Isochoric Nuclear Heating and Design Implications

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• Examples of time-dependent variation of nuclear heating in thick liquid wall and solid structure.

• Impact of instantaneous deposition of nuclear heating.
Is Time-Dependent Nuclear Analysis Essential for IFE?

- **In MFE**, fusion reactions are sustained for time much longer than neutrons time-of-flight (TOF) to FW and slowing down time in blanket
  - Steady-state calculation is sufficient for MFE.

- **In IFE**, fusion reactions occur during very short burn time (10-100 ps). Neutrons TOF and slowing down time are much greater than burn time (n’s reach blanket surface in 10-150 ns and slow down in blanket in 10’s of ns)
  - Time-dependent analysis is essential for IFE to evaluate instantaneous peaking of radiation effects.

- Over past 25 y, only HIBALL study (UW-1981) performed rigorous time-dependent heating and radiation damage analyses for IFE power plants.
Thick Liquid Walls Could Protect FS Structure for Plant Life

Target

\[ \geq 0.5 \text{ m Radius} \]

Thick Liquid Wall

Gap

Solid FW Structure

FS Shield

<table>
<thead>
<tr>
<th>Component</th>
<th>0.5 m Radius</th>
<th>5 m Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>X rays</td>
<td>~0.1 - 2 ns</td>
<td>~1 - 20 ns</td>
</tr>
<tr>
<td>n’s</td>
<td>~10 - 20 ns</td>
<td>~100-150 ns</td>
</tr>
<tr>
<td>Ions</td>
<td>~20-200 ns</td>
<td>~0.2 - 2 µs</td>
</tr>
</tbody>
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X rays and n’s spend tens of ns traveling through liquid before reaching FS wall.
Evolution of Liquid Wall

- **X rays** rapidly deposit their energy at liquid surface (in μm’s):
  - Vaporizing few microns
  - Producing vapor that rapidly blows off of liquid surface
  - Driving strong shock waves into liquid.
- Geometry of liquid hardly changes before neutron arrival.
- **Neutrons** deposit their energy **volumetrically**, causing rapid expansion of liquid.
- Vapor:
  - Cools down during expansion
  - Stops **ions**
  - Gets reheated by **ions**
  - Radiates heat, vaporizing more liquid
    - **ions** heat liquid indirectly.
- Hydro-motion leads to splash and break-up of liquid.
HYLIFE Design Allows Flibe Jets Disintegration Between Shots

- Crossing cylindrical Jets form beam ports
- Oscillating jets form main pocket
- Vortices shield beam line penetrations

42% Void
58% Flibe

HYLIFE-II
HIBALL’s Porous SiC Tubes Prevent LiPb Columns from Disassembly Between Shots

- 400 MJ Target
- 10 GeV Bi++ ions
- 5 Hz

66% Void
33% LiPb
1% SiC
Time integrated, space average power density \((PD)\) is \(\sim 150 \text{ W/cm}^3\) for ARIES-IFE-HIB and \(\sim 2 \text{ W/cm}^3\) for HIBALL.
Neutrons Deposit Their Energy Volumetrically, Unlike X-rays and Ions

First cm of liquid exhibits slight change (~2%) in nuclear heating distribution, unlike x-ray and ion energy deposition that diminishes after few microns.
Instantaneous Nuclear Energy Deposition Exceeds Time Average PD @ Liquid Surface by ~7 Orders of Magnitude

Large instantaneous energy deposition heats up liquid volumetrically and results in strong pressure wave that breaks-up liquid wall.
At FW FS Structure, Instantaneous Nuclear Energy Deposition Exceeds Time Average PD by ~5 Orders of Magnitude

- FS temperature fluctuates 5 times per second.
- Nuclear heating will induce stresses on the order of 10 MPa in FS, per Hassanein (ANL).
- Inertial effects are not likely to be an issue.
- For these low stresses, fatigue in unirradiated FS should not be an issue, per Blanchard (UW).
- Fatigue in irradiated material is expected to be OK as well, but needs to be quantified.
- Assessing FS lifetime:
  1. Quantify fatigue effects in unirradiated material
  2. Assess radiation damage effects (e.g., 200 dpa @ EOL)
  3. Quantify fatigue effects in irradiated material.

Instantaneous nuclear energy deposition combined with 200 dpa may shorten FW service life
Conclusions

• **Instantaneous nuclear heating:**
  - Peak spreads out almost uniformly over few cm
  - ~20 ns duration of peak in liquid
  - $10^7$ peak to average ratio
  - ~$10^5$ lower peak heating compared to x-rays and ions
    - **surface** effect of nuclear heating can be neglected.

• Nuclear energy deposition heats-up thick liquid volumetrically and breaks-up liquid geometry.

• **Instantaneous deposition of nuclear heating** in FW structure 5 times per second produces relatively low stresses in FS.

• Impact of radiation damage on fatigue life needs to be quantified.