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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

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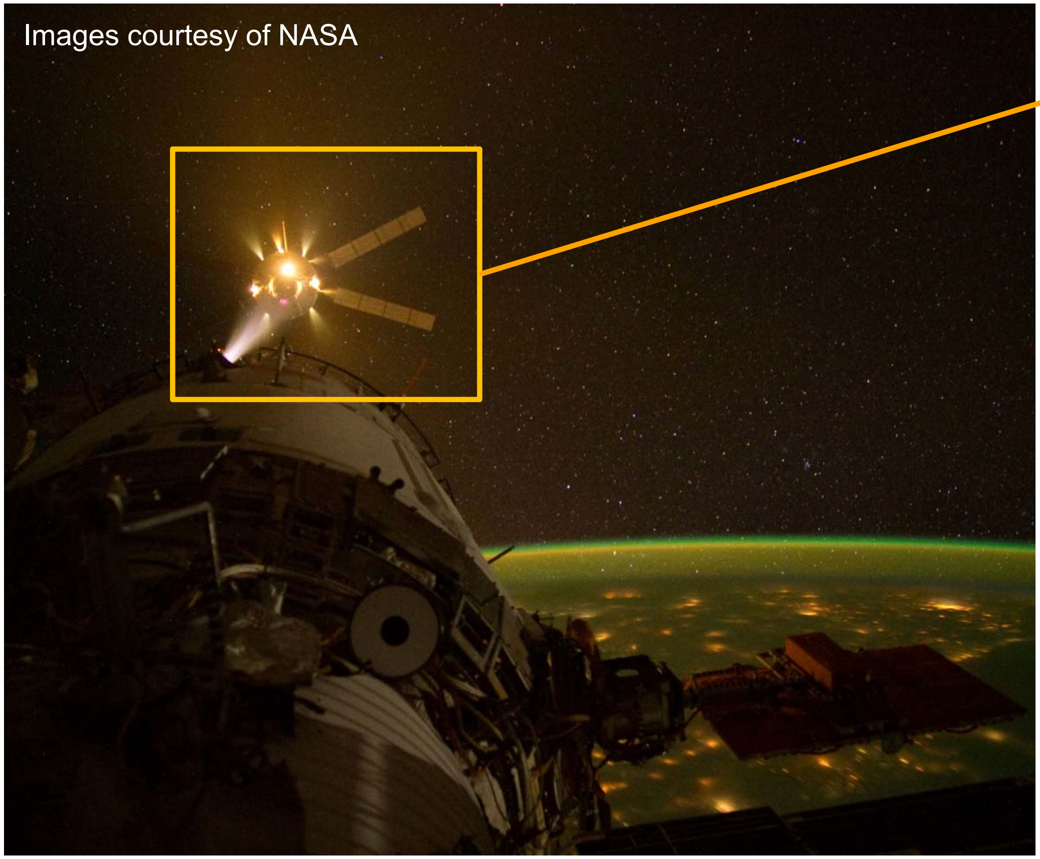

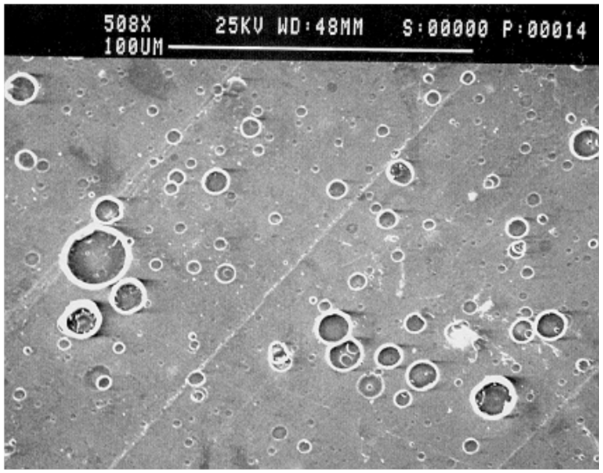

Impacts to Optically Sensitive Surfaces

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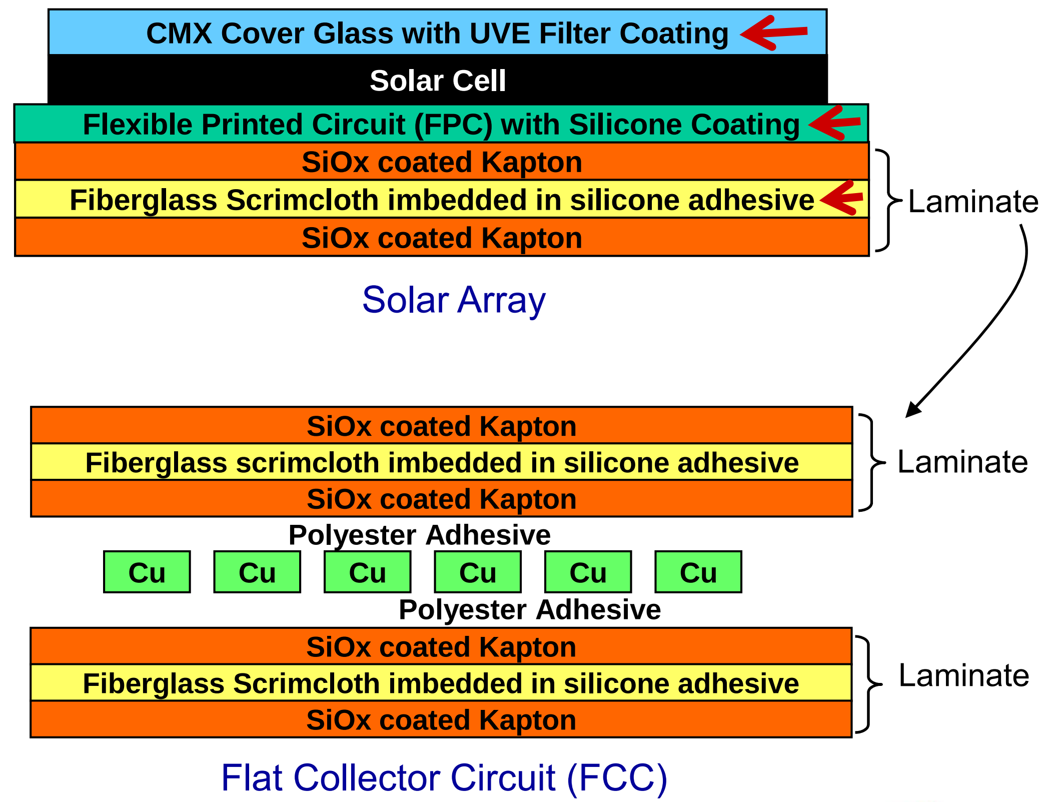
- **Thruster plume induced erosion of solar arrays**
  - Solar cell coverglass is damaged by droplet impacts. Damage impacts the performance of UVE filter coatings and increases optical scatter on the coverglass.
  - The laminates used on solar array thermal side can also be damaged. Thin silicon oxide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

Representative Solar Array Construction



Plume Induced Erosion Concerns

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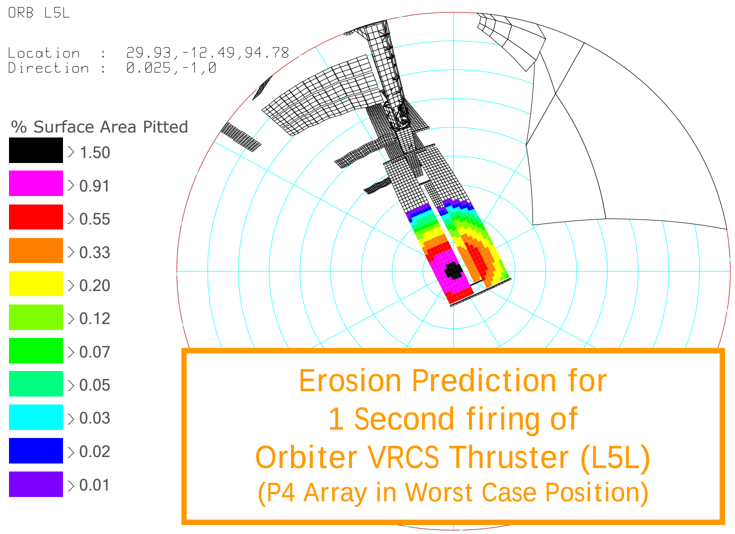
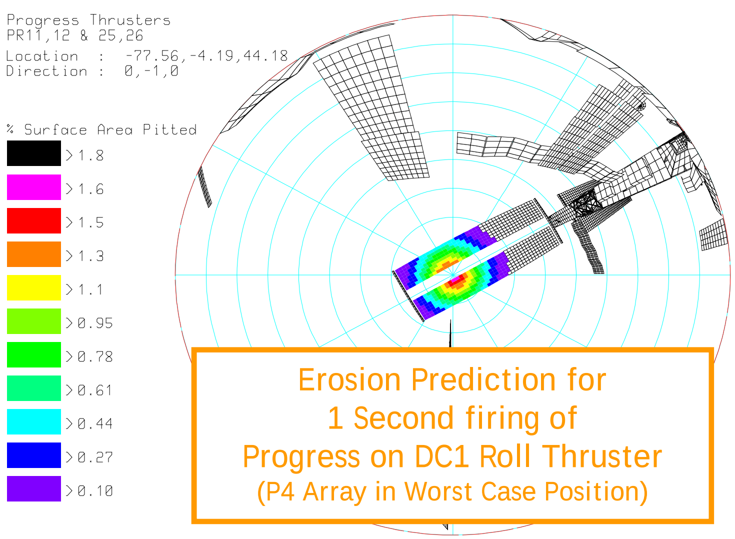


Erosion Prediction for
1 Second firing of
Orbiter VRCS Thruster (L5L)
(P4 Array in Worst Case Position)



Erosion Prediction for
1 Second firing of
Progress on DC1 Roll Thruster
(P4 Array in Worst Case Position)

- 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*

ISS Solar Array Constraints

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

2A

SARJ \ 2A	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
0	###	###	###	8131	###	2261	432	0.00	0.00	0.00	68.2	359	1050	1920	###	6111	###	###
15	###	###	1221	506	119	8.75	0.00	0.00	0.00	64.6	581	1525	###	###	7414	###	###	###
30	###	###	1812	837	100	0.00	0.00	0.00	586	3126	###	###	###	###	###	###	###	###
45	###	###	1641	265	0.00	0.00	0.00	26.4	638	1352	###	3312	###	###	###	###	###	6921
60	855	492	129	0.00	0.00	0.00	0.00	21.7	65.9	167	314	654	1144	1646	###	2241	2134	1598
75	53.3	17.2	2.28	0.00	0.00	0.00	0.00	0.98	3.43	12.4	26.4	52.4	92.9	136	167	171	142	91.2
90	1.46	0.44	0.02	0.00	0.00	0.00	0.00	0.02	0.12	0.40	1.09	1.98	3.60	4.95	5.97	5.85	4.51	3.27
105	0.19	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.21	0.43	0.90	1.50	2.08	2.25	1.86	1.16	0.59
120	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.20	0.33	0.55	0.71	0.75	0.63	0.43	0.22
135	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.13	0.18	0.22	0.24	0.21	0.15	0.08
150	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.08	0.09	0.07	0.06	0.04
165	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.02
180	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
195	0.02	0.04	0.06	0.08	0.09	0.07	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
210	0.06	0.11	0.19	0.26	0.29	0.27	0.24	0.14	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
225	0.15	0.34	0.65	0.95	1.12	1.06	0.80	0.48	0.29	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.06
240	0.39	1.03	2.01	3.19	3.83	3.54	2.56	1.57	0.72	0.35	0.08	0.00	0.00	0.00	0.00	0.00	0.03	0.16
255	0.97	2.77	5.69	9.06	9.66	9.84	6.88	3.85	1.84	0.76	0.23	0.04	0.00	0.00	0.00	0.00	0.06	0.40
270	2.19	6.01	12.2	16.4	13.6	15.3	13.2	7.21	3.34	1.28	0.42	0.08	0.00	0.00	0.00	0.00	0.15	0.91
285	55.0	105	146	163	148	110	68.8	36.0	16.4	6.91	2.03	0.61	0.00	0.00	0.00	0.00	8.59	32.5
300	906	1267	1422	1373	1129	808	516	298	155	103	43.1	0.09	0.00	0.00	0.00	55.1	261	483
315	1340	1752	2167	###	2361	2413	2125	1605	882	472	67.0	0.00	0.00	0.00	64.4	310	491	845
330	###	5816	5501	###	###	###	1192	496	157	28.4	0.00	0.00	0.00	7.02	426	1273	###	###
345	###	###	8918	###	###	2811	1691	747	54.6	0.00	0.00	0.00	751	2681	###	###	###	9781

SARJ \ 2A	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	###	###	###	###	###	2461	555	0.00	0.00	0.00	51.3	381	1104	1998	###	6313	8019	###
15	###	2410	1363	585	160	8.08	0.00	0.00	0.00	36.6	447	1276	3418	###	7410	7141	###	5651
30	###	###	1683	784	134	0.00	0.00	0.00	446	###	###	###	###	###	###	###	###	###
45	###	###	1712	334	0.00	0.00	0.00	7.22	645	1466	2177	3512	###	###	7021	7617	###	###
60	893	532	148	0.00	0.00	0.00	0.00	21.5	72.1	182	343	702	1229	1761	2173	###	2187	1587
75	58.2	20.4	3.30	0.00	0.00	0.00	0.00	1.03	3.84	13.8	29.8	57.7	101	146	176	175	141	86.5
90	1.67	0.52	0.03	0.00	0.00	0.00	0.00	0.03	0.14	0.44	1.23	2.17	3.84	5.28	6.19	5.86	4.33	3.08
105	0.23	0.07	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.23	0.47	0.96	1.55	2.09	2.17	1.72	1.02	0.50
120	0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.21	0.34	0.55	0.69	0.70	0.57	0.37	0.18
135	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.12	0.18	0.20	0.22	0.18	0.12	0.06
150	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.07	0.08	0.06	0.05	0.03
165	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.01
180	0.01	0.02	0.02	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
195	0.03	0.05	0.08	0.10	0.10	0.08	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
210	0.08	0.13	0.22	0.30	0.32	0.29	0.26	0.14	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
225	0.19	0.41	0.74	1.05	1.19	1.09	0.80	0.46	0.27	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.05
240	0.48	1.22	2.25	3.42	3.94	3.52	2.45	1.46	0.66	0.32	0.07	0.00	0.00	0.00	0.00	0.00	0.02	0.12
255	1.20	3.20	6.24	9.45	9.60	9.42	6.43	3.49	1.64	0.65	0.20	0.04	0.00	0.00	0.00	0.00	0.04	0.30
270	2.67	6.86	13.2	16.7	13.4	14.5	12.2	6.48	2.94	1.09	0.36	0.07	0.00	0.00	0.00	0.00	0.10	0.70
285	58.7	107	143	155	137	101	61.9	32.3	14.4	6.21	1.79	0.61	0.00	0.00	0.00	0.00	7.31	29.1
300	893	1214	1344	1287	1054	754	480	275	142	92.5	39.8	0.33	0.00	0.00	0.00	43.3	241	483
315	1255	1646	###	2101	###	###	1997	1528	841	486	88.7	0.00	0.00	0.00	52.0	319	538	911
330	###	###	###	4431	###	###	1288	531	200	26.4	0.00	0.00	0.00	6.77	332	1140	###	###
345	###	###	###	7144	###	###	1603	709	98.0	0.00	0.00	0.00	660	###	###	###	###	###

Interpolation_Method	Maximum	Green_Min	0.00	Yellow_Min	0.10	Red_Min	1.00

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

$$n(d,\theta)=\underbrace{\frac{D_0(T)}{S_m}}_{\text{Thruster term}}\cdot\underbrace{f_{nr}}_{\text{Range term}}\cdot\underbrace{\left(\frac{d}{d_{\min}}\right)^{-p}}_{\text{Size distribution term}}\cdot\underbrace{e^{-\frac{\theta^2}{2\cdot\sigma^2}}}_{\text{Angular distribution term}}$$

On centerline θ = 0° and term becomes unity

σ is a function of d and contains droplet limiting angle information

- 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:

Total propellant mass flow rate

Droplet number flux

$$\dot{n}(T,d,r,\theta)=\frac{\dot{M}_T\cdot\overbrace{K\cdot T^{-\beta}}^{\text{This is proportional to contaminant mass fraction (K, }\beta\text{ are constants)}}}{S_m}\cdot\overbrace{(r+l_{noz})^{-2}}^{1/r^2\text{ dependence}}\cdot\left(\frac{d}{d_{\min}}\right)^{-4.57}\cdot e^{-\frac{\theta^2}{2\cdot\sigma^2}}$$

Reference: Soares et al., “International Space Station Bipropellant Plume Contamination Model,” AIAA 2002-3016, June 2002

Plume Contamination Model

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

Contamination (e.g. g/cm²/s)

K and β are constants

$1/r^2$ dependence

On centerline θ = 0° and term becomes unity

$$\dot{m}_C(r,\theta) = \underbrace{\underbrace{KT^{-\beta}}_{\text{“Contamination Ratio”}} \cdot \frac{\dot{M}_T}{R_{exit}^2}}_{\text{Thruster term}} \cdot \underbrace{\left(\frac{r + l_{noz}}{R_{exit}}\right)^{-2}}_{\text{Range term}} \cdot \underbrace{\left(2e^{\frac{\theta}{\theta_0}} - e^{-2\frac{\theta}{\theta_0}}\right)}_{\text{Angular distribution term}}$$

- r is range (e.g. in cm)
- θ is angle off thruster plume centerline (degrees)
- 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)
- θ_0 is the “dispersion coefficient” (5 degrees)

Reference: Soares et al., “International Space Station Bipropellant Plume Contamination Model,” AIAA 2002-3016, June 2002

Flight Experiment Data
Pitsweeper Image Analysis

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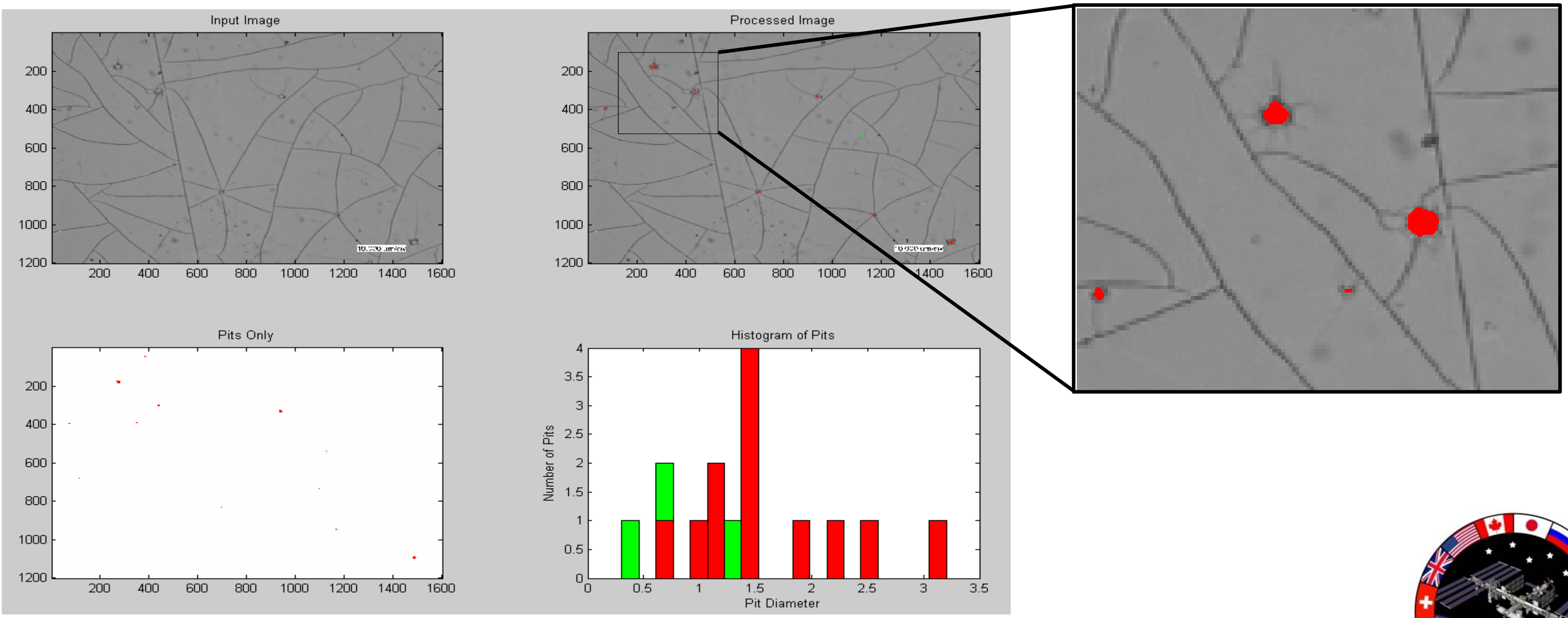
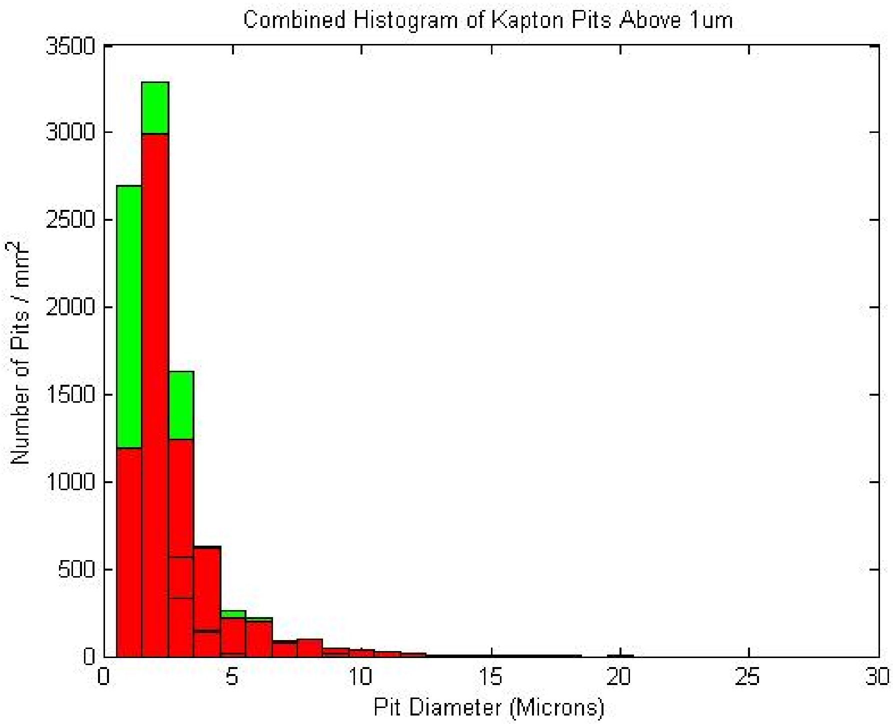
- **Individual images were loaded into Pitsweeper image analysis program**
- **Pits were identified by user and separated into two groups**
  - Pit (red bar)
  - Potential Pit (green bar)
- **Pitsweeper outputed pit size distribution**

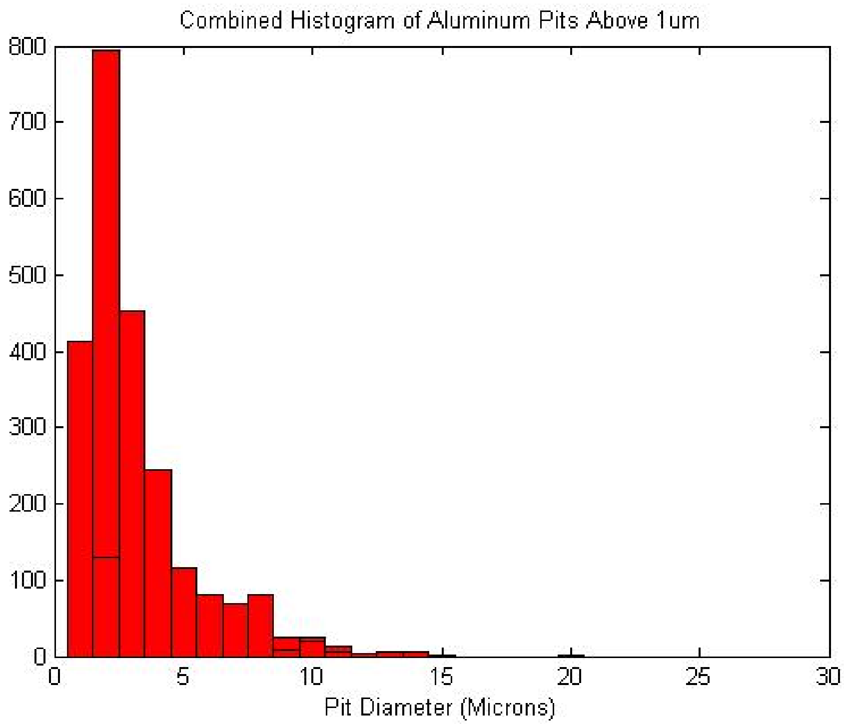


Observed Erosion of SPIFEX Samples

Kapton



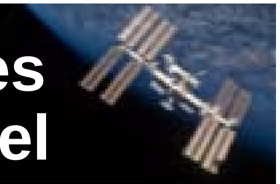
Aluminum

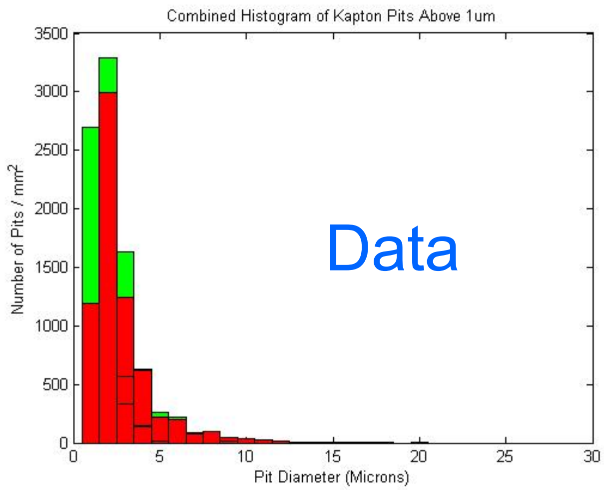


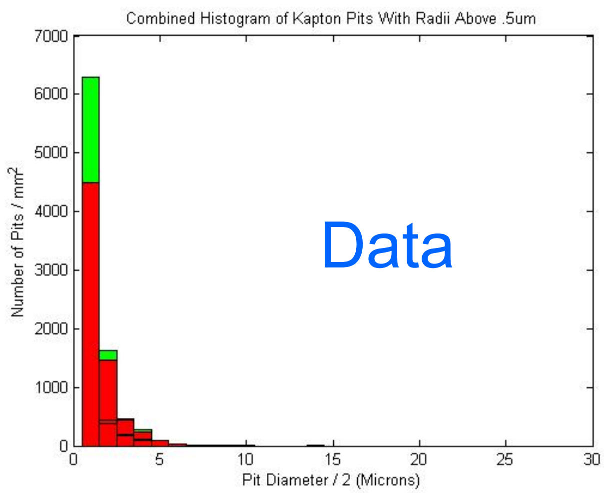
Green bars represent potential pits, or features in images of the samples suggestive of pits, but not well-resolved.

- **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

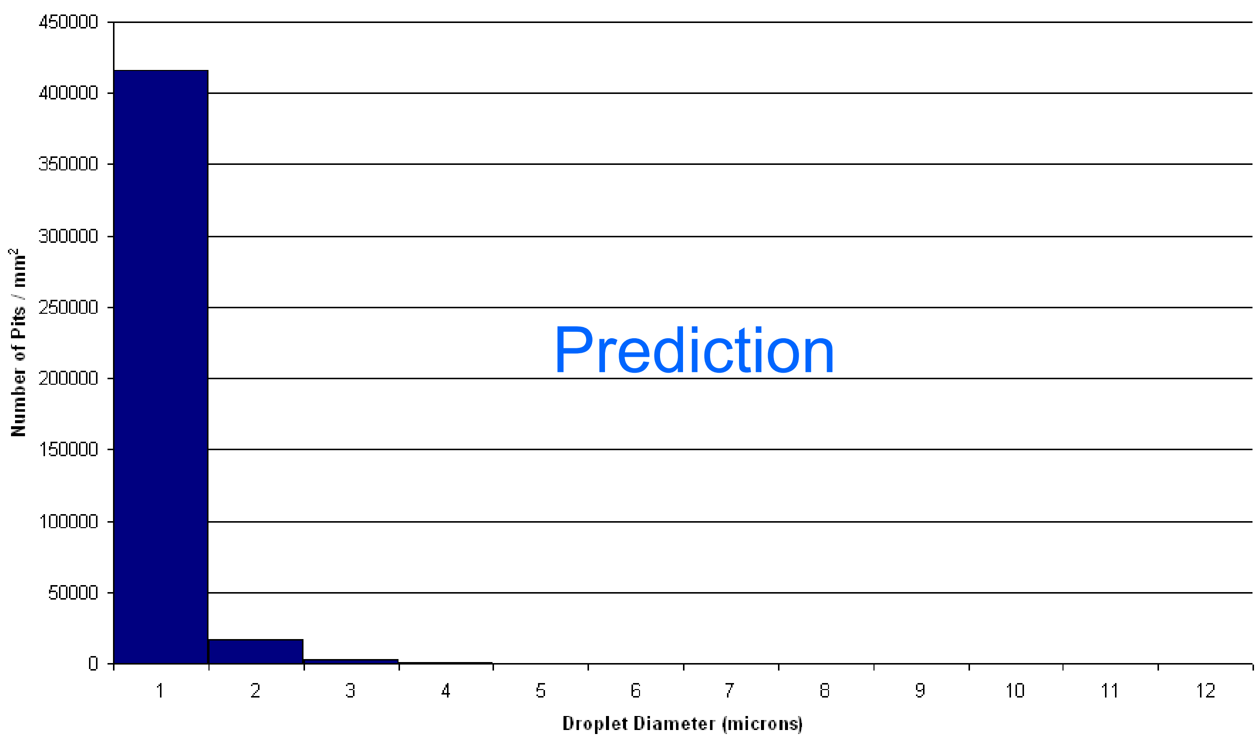






JSC 29181 model assumptions

- Droplet size distribution coefficient: p = 4.57 (controls particle size distribution)
- Maximum droplet diameter = 100 μm

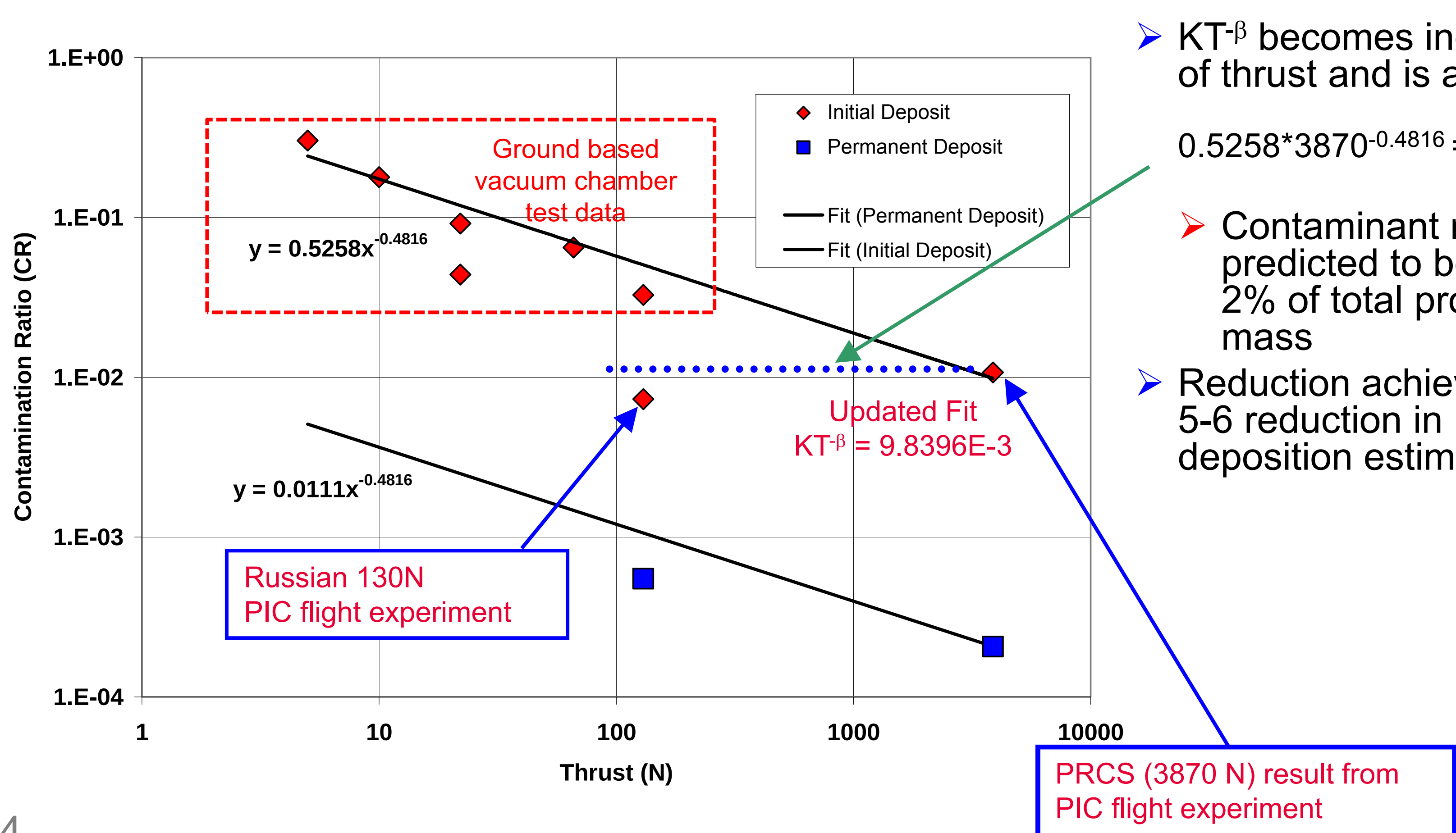


Update to Plume Erosion Model

- **JSC 29181plume 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***

Initial Contaminant Flux

- **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 .**

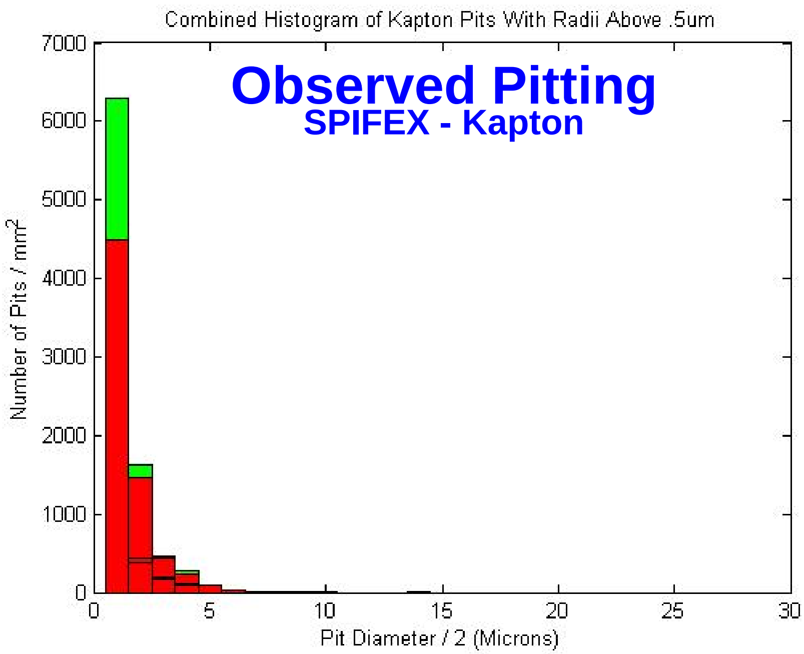


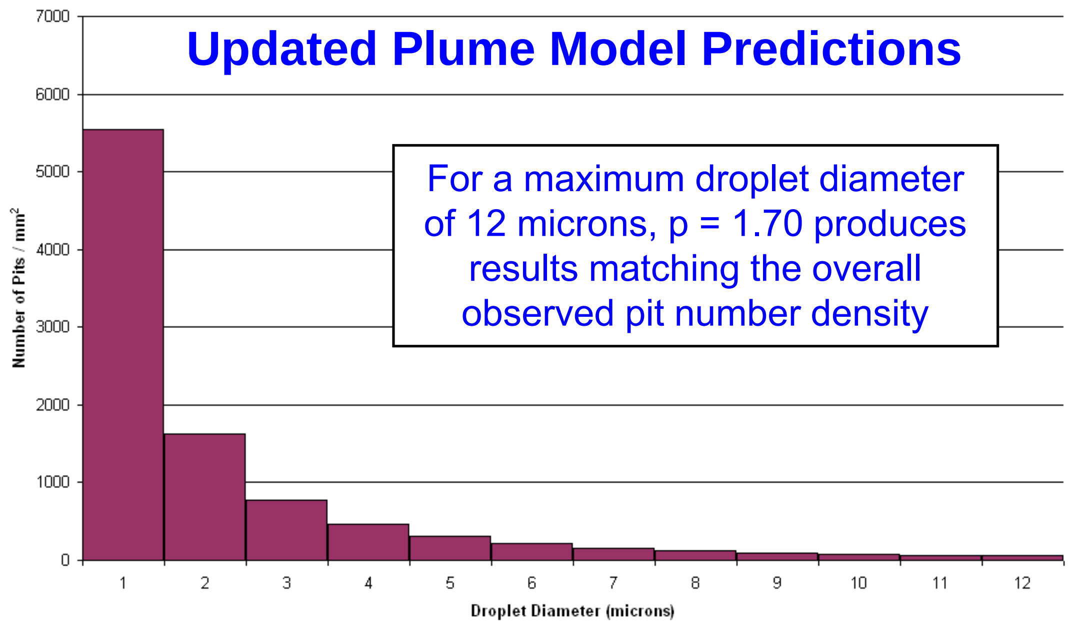
- $KT^{-\beta}$ becomes independent of thrust and is a constant:

  $0.5258*3870^{-0.4816} = 9.8396E-3$

  - Contaminant mass is predicted to be less than 2% of total propellant mass
- Reduction achieves factor of 5-6 reduction in initial deposition estimates

Comparison of SPIFEX Flight Experiment Data with Boeing Space Environments' Updated Plume Model





*

Updated Boeing Plume Model

Model assumptions/notes

- Droplet size distribution coefficient: p = 1.70
- The maximum droplet diameter is 12 µm

<u>Requires</u> 1:2 droplet-to-pit size assumption (allows pits up to 24 µm, as reported for the PIC flight experiment)

1:1 droplet-to-pit ratio did not correlate

Summary of Boeing Space Environments’ Plume Model Update

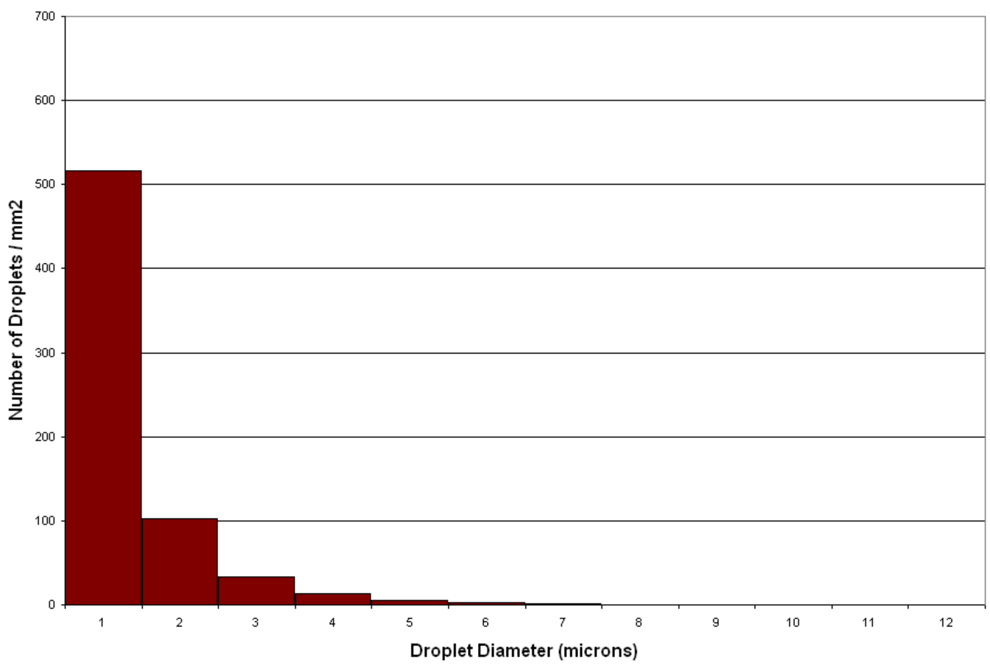
- **Simulations of SPIFEX Kapton pitting levels with the JSC 29181 plume erosion model demonstrated that model needed to be updated**
- **Boeing Space Environments’ plume model update correlates well with observed SPIFEX Kapton pitting results when:**
  - Maximum droplet diameter changed from 100 μm 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

Returned Node 1 Nadir Window Hyzod Cover

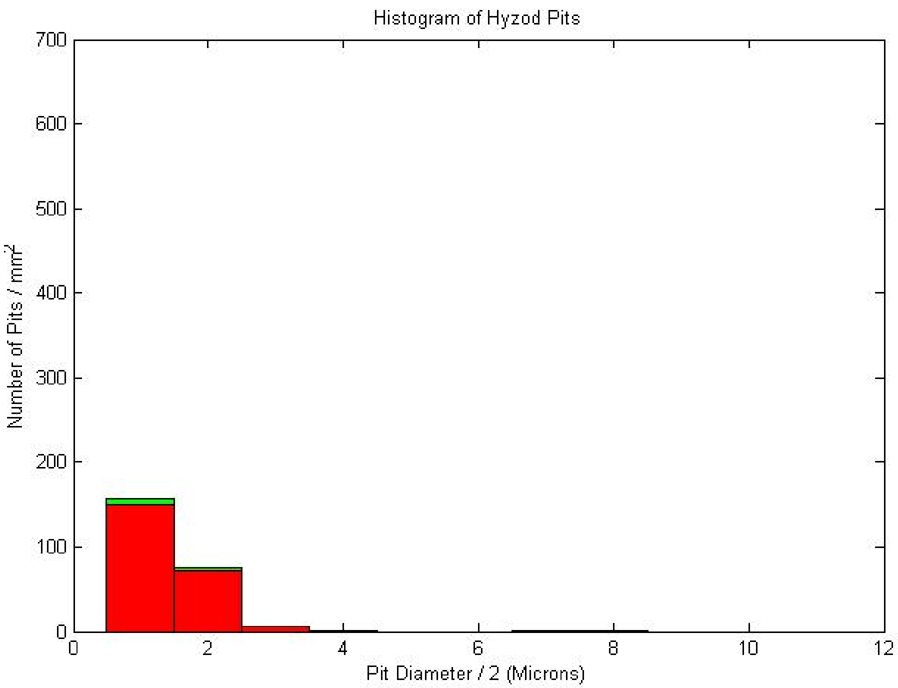
- **Node 1 nadir window Hyzod cover was deployed on ISS from Flight UF2 (June 2002) to Flight LF1 (July 2005) during which it was exposed to thruster firings for various Soyuz and Progress proximity operation events (approaches and separations of vehicles)**
- **NASA JSC Materials Evaluation Laboratory 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



Observed Pitting



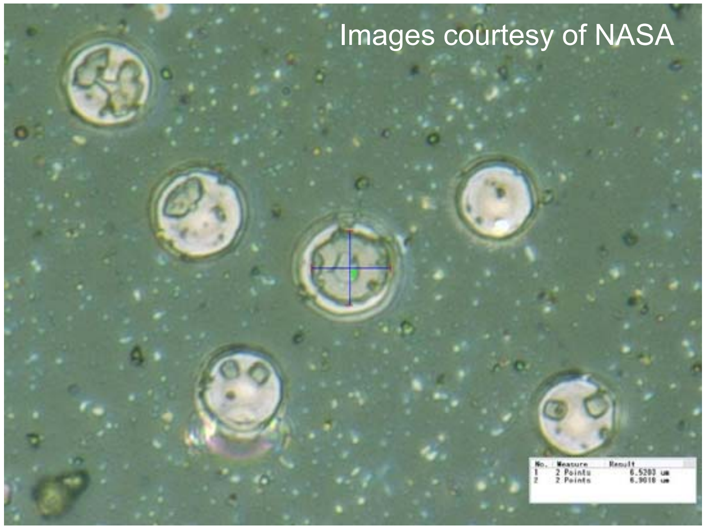
- **Hyzod, as well as aluminum, which are harder materials than Kapton, demonstrate lower pit damage than Kapton which is a softer material**

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

Summary of Ground-Based Light Gas Gun Test Results

- 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



Example Solar Cell Ground Test Image
5 micron impacting at 1.82 km/s
HITF08212 Post Test image (5000X)

Application of Methodology

Engineering, Operations & Technology | **Boeing Research & Technology**

2A

SARJ \ 2A	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	###	###	###	8131	###	2261	432	0.00	0.00	0.00	68.2	359	1050	1920	###	6111	###	###	###	###	###	###	###	2461	555	0.00	0.00	0.00	51.3	381	1104	1998	###	6313	8019	###
15	###	###	1221	506	119	8.75	0.00	0.00	0.00	64.6	581	1525	###	###	7414	###	###	###	###	2410	1363	585	160	8.08	0.00	0.00	0.00	36.6	447	1276	3418	###	7410	7141	###	5651
30	###	###	1812	837	100	0.00	0.00	0.00	586	3126	###	###	###	###	###	###	###	###	###	###	1683	784	134	0.00	0.00	0.00	446	###	###	###	###	###	###	###	###	###
45	###	###	1641	265	0.00	0.00	0.00	26.4	638	1352	###	3312	###	###	###	###	###	6921	###	###	1712	334	0.00	0.00	0.00	7.22	645	1466	2177	3512	###	###	7021	7617	###	###
60	855	492	129	0.00	0.00	0.00	0.00	21.7	65.9	167	314	654	1144	1646	###	2241	2134	1598	893	532	148	0.00	0.00	0.00	0.00	21.5	72.1	182	343	702	1229	1761	2173	###	2187	1587
75	53.3	17.2	2.28	0.00	0.00	0.00	0.00	0.98	3.43	12.4	26.4	52.4	92.9	136	167	171	142	91.2	58.2	20.4	3.30	0.00	0.00	0.00	0.00	1.03	3.84	13.8	29.8	57.7	101	146	176	175	141	86.5
90	1.46	0.44	0.02	0.00	0.00	0.00	0.00	0.02	0.12	0.40	1.09	1.98	3.60	4.95	5.97	5.85	4.51	3.27	1.67	0.52	0.03	0.00	0.00	0.00	0.00	0.03	0.14	0.44	1.23	2.17	3.84	5.28	6.19	5.86	4.33	3.08
105	0.19	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.21	0.43	0.90	1.50	2.08	2.25	1.86	1.16	0.59	0.23	0.07	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.23	0.47	0.96	1.55	2.09	2.17	1.72	1.02	0.50
120	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.20	0.33	0.55	0.71	0.75	0.63	0.43	0.22	0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.21	0.34	0.55	0.69	0.70	0.57	0.37	0.18
135	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.13	0.18	0.22	0.24	0.21	0.15	0.08	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.12	0.18	0.20	0.22	0.18	0.12	0.06
150	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.08	0.09	0.07	0.06	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.07	0.08	0.06	0.05	0.03
165	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.01
180	0.01	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
195	0.02	0.04	0.06	0.08	0.09	0.07	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.08	0.10	0.10	0.08	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
210	0.06	0.11	0.19	0.26	0.29	0.27	0.24	0.14	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.13	0.22	0.30	0.32	0.29	0.26	0.14	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
225	0.15	0.34	0.65	0.95	1.12	1.06	0.80	0.48	0.29	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.19	0.41	0.74	1.05	1.19	1.09	0.80	0.46	0.27	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.05
240	0.39	1.03	2.01	3.19	3.83	3.54	2.56	1.57	0.72	0.35	0.08	0.00	0.00	0.00	0.00	0.00	0.03	0.16	0.48	1.22	2.25	3.42	3.94	3.52	2.45	1.46	0.66	0.32	0.07	0.00	0.00	0.00	0.00	0.00	0.02	0.12
255	0.97	2.77	5.69	9.06	9.66	9.84	6.88	3.85	1.84	0.76	0.23	0.04	0.00	0.00	0.00	0.00	0.06	0.40	1.20	3.20	6.24	9.45	9.60	9.42	6.43	3.49	1.64	0.65	0.20	0.04	0.00	0.00	0.00	0.00	0.04	0.30
270	2.19	6.01	12.2	16.4	13.6	15.3	13.2	7.21	3.34	1.28	0.42	0.08	0.00	0.00	0.00	0.00	0.15	0.91	2.67	6.86	13.2	16.7	13.4	14.5	12.2	6.48	2.94	1.09	0.36	0.07	0.00	0.00	0.00	0.00	0.10	0.70
285	55.0	105	146	163	148	110	68.8	36.0	16.4	6.91	2.03	0.61	0.00	0.00	0.00	0.00	8.59	32.5	58.7	107	143	155	137	101	61.9	32.3	14.4	6.21	1.79	0.61	0.00	0.00	0.00	0.00	7.31	29.1
300	906	1267	1422	1373	1129	808	516	298	155	103	43.1	0.09	0.00	0.00	0.00	55.1	261	483	893	1214	1344	1287	1054	754	480	275	142	92.5	39.8	0.33	0.00	0.00	0.00	43.3	241	483
315	1340	1752	2167	###	2361	2413	2125	1605	882	472	67.0	0.00	0.00	0.00	64.4	310	491	845	1255	1646	###	2101	###	###	1997	1528	841	486	88.7	0.00	0.00	0.00	52.0	319	538	911
330	###	5816	5501	###	###	###	1192	496	157	28.4	0.00	0.00	0.00	7.02	426	1273	###	###	###	###	###	4431	###	###	1288	531	200	26.4	0.00	0.00	0.00	6.77	332	1140	###	###
345	###	###	8918	###	###	2811	1691	747	54.6	0.00	0.00	0.00	751	2681	###	###	###	9781	###	###	###	7144	###	###	1603	709	98.0	0.00	0.00	0.00	660	###	###	###	###	###

Interpolation_Method	Maximum	Green_Min	0.00	Yellow_Min	0.10	Red_Min	1.00

JSC 29181 Plume Model

2A

SARJ \ 2A	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	1381	1336	1234	1006	607	284	46.5	0.00	0.00	0.00	2.13	25.3	104	264	451	729	961	1157	1339	1298	1198	994	636	329	66.8	0.00	0.00	0.00	1.80	27.1	109	277	469	749	985	1190
15	88.6	71.4	35.2	13.1	2.92	0.07	0.00	0.00	0.00	0.99	11.1	29.2	76.9	109	124	147	118	103	92.6	78.6	42.3	16.5	4.24	0.07	0.00	0.00	0.00	0.52	8.05	23.2	66.4	101	121	151	126	103
30	212	106	61.2	23.0	2.89	0.00	0.00	0.00	30.7	175	317	540	616	584	590	480	383	316	198	98.6	56.0	20.7	3.59	0.00	0.00	0.00	22.2	158	309	551	651	623	629	511	409	337
45	212	138	77.8	12.3	0.00	0.00	0.00	0.74	20.0	37.2	54.1	88.2	128	144	160	180	203	231	199	131	80.0	15.6	0.00	0.00	0.00	0.13	21.5	41.7	59.5	95.8	139	156	174	196	222	252
60	18.6	11.1	2.73	0.00	0.00	0.00	0.00	0.28	0.97	2.72	5.14	11.1	20.2	27.7	33.9	39.7	43.9	34.1	19.6	12.1	3.28	0.00	0.00	0.00	0.00	0.29	1.09	3.04	5.78	12.2	22.3	30.6	36.9	42.3	45.7	33.9
75	0.56	0.20	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.11	0.23	0.48	0.88	1.34	1.69	1.77	1.50	0.97	0.62	0.24	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.13	0.27	0.54	0.98	1.46	1.80	1.82	1.48	0.91
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.03	0.03	0.02	0.01
105	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
120	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
135	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
165	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
180	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
195	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
210	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
225	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
240	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
255	0.00	0.01	0.02	0.04	0.04	0.04	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.04	0.04	0.04	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
270	0.01	0.03	0.06	0.08	0.09	0.08	0.06	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.07	0.08	0.09	0.08	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
285	0.50	0.95	1.31	1.26	1.09	0.85	0.55	0.28	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.08	0.32	0.54	0.97	1.26	1.18	0.99	0.76	0.49	0.24	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.07	0.28
300	13.6	17.2	15.5	13.4	11.2	9.01	6.39	3.51	1.79	1.17	0.58	0.00	0.00	0.00	0.00	0.86	4.56	7.53	13.3	16.2	14.4	12.3	10.2	8.20	5.85	3.19	1.60	1.02	0.52	0.00	0.00	0.00	0.00	0.66	4.20	7.53
315	19.2	20.5	21.8	25.5	26.3	26.2	28.6	25.9	15.3	9.46	1.24	0.00	0.00	0.00	1.06	5.27	7.16	11.8	17.5	19.2	20.3	23.8	24.6	24.3	26.4	24.2	14.4	9.58	1.64	0.00	0.00	0.00	0.88	5.62	7.98	12.8
330	324	387	362	280	207	118	50.4	22.7	5.34	0.48	0.00	0.00	0.00	0.19	18.1	65.2	159	272	336	383	344	257	185	103	43.5	19.3	4.67	0.44	0.00	0.00	0.00	0.05	12.7	52.3	136	250
345	1379	1297	1100	890	613	366	193	56.6	3.56	0.00	0.00	0.00	108	371	561	840	1075	1220	1339	1260	1065	861	590	354	185	53.9	5.81	0.00	0.00	0.00	95.6	374	591	870	1107	1259

Interpolation_Method	Maximum	Green_Min	0.00	Yellow_Min	0.10	Red_Min	1.00

Service Module
Roll/Pitch/Yaw Attitude Control
Port Inboard SAW

Boeing Space Environments Updated Plume Model

Application of Methodology (concluded)

Engineering, Operations & Technology | **Boeing Research & Technology**

2A

SARJ \ 2A	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	###	###	###	8131	###	2261	432	4.68	7.61	9.93	68.2	359	1050	1920	###	6111	###	###	###	###	###	###	###	2461	555	4.56	7.49	9.87	51.3	381	1104	1998	###	6313	8019	###
15	###	###	1221	506	119	8.75	2.16	4.32	7.37	64.6	581	1525	###	###	7414	###	###	###	###	2410	1363	585	160	8.08	2.07	4.17	7.19	36.6	447	1276	3418	###	7410	7141	###	5651
30	###	###	1812	837	100	0.48	1.57	2.95	586	3126	###	###	###	###	###	###	###	###	###	###	1683	784	134	0.44	1.49	2.82	446	###	###	###	###	###	###	###	###	###
45	###	###	1641	265	0.00	0.09	0.62	26.4	638	1352	###	3312	###	###	###	###	###	6921	###	###	1712	334	0.00	0.08	0.57	7.22	645	1466	2177	3512	###	###	7021	7617	###	###
60	855	492	129	0.00	0.00	0.00	0.00	21.7	65.9	167	314	654	1144	1646	###	2241	2134	1598	893	532	148	0.00	0.00	0.00	0.00	21.5	72.1	182	343	702	1229	1761	2173	###	2187	1587
75	53.3	17.2	2.28	0.00	0.00	0.00	0.00	0.98	3.43	12.4	26.4	52.4	92.9	136	167	171	142	91.2	58.2	20.4	3.30	0.00	0.00	0.00	0.00	1.03	3.84	13.8	29.8	57.7	101	146	176	175	141	86.5
90	1.46	0.44	0.04	0.01	0.00	0.00	0.00	0.02	0.12	0.40	1.09	1.98	3.60	4.95	5.97	5.85	4.51	3.27	1.67	0.52	0.04	0.01	0.00	0.00	0.00	0.03	0.14	0.44	1.23	2.17	3.84	5.28	6.19	5.86	4.33	3.08
105	0.19	0.16	0.18	0.17	0.10	0.01	0.00	0.01	0.05	0.21	0.43	0.90	1.50	2.08	2.25	1.86	1.16	0.59	0.23	0.16	0.18	0.17	0.11	0.02	0.00	0.01	0.06	0.23	0.47	0.96	1.55	2.09	2.17	1.72	1.02	0.50
120	0.23	0.30	0.53	0.79	0.96	0.99	0.92	0.73	0.41	0.13	0.20	0.33	0.55	0.71	0.75	0.63	0.43	0.22	0.24	0.30	0.52	0.77	0.95	0.99	0.92	0.75	0.43	0.14	0.21	0.34	0.55	0.69	0.70	0.57	0.37	0.18
135	0.44	0.63	1.08	1.84	2.62	3.17	3.44	3.34	2.89	2.13	1.27	0.55	0.18	0.22	0.24	0.21	0.24	0.34	0.45	0.63	1.05	1.80	2.57	3.12	3.40	3.33	2.92	2.18	1.31	0.57	0.18	0.20	0.22	0.18	0.21	0.32
150	0.87	1.23	1.70	2.96	4.22	5.88	7.12	7.42	6.69	5.27	3.73	2.38	1.09	0.27	0.10	0.24	0.44	0.67	0.87	1.20	1.63	2.88	4.12	5.79	7.05	7.40	6.72	5.33	3.80	2.45	1.13	0.29	0.08	0.20	0.39	0.63
165	1.56	2.15	2.78	3.93	6.71	9.91	11.8	12.5	12.0	10.3	7.37	4.38	2.39	0.86	0.11	0.38	0.68	1.15	1.56	2.10	2.67	3.82	6.57	9.72	11.6	12.4	12.0	10.3	7.49	4.49	2.46	0.91	0.11	0.33	0.62	1.09
180	3.85	5.01	5.74	5.83	8.49	12.0	14.4	15.2	14.9	13.1	10.1	6.26	3.17	1.38	0.24	0.80	1.74	2.67	3.90	4.94	5.55	5.58	8.30	11.7	14.1	15.1	14.9	13.2	10.3	6.41	3.28	1.44	0.26	0.68	1.60	2.54
195	10.4	13.4	14.7	14.0	12.5	12.2	14.2	15.1	15.2	13.5	10.4	6.47	3.24	1.44	0.32	1.87	4.67	6.93	10.5	13.3	14.3	13.5	12.0	12.0	14.0	15.0	15.1	13.5	10.6	6.63	3.35	1.51	0.28	1.64	4.39	6.67
210	21.0	26.6	28.8	27.6	24.4	19.6	15.2	14.1	13.5	11.4	8.33	4.74	2.61	1.00	0.55	3.84	9.24	13.8	20.8	26.2	28.3	27.1	23.8	19.1	14.7	13.7	13.3	11.4	8.48	4.87	2.70	1.05	0.40	3.52	9.02	13.7
225	24.0	31.8	35.8	37.5	36.7	34.2	29.3	22.6	17.2	10.2	4.50	2.81	1.40	0.40	1.00	5.04	9.94	15.4	23.5	31.2	35.2	36.8	35.9	33.4	28.6	22.1	16.9	10.3	4.65	2.89	1.46	0.42	0.84	4.96	10.2	15.7
240	24.0	34.6	42.0	47.3	49.2	48.3	42.2	28.3	17.1	9.68	3.65	0.93	0.32	0.00	1.04	3.66	7.99	13.3	23.5	33.9	41.2	46.4	48.2	47.3	41.8	28.5	17.5	9.80	3.81	0.96	0.34	0.00	1.06	3.78	8.12	13.6
255	23.2	33.0	41.3	45.6	47.1	44.6	36.6	23.1	11.5	3.98	0.40	0.04	0.00	0.03	0.63	2.46	6.41	11.9	22.4	32.0	40.3	44.7	46.4	44.3	36.9	24.0	12.1	4.62	0.48	0.04	0.00	0.01	0.66	2.54	6.66	12.3
270	12.1	17.0	19.1	19.7	19.0	15.3	13.2	7.21	3.34	1.28	0.42	0.08	0.00	0.05	0.35	1.36	2.90	6.61	11.3	16.2	18.5	19.5	19.3	14.6	12.2	6.48	2.94	1.09	0.36	0.07	0.00	0.05	0.39	1.50	3.13	7.13
285	55.0	105	146	163	148	110	68.8	36.0	16.4	6.91	2.03	0.61	0.07	0.11	0.23	0.51	8.59	32.5	58.7	107	143	155	137	101	61.9	32.3	14.4	6.21	1.79	0.61	0.07	0.11	0.25	0.57	7.31	29.1
300	906	1267	1422	1373	1129	808	516	298	155	103	43.1	0.81	0.98	1.37	2.60	55.1	261	483	893	1214	1344	1287	1054	754	480	275	142	92.5	39.8	0.81	1.00	1.19	2.41	43.3	241	483
315	1340	1752	2167	###	2361	2413	2125	1605	882	472	67.0	10.4	20.7	33.9	64.4	310	491	845	1255	1646	###	2101	###	###	1997	1528	841	486	88.7	9.49	19.6	33.5	52.0	319	538	911
330	###	5816	5501	###	###	###	1192	496	157	28.4	9.85	20.2	31.1	41.7	426	1273	###	###	###	###	###	4431	###	###	1288	531	200	26.4	9.66	20.6	32.3	43.8	332	1140	###	###
345	###	###	8918	###	###	2811	1691	747	54.6	8.21	9.41	9.65	751	2681	###	###	###	9781	###	###	###	7144	###	###	1603	709	98.0	8.22	9.50	9.81	660	###	###	###	###	###

Interpolation_Method	Maximum	Green_Min	0.00	Yellow_Min	0.10	Red_Min	1.00

JSC 29181 Plume Model

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

2A

SARJ \ 2A	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
0	1381	1336	1234	1006	607	284	46.5	0.21	0.31	0.36	2.13	25.3	104	264	451	729	961	1157	1339	1298	1198	994	636	329	66.8	0.20	0.30	0.35	1.80	27.1	109	277	469	749	985	1190
15	88.6	71.4	35.2	13.1	2.92	0.07	0.10	0.19	0.31	0.99	11.1	29.2	76.9	109	124	147	118	103	92.6	78.6	42.3	16.5	4.24	0.07	0.09	0.18	0.29	0.52	8.05	23.2	66.4	101	121	151	126	103
30	212	106	61.2	23.0	2.89	0.02	0.07	0.14	30.7	175	317	540	616	584	590	480	383	316	198	98.6	56.0	20.7	3.59	0.02	0.07	0.13	22.2	158	309	551	651	623	629	511	409	337
45	212	138	77.8	12.3	0.00	0.00	0.03	0.74	20.0	37.2	54.1	88.2	128	144	160	180	203	231	199	131	80.0	15.6	0.00	0.00	0.02	0.13	21.5	41.7	59.5	95.8	139	156	174	196	222	252
60	18.6	11.1	2.73	0.00	0.00	0.00	0.00	0.28	0.97	2.72	5.14	11.1	20.2	27.7	33.9	39.7	43.9	34.1	19.6	12.1	3.28	0.00	0.00	0.00	0.00	0.29	1.09	3.04	5.78	12.2	22.3	30.6	36.9	42.3	45.7	33.9
75	0.56	0.20	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.11	0.23	0.48	0.88	1.34	1.69	1.77	1.50	0.97	0.62	0.24	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.13	0.27	0.54	0.98	1.46	1.80	1.82	1.48	0.91
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.03	0.03	0.02	0.01
105	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
120	0.00	0.00	0.02	0.04	0.05	0.06	0.06	0.05	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.05	0.06	0.06	0.05	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
135	0.00	0.01	0.06	0.11	0.18	0.23	0.27	0.27	0.24	0.18	0.11	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.10	0.17	0.23	0.26	0.27	0.24	0.19	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.00
150	0.01	0.03	0.09	0.20	0.31	0.41	0.51	0.55	0.52	0.44	0.34	0.23	0.10	0.03	0.00	0.00	0.00	0.00	0.01	0.03	0.09	0.20	0.30	0.40	0.50	0.54	0.52	0.45	0.35	0.24	0.11	0.03	0.00	0.00	0.00	0.00
165	0.02	0.05	0.13	0.27	0.44	0.65	0.81	0.88	0.87	0.78	0.60	0.39	0.23	0.08	0.01	0.00	0.01	0.01	0.02	0.05	0.12	0.26	0.43	0.63	0.79	0.87	0.87	0.78	0.61	0.40	0.24	0.09	0.01	0.00	0.00	0.01
180	0.10	0.15	0.20	0.30	0.54	0.76	0.92	1.08	1.10	0.95	0.77	0.52	0.29	0.13	0.02	0.02	0.04	0.07	0.11	0.15	0.19	0.29	0.52	0.74	0.90	1.07	1.10	0.96	0.79	0.54	0.30	0.14	0.03	0.01	0.04	0.06
195	0.65	0.83	0.90	0.83	0.70	0.75	0.94	1.19	1.18	0.95	0.78	0.53	0.29	0.14	0.03	0.10	0.29	0.45	0.67	0.83	0.88	0.79	0.65	0.73	0.92	1.17	1.18	0.96	0.79	0.54	0.30	0.14	0.03	0.09	0.25	0.45
210	2.16	2.57	2.68	2.49	2.12	1.61	1.14	0.91	0.87	0.79	0.63	0.40	0.23	0.09	0.05	0.41	1.08	1.56	2.13	2.52	2.62	2.44	2.07	1.57	1.10	0.88	0.86	0.80	0.64	0.41	0.24	0.10	0.03	0.36	1.03	1.54
225	2.31	2.98	3.25	3.29	3.11	2.77	2.27	1.66	1.22	0.77	0.35	0.24	0.12	0.03	0.10	0.48	1.07	1.56	2.27	2.89	3.17	3.24	3.07	2.67	2.18	1.59	1.17	0.76	0.37	0.25	0.13	0.04	0.09	0.50	1.11	1.59
240	2.32	3.25	3.90	4.39	4.53	4.31	3.82	2.78	1.78	0.69	0.29	0.06	0.02	0.00	0.04	0.27	0.79	1.36	2.26	3.18	3.82	4.30	4.44	4.20	3.73	2.77	1.84	0.75	0.29	0.07	0.02	0.00	0.05	0.28	0.82	1.40
255	1.96	2.88	3.61	4.49	4.75	4.11	3.42	2.24	1.16	0.33	0.01	0.00	0.00	0.00	0.02	0.15	0.54	1.04	1.89	2.79	3.52	4.39	4.66	4.07	3.45	2.36	1.28	0.42	0.02	0.00	0.00	0.00	0.02	0.16	0.58	1.09
270	0.31	0.40	0.57	0.61	0.43	0.35	0.18	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.16	0.27	0.36	0.54	0.61	0.46	0.38	0.22	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.19
285	0.50	0.95	1.31	1.26	1.09	0.85	0.55	0.28	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.08	0.32	0.54	0.97	1.26	1.18	0.99	0.76	0.49	0.24	0.10	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.07	0.28
300	13.6	17.2	15.5	13.4	11.2	9.01	6.39	3.51	1.79	1.17	0.58	0.03	0.04	0.03	0.02	0.86	4.56	7.53	13.3	16.2	14.4	12.3	10.2	8.20	5.85	3.19	1.60	1.02	0.52	0.03	0.04	0.03	0.03	0.66	4.20	7.53
315	19.2	20.5	21.8	25.5	26.3	26.2	28.6	25.9	15.3	9.46	1.24	0.11	0.12	0.20	1.06	5.27	7.16	11.8	17.5	19.2	20.3	23.8	24.6	24.3	26.4	24.2	14.4	9.58	1.64	0.11	0.11	0.19	0.88	5.62	7.98	12.8
330	324	387	362	280	207	118	50.4	22.7	5.34	0.48	0.24	0.47	0.70	0.91	18.1	65.2	159	272	336	383	344	257	185	103	43.5	19.3	4.67	0.44	0.25	0.46	0.73	0.98	12.7	52.3	136	250
345	1379	1297	1100	890	613	366	193	56.6	3.56	0.31	0.32	0.30	108	371	561	840	1075	1220	1339	1260	1065	861	590	354	185	53.9	5.81	0.32	0.33	0.31	95.6	374	591	870	1107	1259

Interpolation_Method	Maximum	Green_Min	0.00	Yellow_Min	0.10	Red_Min	1.00

Boeing Space Environments Updated Plume Model

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 successful 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

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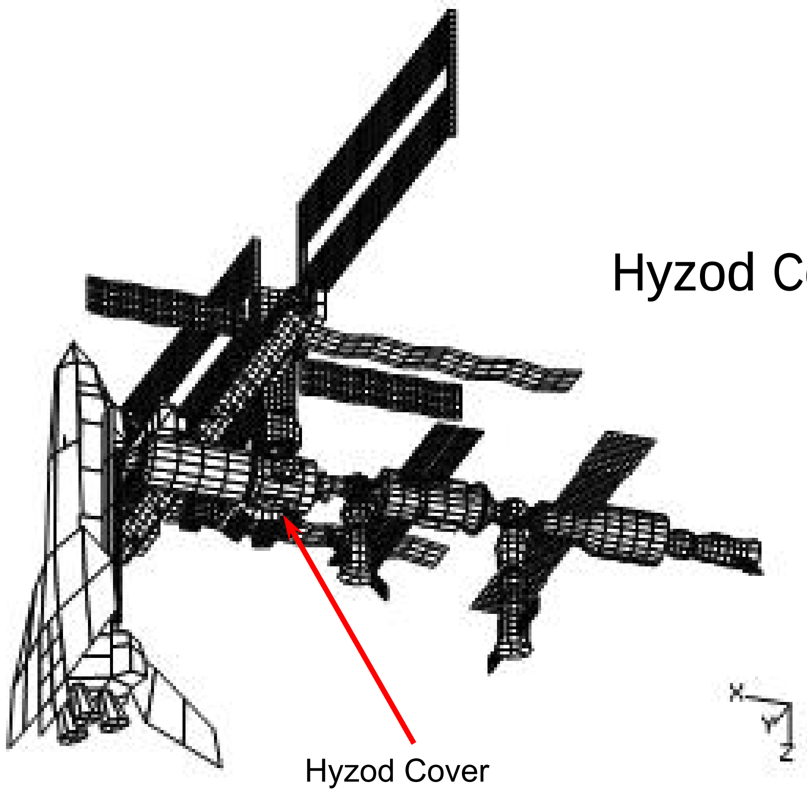
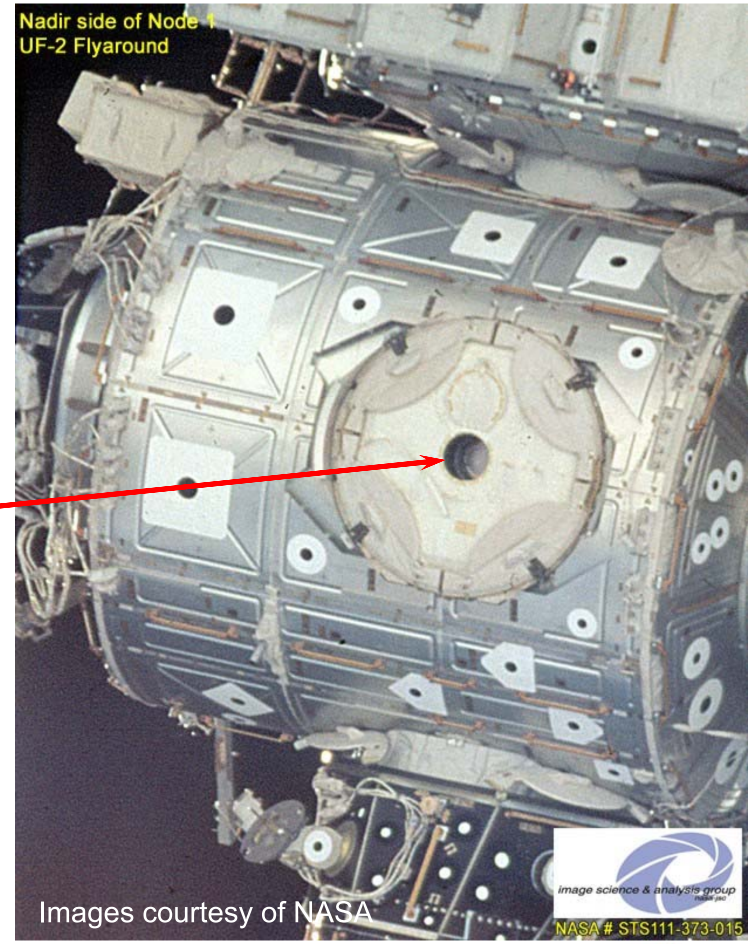
- Node 1 nadir window cover
- Exposed from June 2002 (STS-111/UF2) to July 2005 (STS-114/LF1)



Hyzod Cover



Hyzod Exposures to Thruster Plumes

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

Thruster	Docking Port	Number of Approaches	Number of Separations
Orbiter	PMA2	3	3
Soyuz*	FGB	4	4
Soyuz	DC1	4	4
Progress	DC1	1	1
Progress	SM Aft	10	10

* Expected to be the dominant source of plume effects

Example Hyzod Image (1000x Magnification)

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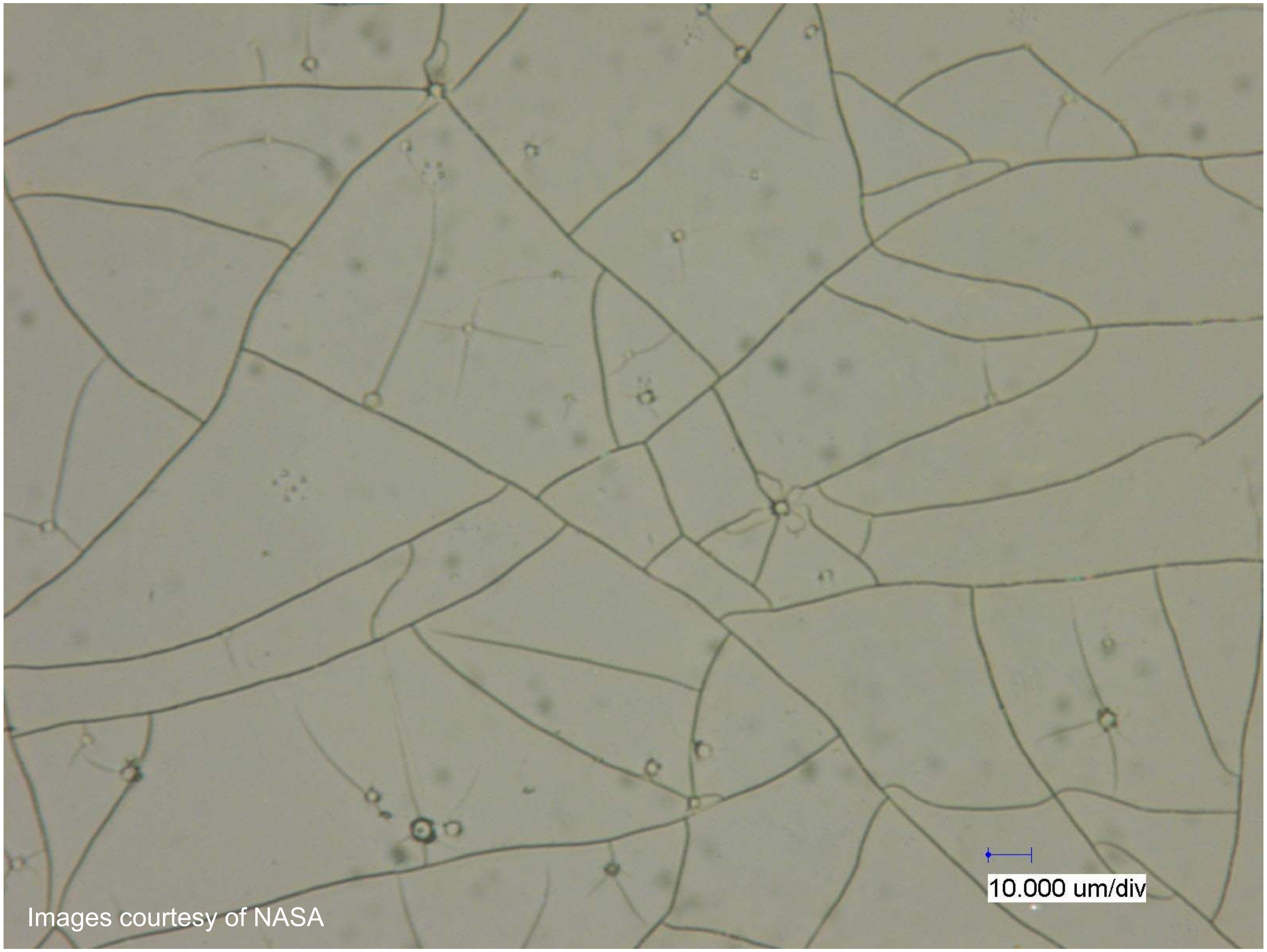

Summary of Hyzod Image Analysis Results

- **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

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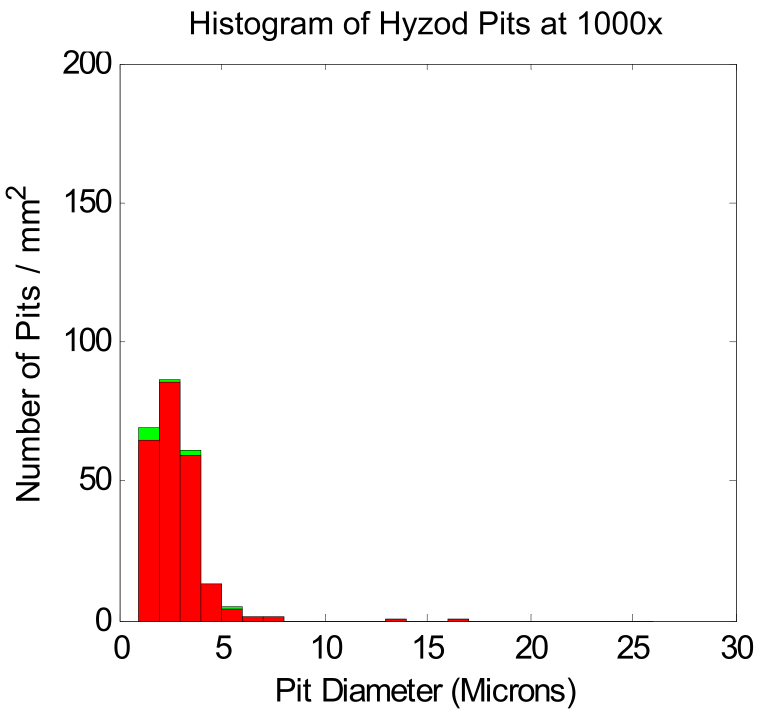
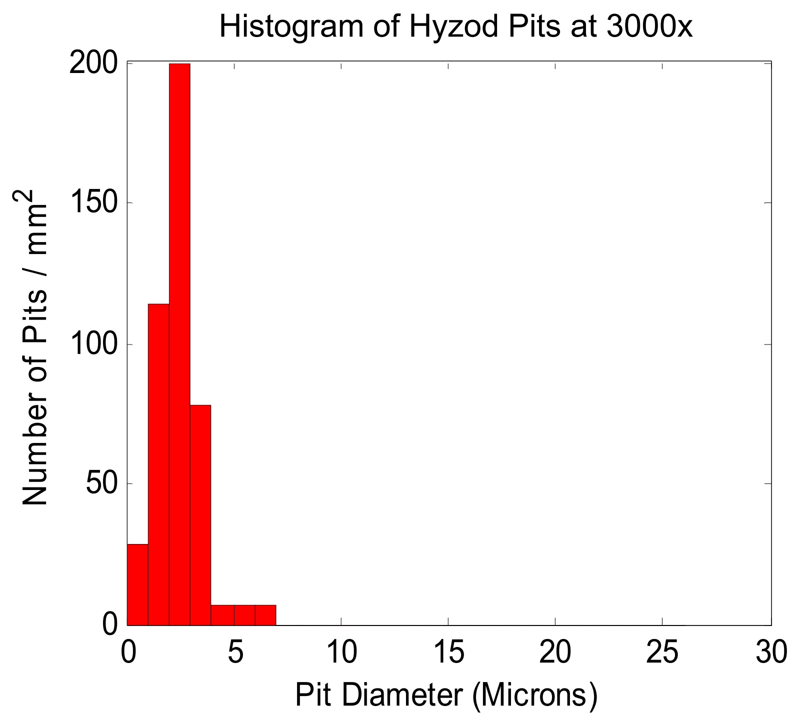
90 Images
5.7 mm^2

20 Images
0.2 mm^2





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 Excluding Potential Pits (pits / mm^2)	Approximate Pit Number Density Including Potential Pits (pits / mm^2)
1000x	230	240
3000x	410	410

Note: Pit density rounded to the nearest multiple of ten pits / mm^2

Magnification	Approximate % Total Area Pitted Excluding Potential Pits	Approximate % Total Area Pitted Including Potential Pits
1000x	0.16 %	0.16 %
3000x	0.24%	0.24%

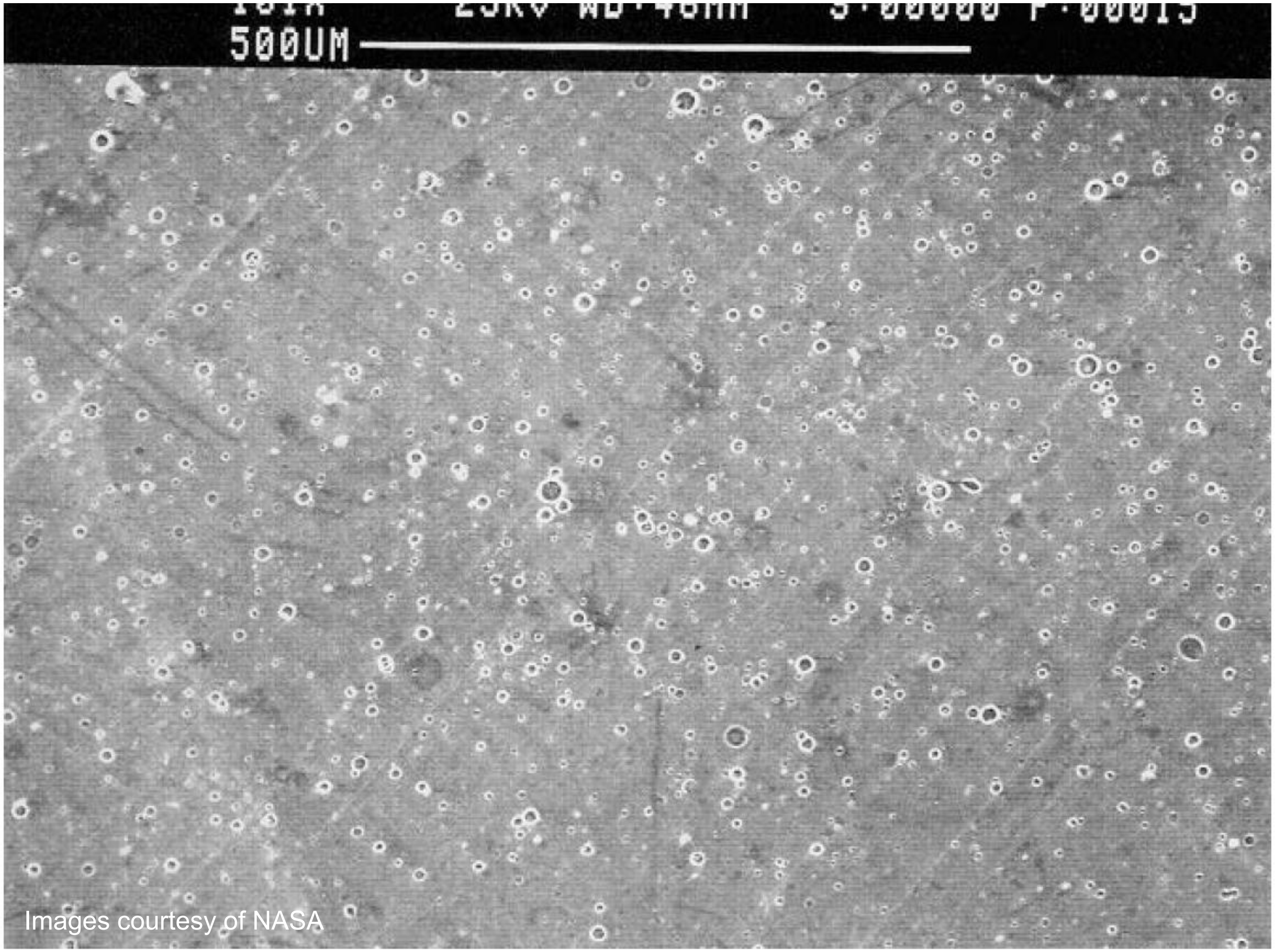
Note: 3000x magnification images provided only for comparison purposes. Image samples insufficient for quantitative assessment

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**

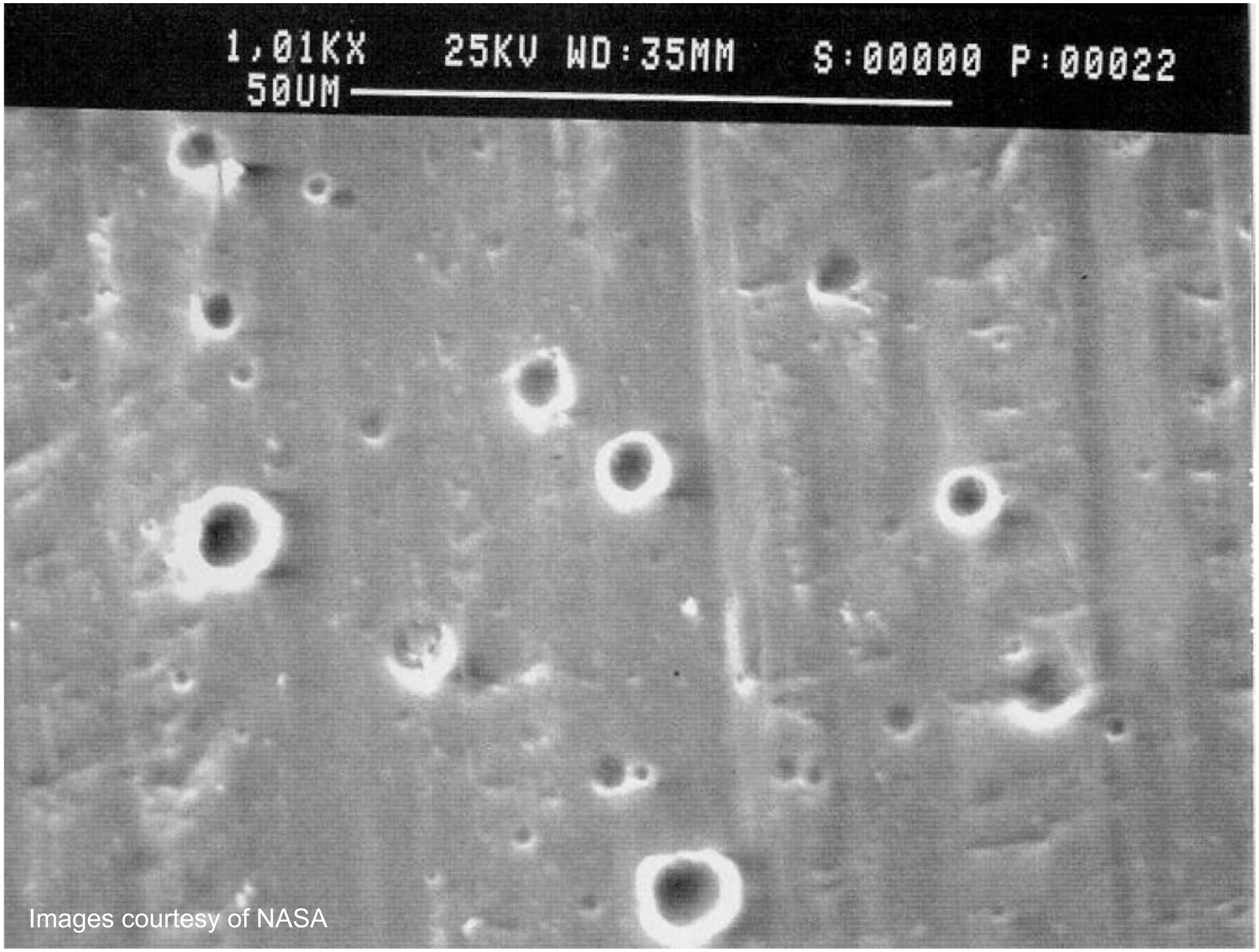
Example SPIFEX Kapton Tape Image: 1500x Magnification (20 µm Scale)

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)

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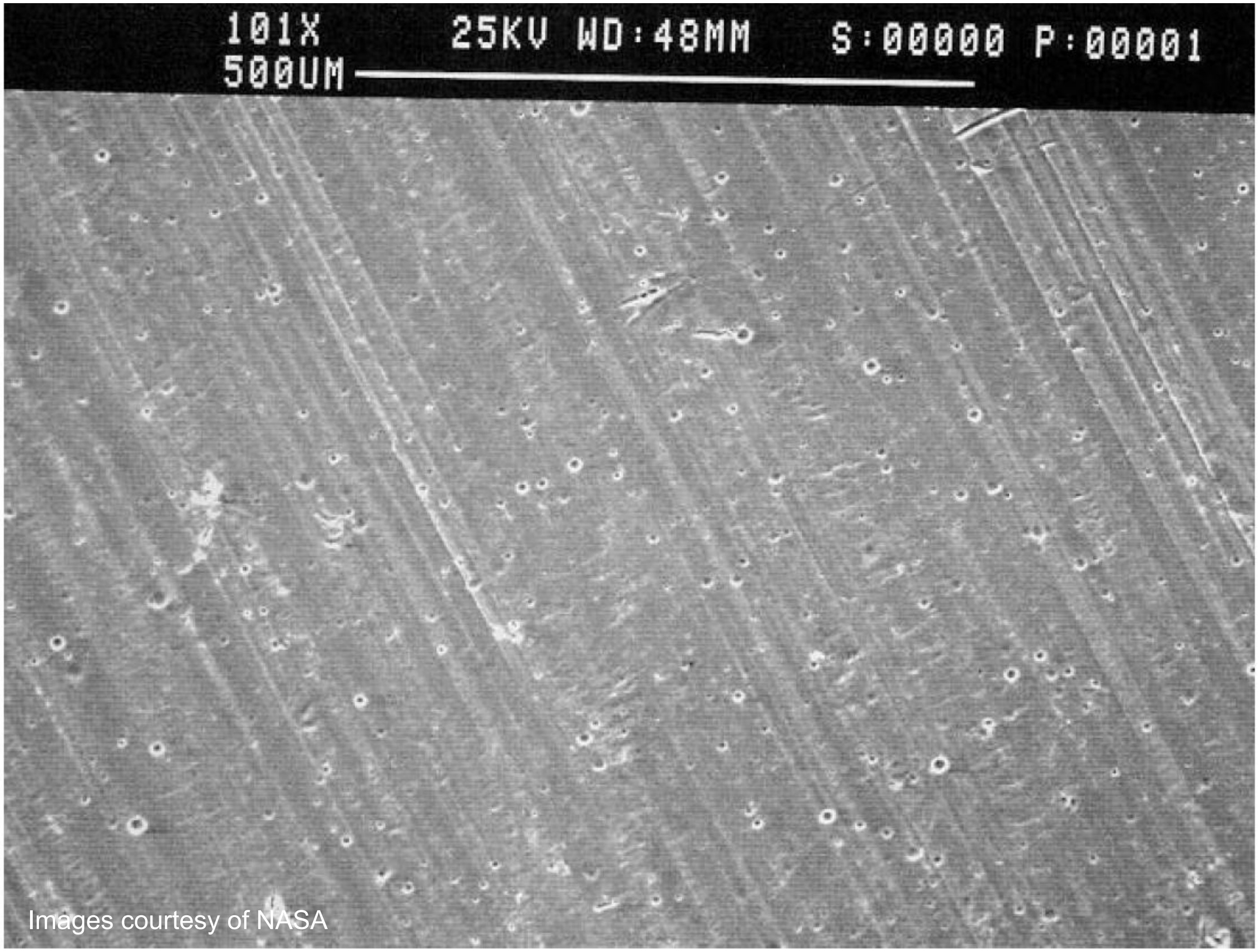


Images courtesy of NASA

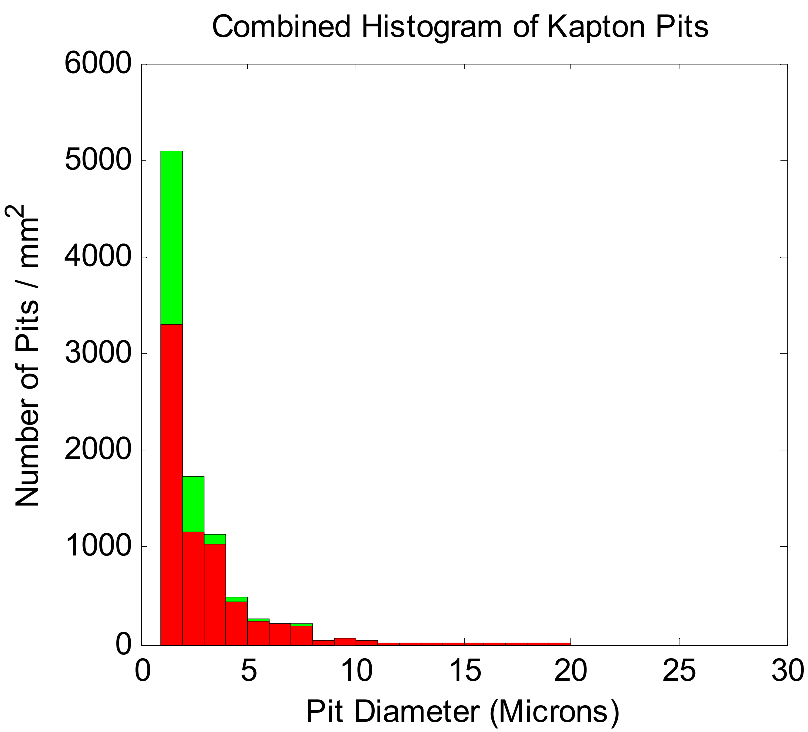
SPIFEX Image Analysis Results

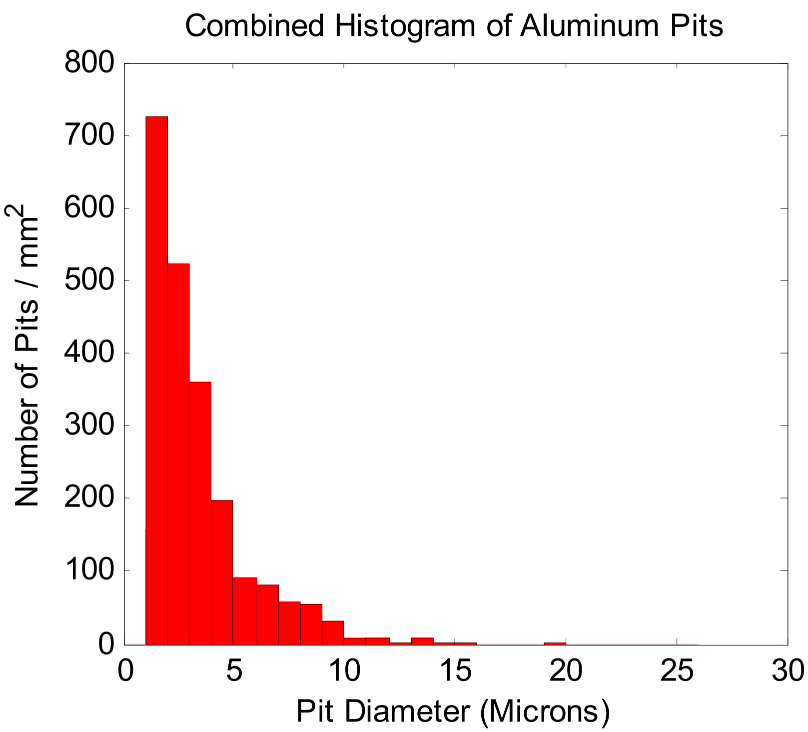
Sample	Approximate Pit Number Density Excluding Potential Pits (pits / mm^2)	Approximate Pit Number Density Including Potential Pits (pits / mm^2)
Kapton Tape	6710	9300
Aluminum Foil	2160	2160

Note: Pit density rounded to the nearest multiple of ten pits / mm^2

Sample	Approximate % Total Area Pitted Excluding Potential Pits	Approximate % Total Area Pitted Including Potential Pits
Kapton Tape	6.4%	7.5%
Aluminum Foil	2.8%	2.8%

SPIFEX Image Analysis Results





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 with Original Aluminum Foil Image Analysis Results (By KSC)

Comparison of number of pits identified per mm^2

Pit Diameter	Original Count / mm^2	Approximate Current Count / mm^2
≤ 4 μm	449	1600
5 – 10 μm	231	320
11 – 20 μm	60	30

Reference: Soares, C., Barsamian, H., Rauer, S.: "*Thruster Plume Induced Contamination Measurements From the PIC and SPIFEX Flight Experiments*," The Boeing Company, NASA JSC

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

Soares, C., Barsamian, H., Rauer, S.: “*Thruster Plume Induced Contamination Measurements From the PIC and SPIFEX Flight Experiments*,” The Boeing Company, NASA JSC

PIC Statistics

- **61 pits / mm^2**
- **Pitted area represents 1.8% of the camera lens surface area**[1]
- **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

Pit Diameter	Pit Density / mm^2
2 - 5 µm	21
6 - 13 µm	30
14 - 24 µm	10

PIC Camera Lens Pit Density

1. Soares, C., Barsamian, H., Rauer, S.: "Thruster Plume Induced Contamination Measurements From the PIC and SPIFEX Flight Experiments," The Boeing Company, NASA JSC