Mechanisms of Aerosol Generation in Liquid-Protected IFE Chambers

M. S. Tillack, A. R. Raffray and M. R. Zaghloul
Center for Energy Research
and Mechanical and Aerospace Engineering Department
Jacobs School of Engineering

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Aerosols can interfere with several processes in the target chamber

- Direct-drive target contamination can affect implosion symmetry
- Indirect-drive target contamination can block entrance hole and absorb ion energy
- Laser driver beam can be distorted
- Ion propagation can be affected, depending on transport mode: $\partial E/dx$, scattering, stripping, charged droplet effects, ...
- Target trajectory can be perturbed
- In-chamber target tracking can be obscured
- Final optic may become contaminated
Design limits have been developed in ARIES-IFE

<table>
<thead>
<tr>
<th>Process</th>
<th>Size limit and basis</th>
<th>Density limit and basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drive target contamination</td>
<td>50 nm: surface finish degradation</td>
<td>5 mg/m³ Pb: thickness variation</td>
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<tr>
<td>Indirect drive target contamination</td>
<td></td>
<td>1 g/m³ Pb (0.3 mg/cm²): beam</td>
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<tr>
<td></td>
<td></td>
<td>absorption on target surface</td>
</tr>
<tr>
<td>Target tracking system obscuration</td>
<td>1 µm: position measurement error</td>
<td>10 mg/m³: tracking &amp; beam</td>
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<tr>
<td></td>
<td></td>
<td>absorption</td>
</tr>
<tr>
<td>Laser propagation</td>
<td>~0.25 µm: diffraction</td>
<td>~ 1 Torr (3e¹⁹/cm³) equivalent:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>absorption and refraction</td>
</tr>
<tr>
<td><strong>Ion propagation:</strong></td>
<td></td>
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<tr>
<td>Neutralized ballistic transport</td>
<td></td>
<td>Stripping: ~1 mTorr equiv.</td>
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<tr>
<td>Pre-formed channel</td>
<td></td>
<td>Scattering: ~1 Torr equiv.</td>
</tr>
<tr>
<td>Self-pinched</td>
<td></td>
<td>Self-pinching process: ~100 mTorr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equivalent</td>
</tr>
</tbody>
</table>

A dedicated R&D program is needed to determine values of particle size and density expected to occur in a power plant.
Mechanisms of aerosol generation

• Homogeneous nucleation and growth from the vapor phase
  1. Supersaturated vapor
  2. Ion seeded vapor

• Phase decomposition from the liquid phase
  3. Thermally driven phase explosion
  4. Pressure driven fracture

• Hydrodynamic droplet formation (not considered in this talk)
Homogeneous nucleation.

1. Supersaturation drives rapid condensation

- High saturation ratios result from rapid cooling due to plume expansion and heat transfer to the background gas
- Very high nucleation rate and small critical radius result
- Reduction in S due to condensation shuts down HNR quickly; competition between homogeneous and heterogeneous condensation determines final size and density distribution

\[ \Delta G = \frac{4\pi r^3}{3V_m} (\mu_L - \mu_v) + 4\pi \sigma r^2 \]

\[ r^* = \frac{2v}{nDn} \]

\[ \Delta \mu = k \]

\[ J_h = Z \beta C^* \quad C^* = \frac{p}{kT} \exp \left( - \frac{D W_k}{kT} \right) \]

Si, \( n=10^{20} \text{ cm}^{-3} \), \( T=2000 \text{ K} \)
Homogeneous nucleation.
2. Ions enhance the nucleation rate

- Ion jacketing produces seed sites
- Dielectric constant of vapor reduces free energy

\[
\Delta G = \frac{4\pi}{3V_m}(r^3 - r_a^3)(\mu_L - \mu_v) + 4\pi\sigma(r^2 - r_a^2) + \frac{e^2}{2}(1 - \varepsilon^{-1})(r^{-1} - r^{-1}_a)
\]

Si, n=10^{20} \text{ cm}^{-3}, T=2000 \text{ K}, Z_{\text{eff}}=0.01
Mechanisms for phase decomposition:
3. Spinodal decomposition

- Rapid heating (faster than the homogeneous vapor nucleation rate) can drive liquid beyond equilibrium (*superheating*) to a metastable state.
- The metastable liquid has an excess of free energy, so it decomposes explosively into liquid and vapor phases.
- As $T/T_{tc} \rightarrow$ spinodal, Becker-Döhring theory predicts an avalanche-like explosive growth of the nucleation rate (by 20-30 orders of magnitude).
Disequilibrium alters the free energy
equation

The physics of nucleation of vapor in liquid is identical to nucleation of liquid in vapor

But, for explosive evaporation we need to consider disequilibrium in the pressure balance.

\[ W(r) = \frac{4r}{3V_m} n_g \cdot n_i + 4r^2 v - (p_g - p_l) V \]

equilibrium: \[ p_g = p_l + \frac{2v}{r_c} \]
Example: depth of Flibe released, $R=6.5$

![Graph showing energy deposition and penetration depth](image)

- **Cohesion energy (total evaporation energy)**
- **Sensible energy (energy to reach saturation)**
- **Explosive boiling region**
- **Evap. region**
- **2-phase region**

**Axes:**
- **Energy deposition (J/m$^3$)**
- **Penetration depth (micron)**

Values shown:
- $E_{\text{dep}} = 1 \times 10^7$ to $1 \times 10^{12}$ J/m$^3$
- $R = 6.5$
- $T_{\text{critical}} = 0.9 T_{\text{critical}}$
- $E_{\text{evap}} = 2.5$
- $E_{\text{2-phase}} = 10.4$
Mechanisms for phase decomposition:
4. Liquid fracture and spalling

3-parameter Morse potential:

$$U(v) = U_{coh} \left[ \exp \left( \frac{-2(v-v_0)}{a} \right) - 2 \exp \left( \frac{-(v-v_0)}{a} \right) \right]$$

Cold pressure:

$$P(v) = \frac{-dU}{dv} = \frac{2U_{coh}}{a} \left[ \exp \left( \frac{-2(v-v_0)}{a} \right) - \exp \left( \frac{-(v-v_0)}{a} \right) \right]$$

Theoretical spall strength, $P_{th}$, is given by minimum of $P(v)$:

$$P_{th} = \sqrt{\frac{U_{coh} B_0}{8 v_0}}$$

$U_{coh} = $ Specific cohesive energy
$v = 1/\rho = $ Specific volume
$v_0 = $ Specific volume at zero pressure
$a = (2v_0 U_{coh} / B_0)^{1/2}$
$B_0 = $ Bulk modulus

Beryllium data

[Graph showing energy and pressure with $P(v)$ and $dp/dv=0$ spinodal points marked.]

Compression
Tension

Energy (MJ/kg) or Pressure (GPa)

Specific Volume, m^3/kg
Spalling due to a pressure wave in Flibe reflecting from a perfectly stiff wall @ 6.5m

\[ \rho \approx 2000 \text{ kg/m}^3, \quad C_s \approx 3300 \text{ m/s}, \quad T_{in} = 885.7 \text{ K}, \quad P_{th} = -1.887 \text{ GPa} \]

1. For a perfectly stiff wall, the pressure wave reflects from the wall and returns to the free surface as a pressure pulse.
2. \[ P_{\text{free-surface}} = P_{\text{chamber}} \] and the pressure pulse arriving at the free boundary is reflected back as a tensile wave.
3. If the net tensile stress > the spall strength, rupture occurs establishing a new surface.

"Spalled Thickness \approx 2.1 \mu m & Spall Time (t_3 - t_2) \approx 16.9 \text{ ns}

Spall time from the beginning of the pressure pulse:

\[ 2 \frac{L}{C_s} + (t_3-t_1) \approx 200 \text{ ns for a 0.3 mm flibe layer} \]
## Summary of ablation results

<table>
<thead>
<tr>
<th></th>
<th>Flibe</th>
<th>Pb</th>
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</thead>
<tbody>
<tr>
<td><strong>Explosive boiling</strong></td>
<td></td>
<td></td>
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<tr>
<td>thickness (µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R=0.5 m</td>
<td>127</td>
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<tr>
<td>R=3.5 m</td>
<td>10.9</td>
<td>3.8</td>
</tr>
<tr>
<td>R=6.5 m</td>
<td>4.1</td>
<td>2.5</td>
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<tr>
<td><strong>Spall thickness</strong></td>
<td></td>
<td></td>
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<tr>
<td>(µm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R=0.5 m</td>
<td>28</td>
<td>28</td>
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<tr>
<td>from free surface</td>
<td></td>
<td></td>
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<tr>
<td>at rear of jet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R=3.5 m</td>
<td>4.1</td>
<td>1.8</td>
</tr>
<tr>
<td>R=6.5 m</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Total fragmented</strong></td>
<td></td>
<td></td>
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<tr>
<td>thickness (µm)</td>
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<td></td>
</tr>
<tr>
<td>R=3.5 m</td>
<td>15.0</td>
<td>5.6</td>
</tr>
<tr>
<td>R=6.5 m</td>
<td>6.2</td>
<td>3.6</td>
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</tbody>
</table>
Conclusions

• Residual aerosol can interfere with target and driver injection into the chamber

• Several mechanisms exist in liquid-protected IFE chambers to generate aerosol

• These mechanisms strongly depend on the details of target emissions and chamber design

• Further studies are needed in order to demonstrate acceptable levels of aerosol in a liquid-protected power plant chamber
Backup
We performed time-resolved measurements of laser plasma expansion and condensation.

Target: Al, Si
Laser Intensity: $10^7$–$5 \times 10^9$ W/cm$^2$
Ambient: $10^{-8}$ – 100 Torr air
Ionization was shown to dominate condensation in laser ablation plumes.

Maximum charge state at 50 ns, 1 mm from Al target, as derived from spectroscopy and assuming LTE.

Saturation ratio at 1 mm, derived from spectroscopy and assuming LTE.

Comparison of experiments and modeling of mean cluster size vs. laser intensity.