Ablation and Heating During Atmospheric Entry and Its Effect on Airburst Risk

NASA Ames Research Center

Parul Agrawal, Dinesh K. Prabhu
Analytical Mechanics Associates, Inc.

Chris Johnston
NASA Langley Research Center

and Peter Jenniskens
SETI Institute

IPPW 2018, June 11-15, Boulder
Heating and Ablation in Threat Assessment

Asteroid Entry Equation of Motion

\[ dv = \left( -\frac{1}{2} C_d \rho A v^2 A/m + g \sin \theta \right) dt \]
\[ d\theta = \left( \frac{v}{R_e + h} + \frac{g}{v} \right) \cos \theta dt \]
\[ dm = -\frac{1}{2} \rho A v^3 A \sigma_{ab} dt \]

\[ \sigma_{ab} = \frac{C_H}{Q^*} \]

Heat Transfer Coefficient
Heat of Ablation

* Wheeler et al., 2017
Heating and Ablation in Threat Assessment

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\[ dm = -\frac{1}{2} \rho A v^3 A \sigma_{ab} dt \]

\[ \sigma_{ab} = \frac{C_H}{Q^*} = 0.1 \]

Nominal Values

Airburst height

NASA Asteroid Threat Assessment Project working to improve models for these phenomena

* Wheeler et al., 2017
Ablation products mix with shock-heated gas in the wake and emit radiation, producing observed light curves and spectra.

Utilizing high-fidelity Computational Fluid Dynamics (CFD) coupled to full radiation transport and material response.

Shock layer radiation out to the surroundings

Massive ablation from vaporization produces thick layer of ablation products

Flow of melted material

Strong radiative heat flux to the surface

Asteroid Entry Environment
Coupled Ablation and Radiation Modeling

Massive ablation from vaporization produces thick layer of ablation products

Shock layer radiation out to the surroundings

Ablation Products

Air

* Johnston and Stern., 2017
• Fully coupled radiation and ablation results reduces the heat transfer coefficient by nearly \textit{two} orders of magnitude in some cases

Meteoroid Ablation Experiments

- **Continuous Wave Laser Experiment**
  - Tamdakht H5 Chondrite samples tested at heating rates from 5 to 16 kW/cm²

- **Arc Jet Experiment**
  - Heating rates (~4 kW/cm²) produced in the experiment comparable to 30m asteroid at 20 km/s at 65km altitude
  - Machined sphere-cone model allows for high-fidelity simulation of the test environment and material response
High-speed video showing boiling meteorite surface
Laser Experiment Findings

- At low heat flux, effective heat of ablation value close to canonical value of 8 MJ/kg
- Reduction in ablative efficiency at high heat fluxes attributed primarily to radiation blockage from ablation products
Meteoroid Ablation Experiments

- **Continuous Wave Laser Experiment**
  - Source of heating is radiation, which is the dominant source of heating for large meteoroids
  - Tamdakht H5 Chondrite samples tested at heating rates from 5 to 16 kW/cm²

- **Arc Jet Experiment**
  - Heating rates (~4 kW/cm²) produced in the experiment comparable to 30m asteroid at 20 km/s at 65km altitude
  - Machined sphere-cone model allows for high-fidelity simulation of the test environment and material response
High-speed video from arc jet experiment showing widespread melt flow
Arc Jet Experiment
Findings

- Effective heat of ablation ($Q^*$) from the experiment ~ 2 MJ/kg
- Heat is well below the canonical value of 8 MJ/kg for chondrite vaporization
  - Indicates we are in a melt dominated regime

Effect of Ablation Parameter on Energy Deposition

Nominal Value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_H$</td>
<td>0.1</td>
</tr>
<tr>
<td>$Q^*$</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Range based on preceding analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_H$</td>
<td>0.001 to 0.04</td>
</tr>
<tr>
<td>$Q^*$</td>
<td>1.8 to 8.0</td>
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</table>

$\sigma_{ab} = \frac{C_H}{Q^*}$

<table>
<thead>
<tr>
<th>Value</th>
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<tbody>
<tr>
<td>$1.25 \times 10^{-10}$</td>
</tr>
<tr>
<td>$2.20 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Effect of Ablation Parameter on Energy Deposition

| Strongly coupled and vaporization dominated | Nominal | Uncoupled and Melt Dominated |

For 100m impactor, 9km burst height difference corresponds to 25km increase in 4psi blast footprint radius (using Glasstone and Dolan)
Conclusions

• Coupled Fluid Dynamics-Ablation-Radiation calculations show significant reduction in heating over canonical value, particularly at larger sizes relevant to planetary defense
• Ground test experiments yielding insight into ablation phenomena, and being used to develop and validate numerical models
• Bias in ablation parameter toward the low-end results in lower altitude airburst, and therefore larger ground damage footprints

Acknowledgments

• Work was performed under the Asteroid Threat Assessment Project, administered by the NASA Planetary Defense Coordination Officer, Lindley Johnson
• The NASA Interaction Heating Facility (IHF) Team is gratefully acknowledged for supporting the arc jet test
• The Air Force Research Laboratory Laser Hardened Material Evaluation Laboratory is gratefully acknowledged for supporting the laser testing
• Thanks to Greg Gonzalez and Val Kasvin for machining the models for the experiments