Improvements in Modeling Thruster Plume Erosion Damage to Spacecraft Surfaces

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Introduction

- Spacecraft bipropellant thrusters impact spacecraft surfaces with high speed droplets of unburned and partially burned propellant.
  - These impacts can produce erosion damage to optically sensitive hardware and systems (e.g., windows, camera lenses, solar cells and protective coatings)
- On the International Space Station (ISS), operational constraints are levied on the position and orientation of the solar arrays to mitigate erosion effects during thruster operations
- In 2007, the ISS Program requested evaluation of erosion constraint relief to alleviate operational impacts due to an impaired Solar Alpha Rotary Joint (SARJ)
- Boeing Space Environments initiated an activity to identify and remove sources of conservatism in the plume induced erosion model to support an expanded range of acceptable solar array positions
- The original plume erosion model over-predicted plume erosion and was adjusted to better correlate with flight experiment results
- This paper discusses findings from flight experiments and the methodology employed in modifying the original plume erosion model for better correlation of predictions with flight experiment data
- The updated model has been successful employed in reducing conservatism and allowing for enhanced flexibility in ISS solar array operations
Thruster Operations & Plume Effects

Images courtesy of NASA
Impacts to Optically Sensitive Surfaces

- Thruster plume induced erosion of solar arrays
  - Solar cell coverglass is damaged by droplet impacts. Damage impacts the performance of UVE filter coatings and increases optical scatter on the coverglass.
  - The laminates used on solar array thermal side can also be damaged. Thin silicon oxide (SiOx) coatings protect Kapton from Atomic Oxygen erosion.

Representative Solar Array Construction:

- CMX Cover Glass with UVE Filter Coating
- Flexible Printed Circuit (FPC) with Silicone Coating
- SiOx coated Kapton
- Fiberglass Scrimcloth imbedded in silicone adhesive
- SiOx coated Kapton

Solar Array Laminate:

- SiOx coated Kapton
- Fiberglass scrimcloth imbedded in silicone adhesive
- SiOx coated Kapton
- Polyester Adhesive
- Cu

Flat Collector Circuit (FCC):

- SiOx coated Kapton
- Fiberglass Scrimcloth imbedded in silicone adhesive
Plume Induced Erosion Concerns

- Erosion events of concern for the ISS solar arrays
  - Soyuz/Progress approach and separation to Russian Segment docking ports
  - Soyuz relocations
  - Russian Segment reboost and attitude control
  - Soyuz thruster tests
  - Progress and Service Module thruster tests
- Commercial cargo transportation vehicles approach and separation
- Commercial crew transportation vehicles approach and separation
  - Orbiter approach and separation to PMA2
  - Orbiter reboost and attitude control
### Example of Current Erosion Constraint Table

**Service Module Roll/Pitch/Yaw Attitude Control - Inboard SAW Example**

- Results for each alpha/beta combination represent maximum erosion on the entire solar array surface if that particular solar array alpha/beta combination is selected for every event within a year.

| SAW J | 2A | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 | 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
|-------|----|---|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0     | 1  | 6 | 9  | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 | 36  | 39  | 42  | 45  | 48  | 51  | 54  | 57  | 60  | 63  | 66  | 69  | 72  | 75  | 78  | 81  | 84  | 87  | 90  | 93  | 96  | 99  | 102 | 105 |
| 10    | 10 | 16| 20 | 24 | 28 | 32 | 36 | 40 | 44 | 48 | 52 | 56  | 60  | 64  | 68  | 72  | 76  | 80  | 84  | 88  | 92  | 96  | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 |
| 20    | 20 | 24| 28 | 32 | 36 | 40 | 44 | 48 | 52 | 56 | 60 | 64  | 68  | 72  | 76  | 80  | 84  | 88  | 92  | 96  | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 |
| 30    | 30 | 32| 36 | 40 | 44 | 48 | 52 | 56 | 60 | 64 | 68 | 72  | 76  | 80  | 84  | 88  | 92  | 96  | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 |
| 40    | 40 | 42| 44 | 48 | 52 | 56 | 60 | 64 | 68 | 72 | 76 | 80  | 84  | 88  | 92  | 96  | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 |
| 50    | 50 | 52| 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 | 70 | 72  | 74  | 76  | 78  | 80  | 82  | 84  | 86  | 88  | 90  | 92  | 94  | 96  | 98  | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 |
| 60    | 60 | 62| 64 | 66 | 68 | 70 | 72 | 74 | 76 | 78 | 80 | 82  | 84  | 86  | 88  | 90  | 92  | 94  | 96  | 98  | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 |
| 70    | 70 | 72| 74 | 76 | 78 | 80 | 82 | 84 | 86 | 88 | 90 | 92  | 94  | 96  | 98  | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 |
| 80    | 80 | 82| 84 | 86 | 88 | 90 | 92 | 94 | 96 | 98 | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 | 144 |
| 90    | 90 | 92| 94 | 96 | 98 | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 | 144 | 146 | 148 | 150 | 152 |

**NASA JSC 29181 Plume Model**
Original ISS Plume Erosion Model

- Original liquid droplet distribution/flux model used by Space Environments was developed by NASA (JSC 29181)
  
  Reference: Larin, M.E., “Model For Predicting Liquid Droplet Distribution and Velocities In The Plumes Of Small Bipropellant Thrusters,” JSC 29181, September 2000

- Model was designed to determine feathering angles for ISS sensitive surfaces
  
  - Quantifies liquid droplet distribution and velocities in the thruster plume through the analysis of the two-phase droplet-gas flow

- Model was based on ground-based vacuum chamber data, and not correlated against light experiment data [SPIFEX, PIC]

- Space Environments’ assessment of model predictions with SPIFEX flight experiment measurements demonstrated overestimation of droplet flux when compared to flight experiment data

- Plume erosion model was reassessed and updated to correlate with flight and high-speed impact test data
Plume Erosion Model

A value of 4.57 was determined for ‘p’ through an iterative procedure requiring a close match with droplet mass angular distribution results from a MBB 10 N thruster test by H. Trinks.

Implementation by Space Environments of the droplet distribution model follows AIAA 2001-2816:

\[ n(d, \theta) = \frac{D_0(T)}{S_m} \cdot f_{nr} \cdot \left( \frac{d}{d_{\text{min}}} \right)^{-p} \cdot e^{-\frac{\theta^2}{2\sigma^2}} \]

- \( n(d, \theta) \) is the droplet number flux.
- \( D_0(T) \) is the initial droplet number density.
- \( S_m \) is the nozzle throat area.
- \( f_{nr} \) is the range term.
- \( \left( \frac{d}{d_{\text{min}}} \right)^{-p} \) is the size distribution term.
- \( e^{-\frac{\theta^2}{2\sigma^2}} \) is the angular distribution term.
- \( \sigma \) is a function of \( d \) and contains droplet limiting angle information.
- On centerline \( \theta = 0^\circ \) and term becomes unity.

This is proportional to contaminant mass fraction \((K, \beta \text{ are constants})\) with a \(1/r^2\) dependence.

\[ \dot{n}(T, d, r, \theta) = \frac{\dot{M}_T \cdot K \cdot T^{-\beta}}{S_m} \cdot (r + l_{\text{noz}})^{-2} \cdot \left( \frac{d}{d_{\text{min}}} \right)^{-4.57} \cdot e^{-\frac{\theta^2}{2\sigma^2}} \]

The plume erosion model uses the total liquid-phase contaminant flux from the plume contamination model (AIAA 2002-2016):

\[ \dot{m}_C(r, \theta) = K T^{-\beta} \cdot \frac{\dot{M}_T}{R_{exit}^2} \cdot \left( \frac{r + l_{noz}}{R_{exit}} \right)^{-2} \cdot \left( 2e^{\frac{\theta}{\theta_0}} - e^{-\frac{2\theta}{\theta_0}} \right) \]

- \( \dot{m}_C \) is the contaminant mass flux (e.g. g/cm²/s)
- \( K \) and \( \beta \) are constants
- \( T \) is thrust (N)
- \( \dot{M}_T \) is the total propellant mass flow rate (e.g. in g/s)
- \( R_{exit} \) is the nozzle exit radius (e.g. in cm; note this is just a reference distance)
- \( l_{noz} \) is nozzle length (e.g. in cm)
- \( \theta_0 \) is the "dispersion coefficient" (5 degrees)

On centerline \( \theta = 0^\circ \) and term becomes unity.

Flight Experiment Data
Pitsweeper Image Analysis

- Individual images were loaded into Pitsweeper image analysis program
- Pits were identified by user and separated into two groups
  - Pit (red bar)
  - Potential Pit (green bar)
- Pitsweeper outputed pit size distribution
The Kapton and aluminum samples were adjacent in the experiment. Significant differences between the plots above indicate that surface material properties (i.e., hardness) has an important effect.
Comparison of SPIFEX Kapton Pitting Fluences with Fluences Calculated with JSC 29181 Model

JSC 29181 model assumptions

- Droplet size distribution coefficient: $p = 4.57$
  (controls particle size distribution)
- Maximum droplet diameter = 100 µm
Update to Plume Erosion Model

- JSC 29181 plume model assumes a maximum droplet diameter of 100 µm

- Flight experiment measurements support a maximum droplet size of 12 to 24 µm (based on calculations showing that droplets produce pits one to two times their diameter):
  - Top five pit diameters (µm) on SPIFEX samples:
    - Kapton: 20.3, 19.7, 18.4, 17.9, 17.4
    - Aluminum: 19.8, 15.5, 15.5, 15.5, 15.3
  - Largest pit diameter (µm) reported for PIC experiment: 24

- Boeing Space Environments conducted a parametric study and arrived at an updated plume model producing good correlation with the SPIFEX Kapton data. This was achieved by lowering the maximum droplet size and adjusting the droplet size distribution coefficient $p$
For the thrust level of interest (100-3870N), the contamination ratio \((KT^{-\beta})\) was revised to fit the on-orbit data from the PIC flight experiment.

- \(KT^{-\beta}\) becomes independent of thrust and is a constant: 
  
  \[
  0.5258 \times 3870^{-0.4816} = 9.8396E-3
  \]

- Contaminant mass is predicted to be less than 2% of total propellant mass

- Reduction achieves factor of 5-6 reduction in initial deposition estimates

Ground based vacuum chamber test data

\[
y = 0.5258x^{-0.4816}
\]

Updated Fit

\[
y = 0.0111x^{-0.4816}
\]

PRCS (3870 N) result from PIC flight experiment

Russian 130N PIC flight experiment
Comparison of SPIFEX Flight Experiment Data with Boeing Space Environments’ Updated Plume Model

Model assumptions/notes
- Droplet size distribution coefficient: $p = 1.70$
- The maximum droplet diameter is $12 \mu m$

For a maximum droplet diameter of 12 microns, $p = 1.70$ produces results matching the overall observed pit number density.

Updated Boeing Plume Model

*Requires 1:2 droplet-to-pit size assumption (allows pits up to 24 $\mu m$, as reported for the PIC flight experiment)
1:1 droplet-to-pit ratio did not correlate
Simulations of SPIFEX Kapton pitting levels with the JSC 29181 plume erosion model demonstrated that model needed to be updated.

Boeing Space Environments’ plume model update correlates well with observed SPIFEX Kapton pitting results when:

- Maximum droplet diameter changed from 100 µm to 12 µm based on observed maximum pit diameters (and based on 1:2 relationship of droplet diameter to pit diameter).
- Droplet limiting angle calculation updated per input from NASA JSC Aerosciences.
- Droplet size distribution coefficient “p” (which controls particle size distribution) changed from 4.57 to 1.70.
Node 1 nadir window Hyzod cover was deployed on ISS from Flight UF2 (June 2002) to Flight LF1 (July 2005) during which it was exposed to thruster firings for various Soyuz and Progress proximity operation events (approaches and separations of vehicles).

NASA JSC Materials Evaluation Laboratory performed a microscopy imaging survey on the returned Hyzod material. Image survey results were delivered to the Space Environments Team for analysis.

Boeing Space Environments team developed an image analysis technique for this study to measure the damage crater sizes and performed the analysis.

- Top five impact feature (pit) diameters (μm): 16.6, 13.5, 7.5, 7.4, 7.3
Comparison Between Observed Hyzod Pitting Levels with Boeing Updated Plume Model Calculations

Incident Droplet Fluence

- Hyzod, as well as aluminum, which are harder materials than Kapton, demonstrate lower pit damage than Kapton which is a softer material.
Ground Testing & Analyses

- Hypervelocity Impact (HVI) tests supported of reduction of solar array constraints from thruster plume induced erosion
  - HVI test program was conducted by the NASA JSC Hypervelocity Impact Technology Facility (HITF)
    - Light gas gun testing conducted at the NASA JSC White Sands Test Facility (WSTF)
  - Detailed test objectives:
    - Address impact craters as a function of particle size, particle velocity and impacted material
    - Define calibration data for SPHINX
    - Assess solar cell power collection degradation as a function of surface damage
    - Assess scrim cloth mechanical damage due to particle impacts
High-speed impact testing (using a light gas gun system) was performed at the NASA WSTF on Hyzod, solar cell, and scrim cloth samples.

Optical microscopic imaging was performed on the samples at the HITF prior to and after the samples were shot with the light gas gun.

The core damage diameter was estimated from the test samples images.

Results show that the ratio of the core damage diameter/projectile diameter was less than 2.0 for the samples that were tested (Hyzod, solar cell, calibration samples).

- SPHINX analysis results confirm core damage diameter / projectile diameter less than 2.0 for plume droplet impacts.
# Application of Methodology

## Service Module

### Roll/Pitch/Yaw Attitude Control

#### Port Inboard SAW

#### Boeing Space Environments Updated

#### Plume Model

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### JSC 29181 Plume Model

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### Boeing Research & Technology

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Application of Methodology (concluded)

Soyuz/Progress FGB Nadir Approach & SM RPY Attitude Control
Port Inboard SAW

Boeing Space Environments Updated
Plume Model

| JSC 29181 Plume Model |

| Boeing Space Environments Updated |

![Image of a table or diagram related to the text content]
Conclusions

This paper presents the methodology employed in updating the ISS plume induced erosion model for better correlation with flight experiment data and for increased accuracy.

The plume induced erosion model originally developed to support the Program significantly over-predicted erosion damage.

Boeing Space Environments succeeded in adjusting the model for better correlation with flight experiment results.

The updated plume model was successfully applied in the definition of updated constraints for ISS solar array operations while mitigating against excessive erosion to the arrays. Erosion keep-out zones for ISS solar arrays were reduced by 30% to 60% with the updated model.

The authors hope that future efforts to improve the characterization of plume induced erosion will draw upon the expertise developed for the ISS Program in the development of space environments effects modeling.
Backup
Hyzod Window Cover Background

- Node 1 nadir window cover
- Exposed from June 2002 (STS-111/UF2) to July 2005 (STS-114/LF1)

Images courtesy of NASA
Hyzod Exposures to Thruster Plumes

Hyzod window cover exposed to thruster firings during Orbiter, Soyuz, and Progress Proximity Operations

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Docking Port</th>
<th>Number of Approaches</th>
<th>Number of Separations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbiter</td>
<td>PMA2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Soyuz*</td>
<td>FGB</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Soyuz</td>
<td>DC1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Progress</td>
<td>DC1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Progress</td>
<td>SM Aft</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

* Expected to be the dominant source of plume effects
Example Hyzod Image (1000x Magnification)

Images courtesy of NASA
Summary of Hyzod Image Analysis Results

- Most common pit size is 2 – 3 µm for both magnification levels
- Largest pit diameter is approximately 17 µm
- 99.8% of pits are below 8 µm
- Pits with diameters less than 1 µm are visible in 3000x images but not in 1000x images
- Number densities inferred from the 3000x images are up to two times larger than the 1000x images
Hyzod Image Analysis Results

Note: Histograms show normalized pit size distributions
Note: 3000x magnification images provided only for comparison purposes. Image samples insufficient for quantitative assessment
## Hyzod Image Analysis Results

### Magnification Approximate Pit Number Density

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Approximate Pit Number Density Excluding Potential Pits (pits / mm²)</th>
<th>Approximate Pit Number Density Including Potential Pits (pits / mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Pit density rounded to the nearest multiple of ten pits / mm²

### Approximate % Total Area Pitted

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Approximate % Total Area Pitted Excluding Potential Pits</th>
<th>Approximate % Total Area Pitted Including Potential Pits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000x</td>
<td>0.16 %</td>
<td>0.16 %</td>
</tr>
<tr>
<td>3000x</td>
<td>0.24%</td>
<td>0.24%</td>
</tr>
</tbody>
</table>

Note: 3000x magnification images provided only for comparison purposes. Image samples insufficient for quantitative assessment.
SPIFEX Background

- Experiment conducted by the U.S. in September 1994 (STS-64)
- Exposed samples of Kapton tape and aluminum foil to:
  - 84 PRCS firings
  - 17 VRCS firings
  - Average pulse of 248.5 ms
  - Average distance of 46 feet
  - Angles off centerline varied from 0° to 90°
- Of interest to compare results for Kapton tape and aluminum foil to evaluate differences in material susceptibility to impact damage
Example SPIFEX Kapton Tape Image: 1500x Magnification (20 µm Scale)

Images courtesy of NASA
Example SPIFEX Kapton Tape Image: 100x Magnification (500 µm Scale)

Images courtesy of NASA
Example SPIFEX Aluminum Foil Image: 1000x Magnification (50 µm Scale)

Images courtesy of NASA
Example SPIFEX Aluminum Foil Image: 100x Magnification (500 µm Scale)

Images courtesy of NASA
### SPIFEX Image Analysis Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Approximate Pit Number Density Excluding Potential Pits (pits / mm²)</th>
<th>Approximate Pit Number Density Including Potential Pits (pits / mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton Tape</td>
<td>6710</td>
<td>9300</td>
</tr>
<tr>
<td>Aluminum Foil</td>
<td>2160</td>
<td>2160</td>
</tr>
</tbody>
</table>

Note: Pit density rounded to the nearest multiple of ten pits / mm²

<table>
<thead>
<tr>
<th>Sample</th>
<th>Approximate % Total Area Pitted Excluding Potential Pits</th>
<th>Approximate % Total Area Pitted Including Potential Pits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton Tape</td>
<td>6.4%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Aluminum Foil</td>
<td>2.8%</td>
<td>2.8%</td>
</tr>
</tbody>
</table>
SPIFEX Image Analysis Results

Combined Histogram of Kapton Pits

Combined Histogram of Aluminum Pits

Note: Histograms scaled to show similarities and differences in both distributions
Summary of SPIFEX Image Analysis Results

- Most common pit size is 1 – 2 µm
- Largest Kapton tape pit diameter is approximately 20 µm
  - Largest potential pit diameter is approximately 28 µm
- Largest aluminum foil pit diameter is approximately 20 µm
- Both samples were exposed to the same thruster firings
  - Can compare results to evaluate differences in material susceptibility to impact damage
Comparison of number of pits identified per mm²

<table>
<thead>
<tr>
<th>Pit Diameter</th>
<th>Original Count / mm²</th>
<th>Approximate Current Count / mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 4 µm</td>
<td>449</td>
<td>1600</td>
</tr>
<tr>
<td>5 – 10 µm</td>
<td>231</td>
<td>320</td>
</tr>
<tr>
<td>11 – 20 µm</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

PIC Background

- Conducted in 1996 (STS-74)
- Measured initial and permanent plume induced molecular contamination using Quartz Crystal Microbalances (QCM)
- Exposed QCM to:
  - 20 PRCS firings
  - 100 Russian 130 N thruster firings
- Impact features were observed on the camera lens of the Orbiter RMS
  - Consistent with observations from the SPIFEX flight experiment

PIC Statistics

- 61 pits / mm²
- Pitted area represents 1.8% of the camera lens surface area
- PIC statistics given below
  - 6 – 13 µm bin is the most common PIC pit size
  - 2 – 3 µm bin is the most common Hyzod pit size
  - 1 – 2 µm bin is the most common SPIFEX pit size

<table>
<thead>
<tr>
<th>Pit Diameter</th>
<th>Pit Density / mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - 5 µm</td>
<td>21</td>
</tr>
<tr>
<td>6 - 13 µm</td>
<td>30</td>
</tr>
<tr>
<td>14 - 24 µm</td>
<td>10</td>
</tr>
</tbody>
</table>

PIC Camera Lens Pit Density