- Little energy in the X-ray channel for NRL direct-drive target

- Detailed target spectrum available on ARIES Web site http://aries.ucsd.edu/ARIES/
Details of Target Spectra Has 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.

Most of heat flux due to fusion fuel and fusion products (for direct-drive).

Time of flight of ions spread the temporal profile of energy flux on the wall over several µs (resulting heat fluxes are much lower than predicted previously).
Is Gas Necessary to Protect Solid Walls (for NRL Direct-Drive Targets)? NO

- Thermal response of a W flat wall to NRL direct-drive target (6.5-m chamber with no gas protection):
  - 3-mm thick W Chamber Wall
  - Coolant at 500°C
  - Energy Front
  - Evaporation heat flux B.C at incident wall
  - Convection B.C. at coolant wall: \( h = 10 \text{ kW/m}^2\text{-K} \)
  - 1,438 °C peak temperature
  - Wall surface
  - 20 µm depth
  - Coolant

- Temperature variation mainly in thin (0.1-0.2 mm) region.
- Significant margin for design optimization (a conservative limit for tungsten is to avoid reaching the melting point at 3,410°C).
- Material damage due to high ion flux is a remaining issue.
All the Action Takes Place within 0.1-0.2 mm of Surface -- Use an Armor

- 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 and heat flux.
  - First wall is optimized for efficient heat removal.

- Most of neutrons deposited in the back where blanket and coolant temperature will be at quasi steady state due to thermal capacity effect.

- Focus IFE effort on armor design and material issues

- Blanket design can be adapted from MFE blankets
Use of an Armor Allows Adaptation of Efficient MFE Blankets for IFE Applications

- As an example, we considered a variation of ARIES-AT blanket as shown:
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1100°C) while keeping SiC structure temperature below 1000°C leading to a high thermal efficiency of ~ 55%.
- Plausible manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
Candidate Dry Chamber Armor Materials

- **Carbon (and CFC composites)**
  - Erosion (several mechanisms; effects of IFE conditions - pulsed operation)
  - Fabrication - Bonded layer or integrated with structural material?
  - Key tritium retention issue (in particular co-deposition)
  - Oxidation, Safety

- **Tungsten & Other Refractories**
  - Fabrication/bonding and integrity under IFE conditions

- **"Engineered Surfaces"** to increase effective incident area.
  - An example is a C fibrous carpet.
Example of Engineered Material: ESLI Fiber-Infiltrated Substrate

Samples tested in RHEPP ion-beam facility (25 shots)

POCO graphite: Exposed surface recedes ~50 µm at high-flux location

Under the velvet pile, the substrate shows little erosion (epoxy coating over aluminum survives)

Why so much less erosion?

✓ Each pulse is spread over 15x more area, so that <0.1 µm is ablated
✓ The ablated material may redeposit on the nearby fibers: recycling
✓ Thermal penetration into vertical fibers may be providing effective cooling on this time scale
Candidate Dry Chamber Armor Materials

- **Carbon (and CFC composites)**
  - Erosion (several mechanisms; effects of IFE conditions - pulsed operation)
  - Fabrication - Bonded layer or integrated with structural material?
  - Key tritium retention issue (in particular co-deposition)
  - Oxidation, Safety

- **Tungsten & Other Refractories**
  - Fabrication/bonding and integrity under IFE conditions

- **“Engineered Surfaces”** to increase effective incident area.
  - An example is a C fibrous carpet.

- **Others?**

- **Lifetime is the key issue for the armor**
  - Even erosion of one atomic layer per shot results in ~ cm erosion per year
  - Need to better understand molecular surface processes
  - Need to evolve in-situ repair process
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 divert. 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>

- We should make the most of existing R&D in MFE area (and other areas) since conditions can be similar (ELM’s vs IFE)
Design Windows for Direct-Drive Chambers

Laser propagation design window (?)

Operation Window (?)

Target injection/tracking design window

- Some gas may be needed in the chamber:
  - Pumping requirements are reasonable for chamber pressures of ~10-50 mTorr.
Gas pressures of $\geq 0.1$-0.2 torr is needed (due to large power in X-ray channel).

Similar Results for W.

Operation at high gas pressure may be needed to stop all of the debris ions and recycle the target material.

No major constraint from injection/tracking.

Heavy-ion Stand-off issues:
- Pressure too high for non-neutralized transport.
- Pinch transport (self or pre-formed pinch)
Dry-wall chambers are credible and attractive options for both lasers and heavy ion drivers.

- Accurate target output spectrum has been produced.
- Time of flight of ions reduces heat flux on the wall significantly.
- Use of an armor separates energy/particle accommodation function from structural and efficient heat removal function:
  - Armor optimized to handle particle and heat flux.
  - First wall is optimized for efficient heat removal.
- There is considerable synergy and similarity with MFE in-vessel components.

**Recent Concerns and Directions:**
- High ion flux on the wall may lead to low armor life time. < 50 mTorr neutral Xe in the chamber does not slow down the ions. But, X-ray flux and initial fast-ions will ionize Xe.
- Xe is not needed for X-ray attenuation. Other (or no) buffer gas?
- Initial estimates indicate that there is not sufficient time for the chamber gas to equilibrate with wall temperature.