INTERACTION OF TARGET DEBRIS WITH LIQUID-FILM-PROTECTED FIRST WALLS

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Modelled Phenomena

(HEIGHTS Package)

• X-ray (& reflected light) deposition in liquid film & underlying structure

• Thermal response and Evaporation of protective film

• Hydrodynamic-blowoff (transport) of vapor within the cavity

• Ion transport and energy deposition in ablated vapor, liquid film, and underlying structure

• Thermal and hydrodynamic response of vapor cloud and protective film to direct ion energy deposition

• Reradiation from vapor cloud

• Thermal and mechanical response of underlying structure to x-ray deposition, direct ion deposition, and radiation flux from vapor cloud.
OBJECTIVES

• Develop an internally consistent, mechanistic model to determine the thermal-mechanical response of liquid-film-protected first walls to target debris.

• Parametric-study of key phenomena

• Define an operating window for reactor design
PROBLEM DEFINITION

• First wall (porous or solid) covered with a thin liquid film of specified materials

• Specified cavity dimensions (chamber radius)

• Specified target yield & spectra (and reflected laser light, if any)

• Specified initial cavity condition (vacuum or pre-filled gas & vapor)
Assumptions:

- Specified spectrum and energy density
  - Blackbody (0.1 keV and 1.0 keV) or given data
  - 10 ns pulse duration
  - 1-5 J/cm²

- Specified wall material, thickness, and porosity
  - 1 cm thick solid graphite wall

- Specified film material, thickness, and initial temperature
  - 1 mm Li or Pb
  - Li temp of 500 K and Pb temp of 700 K

- Specified chamber cavity radius
  - 6.5 m radius
Self-Consistent Kinetic Model

• **Optical properties are calculated for actual gas/vapor-plasma-debris conditions.**

• During each time step, quantities such as density, temperature, and spectral radiation flux are used to calculate absorption and emission coefficients.

• This is achieved by solving the kinetic equations for ion concentration and for level populations of each charge state.

• **Calculation of emission and absorption coefficients includes the three kinds of radiation:**
  
  – Bremsstrahlung radiation
  
  – Recombination radiation
  
  – Line radiation.
Atomic Physics Package

- Atomic database implemented in the `SUPERATOM package` is used in these calculations.

- Some of the data includes:
  - Ionization potentials
  - Energy levels
  - Statistical weights
  - Quantum levels
  - Degeneracy levels
  - Oscillator force
  - Line transition probabilities
  - Ionization cross sections
Photon Radiation & Transport Model

• Non-LTE Radiation Transport Model

• Both Continuum and Line Radiation are Included

• Up to 4000 Photon Energy Group for the Continuum Spectrum

• Up to 100 Separate Lines can be used for the Low-Z Materials and several 100’s for Higher-Z Materials

• Each Single Line is treated as a Continuum Spectrum (Mini multi-group up to 200 groups/line)

• Doppler and Stark Broadening of Line Radiation

• Numerical Methods
  – Forward/Reverse for 1-1.5D model
  – Ray Tracing Techniques for 2-3D model
HEIGHTS CALCULATION OF FAST ION RANGES

Fast Ions - Direct Target

Li-Graphite Wall
HEIGHTS CALCULATION OF DEBRIS ION RANGES
Debris Ions - Direct Target
Li-Graphite Wall
HEIGHTS CALCULATION OF X-RAY DEPOSITION

1 mm Lithium / 1 cm Graphite

5 J/cm², 6.5 m Radius
HEIGHTS CALCULATION OF X-RAY DEPOSITION

1 mm Lead / 1 cm Graphite

5 J/cm², 6.5 m Radius
HEIGHTS CALCULATION OF X-RAY DEPOSITION

1.0 keV Blackbody X-Ray

5 J/cm², 6.5 m Radius
HEIGHTS CALCULATION OF SURFACE TEMPERATURE

1.0 keV Blackbody X-Ray

5 J/cm², 6.5 m Radius
HEIGHTS CALCULATION OF SURFACE TEMPERATURE

1 mm Lithium / 1 cm Graphite

5 J/cm², 6.5 m Radius
HEIGHTS SIMULATION OF NRL DIRECT TARGET

Temperature rise due to laser, X-ray, and ion depositions

<table>
<thead>
<tr>
<th>Deposition Type</th>
<th>Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td>2.10</td>
</tr>
<tr>
<td>Fast Ions</td>
<td>18.1</td>
</tr>
<tr>
<td>Debris Ions</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Lithium/CFC
HEIGHTS Analysis of Vapor Evolution Dynamics and Radiation Power to Liquid Surface

NRL direct target

Temperature, (x1000)K

Power, kW/cm

Distance from liquid wall, cm

Radiation to Wall

Radiation to Center

T

@ 5 µs

Liquid Wall

Carbon
HEIGHTS Analysis of Vapor Expansion and Continuum/Line Radiation Power to Liquid Surface

NRL direct target

Power, kW/cm²

Distance from liquid wall, cm

@ 5 µs
MODELING IFE CAVITY RESPONSE in HEIGHTS

- Incident Beam
- Target
- X-rays
- Neutrons
- Ion Debris
- Reflected Beam
- VAPOR
- Fragments
- Depositions
- Liquid Film or Wall
- Structure

HASSENEIN (ANL)
Macroscopic Debris Interaction with Vapor Plasma

INcIDENT DEBRIS

VAPOR CLOUD

Liquid-Metal Layer on Chamber Wall

HASSANEIN (ANL)
HEIGHTS Analysis of Spatial Dependence of Lithium Droplet Velocity and Radius

Droplet Velocity and Radius

Distance above divertor surface, cm

Velocity, m/s

Radius, µm

Lithium

Time = 400 µs

Life

Complete Vaporization
CONCLUSIONS

HEIGHTS Calculation Package Provide the Means to Mechanistically Evaluate Effectiveness of Thin Liquid Film or Thick Liquid Wall protection schemes Through an Integrated, Self Consistent Analysis of Coupled Physical Phenomena