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Mitigation of Thruster Plume Erosion of International Space Station Solar Array Coatings

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Optically sensitive surfaces on the International Space Station (ISS) can be damaged (or eroded/pitted) when impacted by high-velocity particles from unburned liquid propellant present in bipropellant thruster plumes. Surfaces with thin optical coatings, such as solar arrays and radiators, are of primary concern. Thruster plume-induced erosion/pitting of sensitive surfaces has been observed on space shuttle flight experiments. The Boeing ISS Environments Team in Houston has developed an approach to modeling thruster plume-induced erosion/pitting of ISS surface materials. The Boeing team has conducted analyses simulating bipropellant thruster particles impacting sensitive ISS surfaces for various assembly stages. Thruster firings for ISS reboost/attitude control, as well as visiting vehicle thruster firings during approach or separation to ISS docking ports, were simulated. The results of these analyses show that particle impingement angle greatly affects surface damage, with normal impacts being the most severe. Particles with highly oblique impact angles (∼75 deg off normal), however, will essentially skid off surfaces without causing any erosion/pitting. A mitigation technique has been developed to prevent plume erosion/pitting of solar array coatings. Before a thruster-firing event, solar arrays may be rotated to a preestablished position that will eliminate plume particle impact damage to the surface. The preestablished positions are defined based on the geometry of the ISS thrusters relative to the solar array panels to ensure that plume particles will impinge at highly oblique angles (greater than 75 deg off normal). Upcoming ISS milestones will introduce new sensitive surfaces and thrusters, making 2005 a critical year for establishing operational constraints to mitigate thruster plume erosion. Some of these milestones include the space shuttle return to flight, the deployment of new ISS solar arrays, and the maiden voyage of ESA's automated transfer vehicle. Operational constraints for plume erosion mitigation are being coordinated with other solar array operational constraints such as power, thermal, and plume-induced structural loads. An integrated operational solution is being implemented to support the ISS assembly flight sequence. This paper will discuss plume erosion analyses and the implementation of operational mitigation as well as ongoing testing to better characterize plume erosion effects.

I. Introduction

DURING International Space Station (ISS) operations, a variety of rocket engines are used by the Space Station and its visiting vehicles (Space Shuttle Orbiter, Soyuz, Progress, etc.) for attitude control, orbit reboost, and docking/undocking. These various engines are bipropellant thrusters using hypergolic components, either monomethyl hydrazine (MMH) or unsymmetrical dimethyl hydrazine (UDMH) as the fuel and nitrogen tetroxide (N_2O_4, or NTO) as the oxidizer. The exhaust plumes (Fig. 1) from these engines have been recognized as a potential source of loads, heating, and contamination.

Laboratory studies have revealed the presence of unburned propellant in the exhaust plume in the form of liquid particles.[1,2] The origin of the particles, which can range from 1 to 100 μm in diameter, is commonly attributed to incomplete combustion. The gases in the exhaust plume accelerate these propellant particles, or frozen drops, to high velocities (1–3 km/s) due to gas drag forces.[1–3] The effect of these high-velocity particles impacting onto sensitive ISS surfaces, such as the solar arrays and active radiators, is akin to the impact of micrometeoroid and orbital debris (MM/OD) particles. The flux of particles in thruster plumes, however, is much larger than the flux of MM/OD particles of comparable diameter, as shown in Fig. 2. The thruster plume particle flux is based on a semiempirical model for the plume centerline of a Space Shuttle Orbiter primary reaction control system thruster.[3] The MM/OD curve is based on NASA's ORDEM96 orbital debris engineering model (J. Theall, JSC Space Science Branch, private communication, November 2000). Given the comparably high flux of thruster plume particles, the plume erosion/pitting effect is of great concern to the ISS program.

Three space-flight experiments, which studied exhaust plume-induced contamination, were the shuttle plume impingement experiment on STS-52, the shuttle plume impingement flight experiment (SPIFEX) on STS-64, and the plume impingement contamination experiment (PIC) on STS-74 (a mission to the Mir space station), which studied plume contamination from both American and Russian thrusters. Both SPIFEX and PIC demonstrated pitting from plume particles.[4,5]

A SPIFEX aluminum witness coupon, which was plumed by the space shuttle reaction control system thrusters, is shown in Fig. 3. The figure shows plume particle pits in the range of 1–10 μm, though pits as large as 40 μm have been observed. A post-flight examination of a glass camera lens on the PIC experiment also revealed impact craters on the surface.[6] An example of these impact craters is shown in Fig. 4; this crater has a diameter of approximately 8 μm. It should be noted that the craters on the SPIFEX and PIC samples were not visible with the unaided eye. Surface pits were observed with a scanning electron microscope.

II. Implications for International Space Station

For many optically sensitive surfaces, special coatings are applied to enhance performance or for environmental protection. For sensitive ISS surfaces, mechanical damage from thruster plume particle impacts has significant implications. Two sensitive surfaces that may see a great number of thruster firings during ISS operations are the ISS photovoltaic (PV) solar arrays and the active thermal control system (ATCS) radiators. Figures 5 and 6 identify these surfaces for two of the major ISS assembly stages. During assembly, the solar array and radiator configuration will change from Stage

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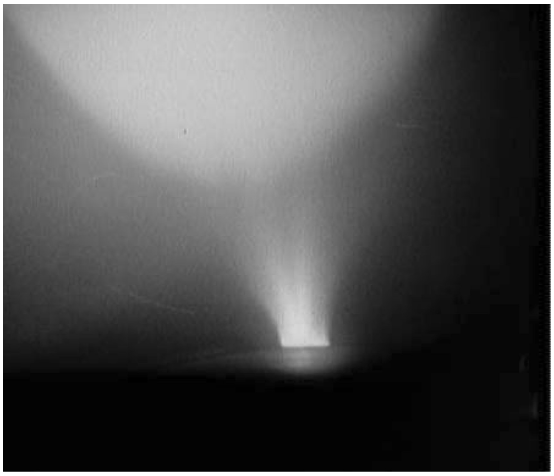

Fig. 1 Exhaust plume of an orbiter primary reaction control system thruster.

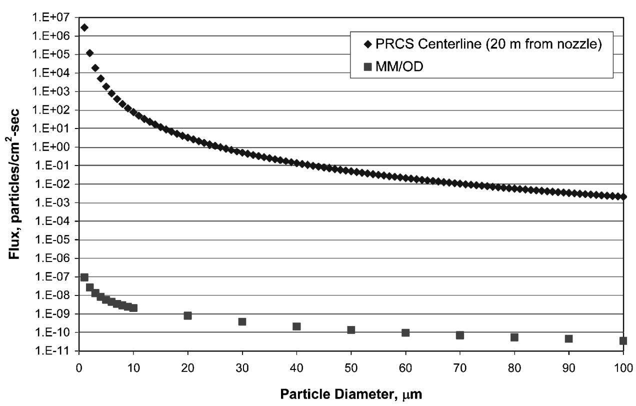

Fig. 2 Flux comparison: orbiter primary reaction control system plume centerline vs MM/OD flux.

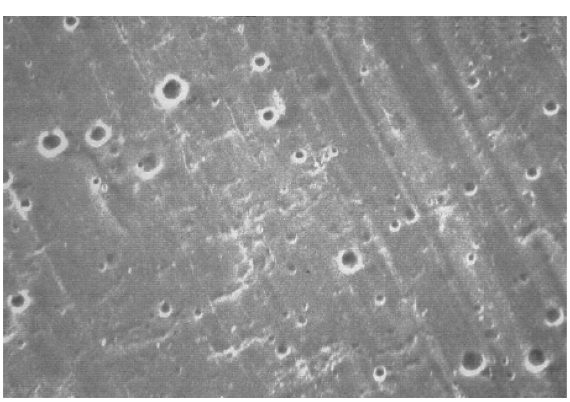

Fig. 3 SPIFEX aluminum witness coupon.

12A to Stage 15A and then remain the same through complete ISS assembly. Stage 12A (shown in Fig. 5) is currently scheduled for late 2005 and Stage 15A (shown in Fig. 6) is currently scheduled for late 2006. This paper will discuss the plume erosion impact to U.S. solar arrays. Plume erosion of ATCS radiators was documented previously.[7] Plume erosion is not a concern for the Russian segment solar arrays (Y. Gerassimov, RSC-Energia, private communication, October 2002).

Each U.S. solar array is composed of 32,800 solar cells covering a deployed area of 115 × 38 ft. The solar cells are mounted on a flexible backing of scrim cloth and Kapton. Each solar cell is topped with a CMX cover glass. The CMX cover glass is coated with an

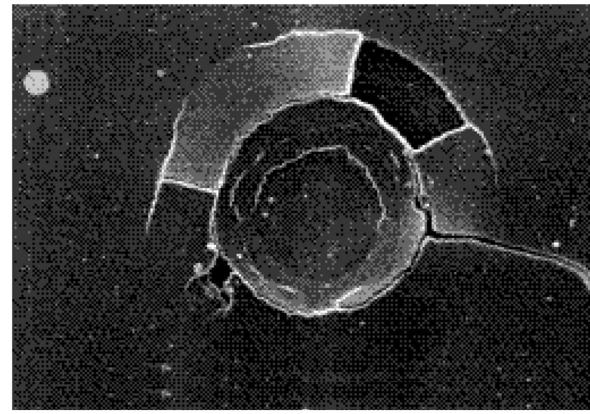

Fig. 4 PIC glass camera lens.

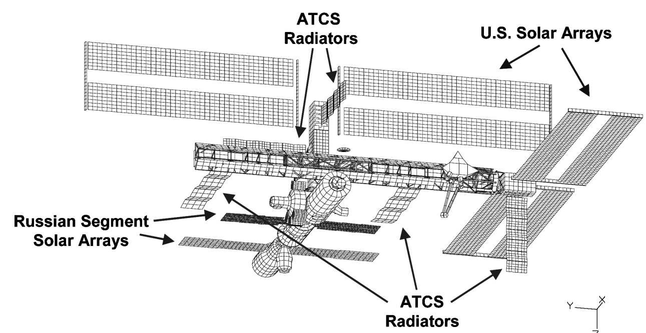

Fig. 5 ISS PV solar arrays and ATCS radiators, Stage 12A.

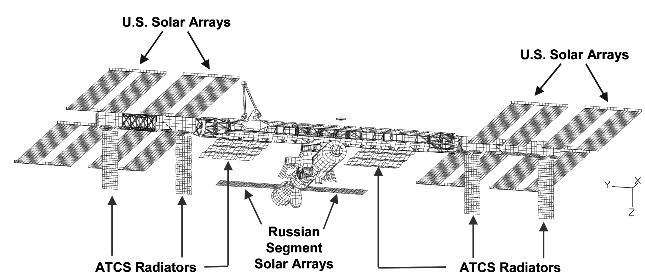

Fig. 6 ISS PV solar arrays and ATCS radiators, Stage 15A.

ultraviolet energy (UVE) filter coating for reflecting UV energy in the wavelength region below 350 nm. The UVE coating thickness is specified at 4.33 μm. Damage to this UVE coating is a primary concern for thruster plume erosion.

The Kapton backing of the solar array wing is susceptible to atomic oxygen (AO) erosion. To prevent such erosion, a 1300-Å AO-resistant SiO_x coating is applied to the Kapton. Although the SiO_x coating performs no optical function, its loss due to thruster plume erosion would allow AO erosion of the Kapton.

III. Thruster Plume Erosion Model

The Boeing ISS Environments Team developed an approach to modeling mechanical erosion on surfaces due to the impact of particles in thruster plumes. A Los Alamos National Laboratory smooth particle hydrodynamics (SPH) code, called SPHINX,[8] was used to simulate thruster plume particle impact damage. SPHINX is a kinematic code and does not model reactions or deposition of contaminants. This is handled as an independent assessment using Boeing's bipropellant plume contamination model.[9] SPHINX has been tested and verified on a number of projectile impacts and astrophysical problems.[8] In addition, the Boeing ISS Environments Team conducted ground tests to verify SPHINX in the regime utilized for thruster particle impact simulation. The results of this ground testing are being prepared for future publication.

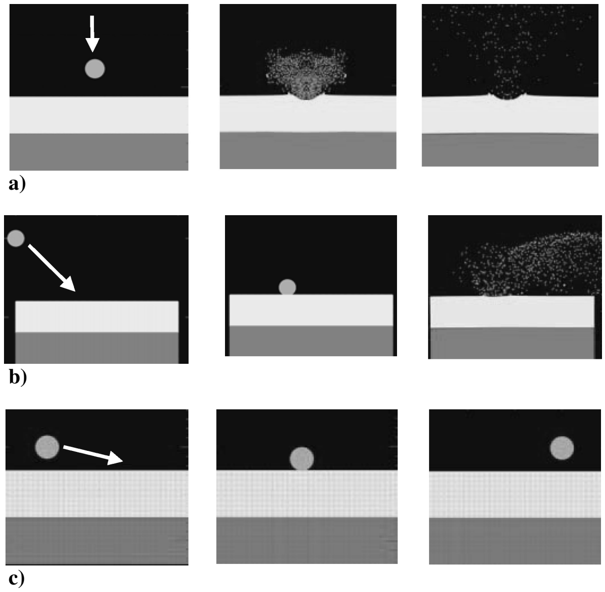

Fig. 7 SPHINX results for impingement angles a) 0, b) 45, and c) 75 deg.

Boeing conducted parametric studies varying plume particle size, impingement angle, and velocity via SPHINX simulations. For analysis purposes, it was assumed that the plume particles consisted of NTO (instead of MMH or UDMH) because this is the heaviest component and would provide conservative damage results. Analysis of the SPHINX output yielded a damage matrix for a specified impacted surface material. One result found during the parametric studies was that particle impacts at angles greater than 75 deg with respect to the normal produce no damage. A synopsis of these analyses is shown in Fig. 7. The application of this result to plume erosion mitigation will be discussed in Sec. V.

The SPHINX damage matrix information was coded inside Boeing's NASAN-II contamination computer model.[10] NASAN-II is an integrated computer model, utilizing input geometric models, view factor calculations, and transport routines to assess a given thruster's effect on an ISS configuration, with results available in tabular or graphics formats. The NASAN-II code was also updated with a thruster plume particle distribution model developed by Hernandez Engineering.[3] This model describes the number density and velocity distribution of unburned fuel droplets (particles) in a thruster plume with respect to particle size and angle from plume centerline. The particle distribution was adapted for each ISS engine type depending on thrust, propellant mass flow rate, and nozzle length. The plume erosion model is applicable only for bipropellant engines (NTO–MMH/UDMH) and assumes a nominal pulse length of 100 ms.

IV. Plume Erosion Analysis

All ISS vehicles that utilize thrusters must be considered as plume erosion sources. The NASAN-II code was used to analyze the effect of plume particle impacts on the U.S. solar arrays from all Russian and U.S. vehicle thruster firings during reboost, attitude control, and proximity operations (which includes visiting vehicle approach and separation to ISS docking ports). Analyses covered the Stage 4A configuration (deployment of the first U.S. solar array) through complete ISS assembly. Preliminary studies showed that solar array coatings would be highly susceptible to plume erosion damage. A higher-fidelity assessment was initiated to identify specific areas of concern. The effect of plume erosion on solar array performance is unknown; therefore, this assessment aimed to predict the percentage of solar array surface area that would be pitted during nominal ISS operations. Solar array damage predictions, described as percent surface area pitted (with average pit depth 1 μm), were used to determine if plume erosion mitigation would be necessary.

Analysis of Russian segment thruster firings included visiting vehicles Progress and Soyuz. The Progress and Soyuz vehicles will fire thrusters during approach to and separation from ISS docking ports at the service module (SM) aft, the docking compartment 1 (DC1) nadir, and the functional cargo block nadir. A diagram of the various ISS docking ports is shown in Fig. 8. The Russian segment lies along the ISS negative X axis.

Progress vehicles may also provide ISS attitude control while mated to the Russian segment. When docked to SM aft, Progress will control ISS pitch and yaw thruster firings. The Progress docked to DC1 nadir performs roll control thruster firings. Depending on ISS configuration, SM thrusters may perform pitch, yaw, and roll control for ISS.

Analysis results for the early ISS assembly phases (i.e., Stages 4A–12A.1) showed that the Progress and Soyuz separation flights are the major contributors to pitting on the solar arrays. Areas on the P6 solar array of up to 25% surface area pitted were predicted, as shown in Fig. 9. This cumulative result is based on semiannual Soyuz flights, quarterly Progress flights, and thousands of thruster pulses for ISS reboost and attitude control. For the analysis, the solar arrays were assumed to rotate as dictated by flight operations.

Russian vehicles were also analyzed for later configurations when new solar arrays will be deployed. The geometry of the ISS and visiting vehicle thrusters to the new solar arrays changes considerably, resulting in new areas of concern.

For the P4 solar array, and all solar arrays deployed subsequently, thruster firings from Progress/Soyuz during approach to and separation from ISS are no longer a plume erosion concern. The thruster pointing direction on these vehicles, though severe for the P6 array, is advantageous for the P4 array. Progress vehicles docked to the SM aft port, for ISS pitch and yaw control, are also in an advantageous position to mitigate plume erosion. In this position, Progress thrusters are so far aft that they do not have a centerline view to the P4 array. Progress docked to the nadir port of the DC1

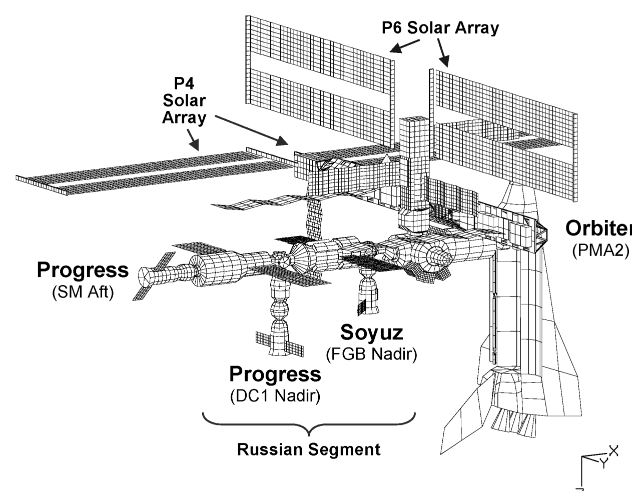

Fig. 8 ISS visiting vehicles and docking ports.

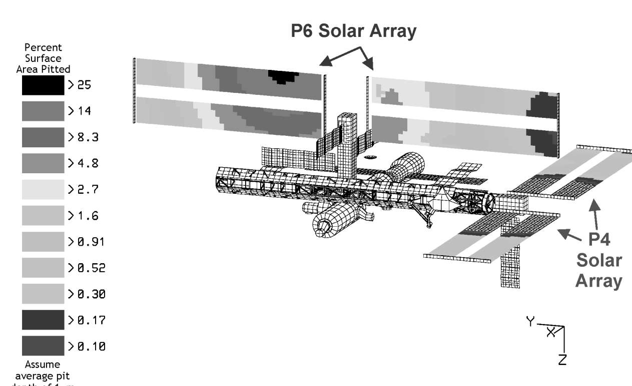

Fig. 9 Predicted cumulative erosion due to Russian segment thruster firings, Stages 4A–12A.1.

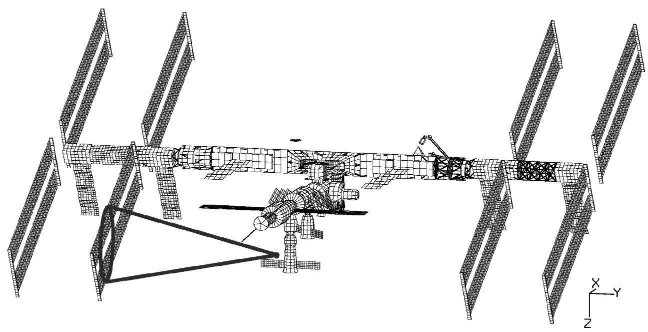

Fig. 10 View of progress roll thruster to P4 solar array.

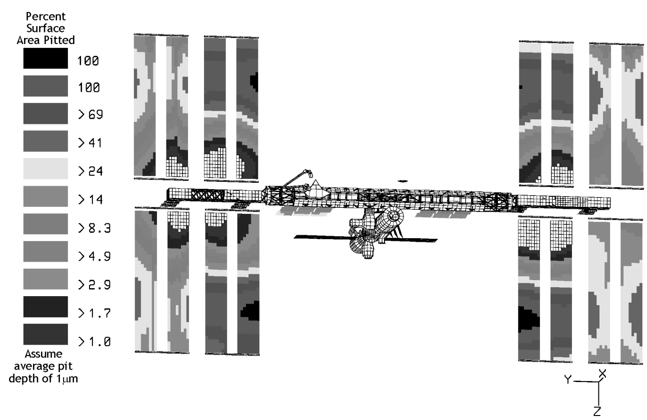

Fig. 11 Predicted cumulative erosion due to Russian segment thruster firings through complete ISS assembly.

for ISS roll control will, however, pose a threat for plume particle impacts. Figure 10 shows a view of the ISS aft end with a cone to represent where a port-side Progress roll thruster would plume the P4 solar array. The starboard-side Progress roll thruster would produce similar pluming to the starboard-side solar arrays.

Analysis results for cumulative erosion to ISS assembly complete (i.e., Stage 4A to assembly complete) predicted that Progress on DC1 nadir thruster firings would be the major Russian segment contributor to pitting on the U.S. solar arrays. Areas of up to 100% surface area pitted were predicted, as shown in Fig. 11. This cumulative result is based on semiannual Soyuz flights, quarterly Progress flights, and thousands of thruster pulses for ISS reboost and attitude control.

On the U.S. segment, the Space Shuttle Orbiter was analyzed for plume erosion impacts on U.S. solar arrays. The orbiter thrusters will fire toward ISS during approach to and separation from the pressurized mating adapter 2 (PMA2) docking port. At close ranges, a different set of side-pointing thrusters may also plume solar arrays.

In addition, the orbiter may perform several reboosts and maneuvers while mated to ISS. These maneuvers, especially reboost, have the potential to cause severe pitting damage to solar arrays given the orbiter thruster configuration and the high thruster firing time.

Analysis results for both Russian segment and orbiter thruster firings indicated that mitigation techniques are needed to protect solar arrays from thruster plume pitting damage.

V. Mitigation

With predictions of solar array surface pitting complete, the next step was to determine the extent of degradation of solar array performance resulting from erosion damage. The data available to perform such an assessment were found to be inadequate. A working group within the NASA ISS Program Office recommended a series of ground-based tests to produce data detailing performance degradation to solar cells due to surface pitting. The data from such tests, however, would not be available in time to affect on-orbit solar array integration issues in the near term. Therefore, the working group concluded that operational mitigation techniques must be put in place now to protect ISS optical surfaces.

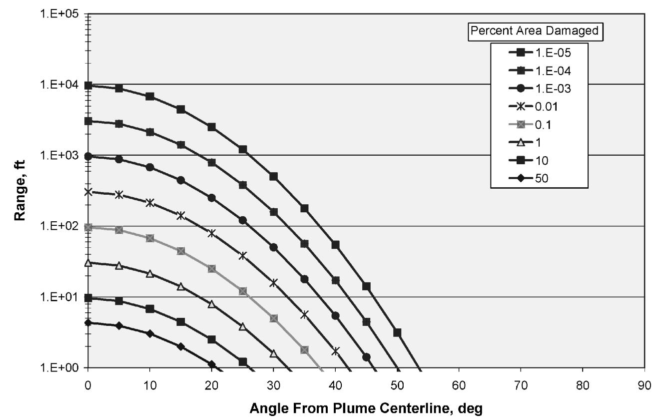

Fig. 12 Damage contours for 130-N Russian thruster (100-ms pulse): surface normal to plume, no crater overlap.

A. Criteria for Mitigation

The Boeing ISS Environments Team was tasked to determine the positions to which the solar arrays could rotate so that thruster plume erosion would be minimal. Based on previous analyses that showed that particle impacts at angles greater than 75 deg to normal produced no damage, the following mitigation conditions were initially derived: 1) the solar array must be rotated so that the plume impingement angle to a solar array surface is greater than 75 deg from the normal, and 2) no thruster plume is allowed to contact the active side of the solar array.

These criteria alone were found, in some cases, to be difficult or impossible to execute operationally. Therefore, an alternative criterion was added to allow more operational flexibility: Solar array positions that induced no greater than 1% surface area damage per year are considered acceptable. This criterion is largely a function of the solar array's position in degrees from the centerline of the thruster plume, because the majority of plume particles are located near the plume centerline. Typically, a solar array positioned 30 to 40 deg from a plume centerline (or farther) would be nearly free of plume particle impact damage. An example of this correlation is shown in Fig. 12 for a 130-N Russian thruster.

In several ISS configurations, the U.S. solar arrays have two degrees of rotational freedom: about the ISS truss (α) and about the solar array wing centerline (β). If the solar array α joint could be rotated away from the plume centerline (to meet the alternative criterion), the β could be rotated freely to optimize view to the sun. Otherwise, both the solar array α and β rotations must be fixed, or "feathered," to mitigate plume erosion (per the first criterion set).

B. Applying the Mitigation Criteria

For the early ISS configurations (e.g., Stage 12A; see Fig. 5), analyses show that the P6 solar array would receive pitting damage during Progress, Soyuz, and orbiter proximity operations. Existing ISS program flight rules for feathering the P6 solar array during Progress/Soyuz approach and orbiter approach and separation (put into place for other requirements) met requirements for plume erosion mitigation, and so no further action was required. For Progress/Soyuz separation, however, new flight rules were drafted to ensure that flight controllers would position the P6 solar array to mitigate plume erosion prior to the separation operation. This flight rule is in effect for the current ISS configuration and will remain in effect until the P6 solar array is relocated to its final outboard position.

Analyses show that additional thrusters will become a plume erosion concern for later ISS configurations (e.g., Stage 15A; see Fig. 6) when additional solar arrays are deployed. The thrusters of concern include Progress on DC1 nadir thruster firings for ISS roll control, orbiter thruster firings during approach and separation to PMA2, and orbiter thruster firings during mated ISS operations. Feathering angles to mitigate plume erosion must be defined for each of these thruster firing events.

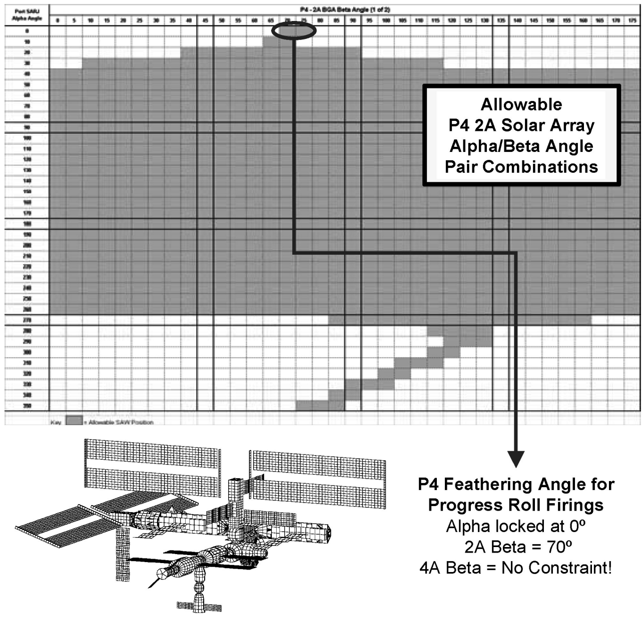

Fig. 13 P4-2A allowable feathering angles for progress on DC1 nadir roll control thruster firings.

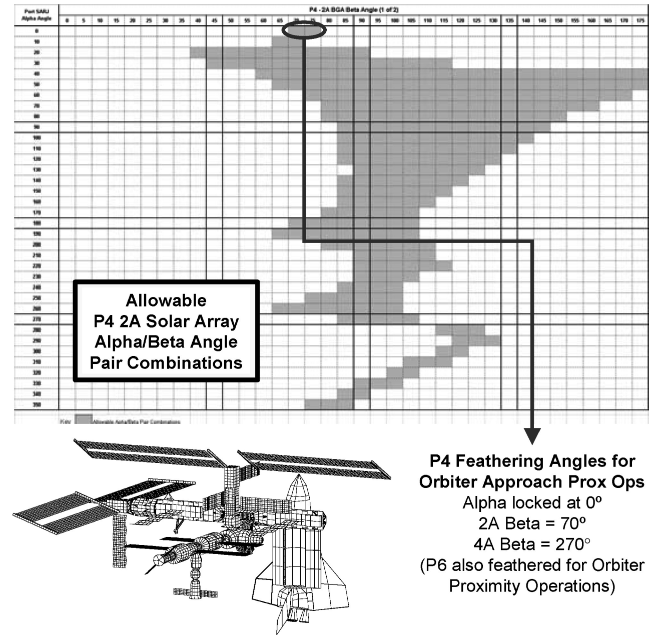

Fig. 14 P4-2A allowable feathering angles for orbiter approach to ISS (with progress on SM aft and progress on DC1 nadir attitude control).

For Progress on DC1 nadir roll control firings, allowable solar array α/β angle pairs to mitigate erosion were defined per the mitigation criteria. These α/β pairs have been tabulated for inclusion into a flight rule to provide flight controllers with the proper settings to ensure solar array protection. A sample table is shown for the P4 solar array in Fig. 13. It should be noted that allowable solar array α/β angle pairs are shown in gray.

Proximity operations have another factor adding complexity to plume erosion mitigation. Solar arrays may need to be positioned to minimize plume erosion from the incoming (or departing) vehicle's thruster firings. In addition, ISS thrusters fire to maintain ISS attitude during proximity operations. Consequently, solar arrays must be positioned to mitigate plume erosion from both the visiting vehicle and the ISS thruster firings for attitude control.

Orbiter proximity operations provide a good example of this scenario. Typically, the Progress docked to SM aft will perform ISS pitch and yaw control and the Progress docked to DC1 nadir will perform ISS roll control during orbiter approach and separation. The solar array position must protect against all thruster firings from these vehicles.

Analyses were conducted to determine the allowable solar array α/β angle pairs that mitigate plume erosion during orbiter proximity operations (with Progress on SM aft and Progress on DC1 nadir performing ISS attitude control). These α/β pairs have been tabulated for inclusion into a flight rule to provide flight controllers with the proper settings to assure solar array protection. An example of this table is shown for the P4 solar array in Fig. 14. By comparison to Fig. 13 (the α/β pairs that mitigate plume erosion from Progress on DC1 nadir alone), it is evident that the added element of orbiter thruster firings severely limits allowable solar array positions.

C. Flight Rule Integration

As the Boeing ISS Environments Team completes plume erosion analyses for ISS thrusters pluming solar arrays, results must be incorporated into ISS program flight rules. The tabulated α/β combinations for allowable solar array positions are prepared for various thruster firing events (Figs. 13 and 14). Before the feathering angle tables can be implemented into flight rules, plume erosion results must be integrated with all other applicable ISS requirements. These requirements may include feathering solar arrays to minimize thruster plume-induced structural loads or heating. Power requirements may also be a driver in determining where solar arrays may be positioned. An integrated solution must be found including all subsystem requirements; this solution then moves forward into the flight rules. Flight controllers use the proper solar array settings defined in flight rules to ensure systemwide performance during thruster firing events.

VI. Ongoing Studies and Future Work

The Boeing ISS Environments Team is continuing plume erosion studies in preparation for upcoming ISS milestones and configuration changes. In addition, testing is being conducted to better characterize plume erosion effects on solar array and radiator coatings. These efforts aim to continually improve plume erosion mitigation techniques to allow maximum protection of optical coatings while minimizing the impact to ISS operations.

A. Return to Flight

A major ISS milestone in the upcoming year will be the space shuttle return to flight. The ISS program has decided on procedural changes during the orbiter approach to ISS, which reduce the risk of an off-nominal event. The procedural changes could affect orbiter thruster firings during the approach to ISS. Simulated man-in-loop thruster firing histories were updated using the new procedure to support analyses of plume effects during the orbiter approach. Work is ongoing to determine how the changes could affect plume erosion of the U.S. solar arrays and what updates are needed to the allowable feathering angles defined for orbiter approach.

This iterative analysis process is typical for plume studies. As a flight nears, more information is available about the ISS configuration and planned operations. Subsequently, better jet firing input data can be generated and used to support plume erosion studies. Flight rule integration and implementation is worked to the flight schedule, allowing for incorporation of updated analyses.

B. New International Space Station Visiting Vehicles

In upcoming years, ISS operations will include two new visiting vehicles: the ESA's automated transfer vehicle (ATV) as well as the Japanese H-II transfer vehicle (HTV). ISS operational mitigation techniques for the U.S. solar arrays during ATV and HTV proximity operations must be developed as well as mitigation techniques for ATV mated operations.

The ATV is schedule to fly to ISS for the first time in the fall of 2005. Preparing for the ATV's maiden voyage will be a significant task over the next year. The Boeing ISS Environments Team has been coordinating with the ESA to collect the information about the ATV thruster configuration and firing patterns needed to support plume erosion analysis. For the current ISS configuration, no feathering angle constraints have been identified for approach or mated thruster firings. Studies are ongoing to determine whether feathering will be required for ATV separation or for future ISS configurations. Any resulting requirements are to be integrated with similar requirements for thermal and structural effects of thruster plume impingement. Integrated requirements will be implemented through ISS program flight rules.

The first HTV is scheduled for flight in 2007. Most HTV analyses are schedule for future work. The Boeing ISS Environments Team has begun coordinating with the Japanese Aerospace Exploration Agency to collect information about the HTV thruster configuration and thruster firing patterns.

C. International Space Station Configuration Changes

Beginning in the fall of 2005, the ISS will undergo several successive configuration changes of high interest for plume erosion studies. Over five space shuttle flights (spanning approximately 1 year), one U.S. solar array will be relocated to a new position on the ISS structure, and three new solar arrays will be installed. The final solar array configuration is shown in Fig. 6.

Flight rules to mitigate plume erosion of the U.S. solar arrays must be implemented for each configuration as solar arrays are relocated and deployed. Many of the studies needed to support flight rule implementation for these upcoming configurations have been conducted as described in Sec. V. In preparation for these upcoming flights, however, analyses must be updated and finalized with any new data that becomes available. Additionally, integration activities will become increasingly important as plume erosion requirements are integrated with other subsystem requirements into flight rules. The Boeing ISS Environments Team will coordinate with other subsystem teams to ensure systemwide performance during this critical time period in the ISS assembly sequence.

D. Impact Testing

In addition to ongoing plume erosion analyses, the Boeing ISS Environments Team has initiated a ground-based test program to improve plume erosion modeling and predictions. The test program is being conducted by the NASA Johnson Space Center Hypervelocity Impact Facility using their light gas gun at Rice University. These tests are designed to determine transmission loss due to solar cell surface pitting. The test data will be used to assess degradation to solar cell power output resulting from plume erosion.

The first part of the test involved pitting the surface of the solar cell with glass beads (5–50 μm in diameter) accelerated to 1.5–2 km/s. Glass beads were selected as the best available option for matching the density, shape, and size of frozen NTO. Density and diameter of the impacting particle are the first-order drivers for impact phenomena.[10] Solar cell samples were impacted at normal and oblique angles for various bead number densities to represent on-orbit thruster plume conditions. Sample results are shown in Fig. 15; the white specks are pits on the solar cell due to the impinging glass particles.

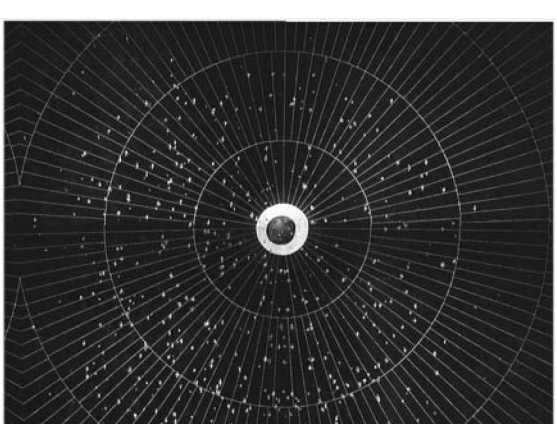

Fig. 15 ISS solar cell plume erosion test example.

The second part of the test, to be performed at Boeing–Seattle, will be to measure the change in reflectance as a function of surface damage. The transmission cannot be measured directly without damaging the solar cell; therefore, the reflectance measurement will be used to determine transmission loss. The first part of the test is complete, with the optical measurement planned for 2005.

VII. Conclusions

Thruster plume particles can cause mechanical damage in the form of erosion/pitting of sensitive ISS surfaces. In general, any sensitive spacecraft surfaces exposed to the exhaust plumes of thrusters on-orbit should either compensate for thruster plume erosion via design or prepare mitigation techniques to minimize thruster plume particle pitting.

In this paper, the development of the erosion model was outlined, along with predictions of damage due to thruster firings on U.S. solar arrays. Characterization of thruster plume-induced erosion/pitting of solar array coatings due to ISS thruster operations was shown for interim and final ISS assembly configurations. The solar array analysis results show that plume erosion mitigation is needed to protect solar array optical coatings.

A mitigation technique for ISS solar arrays, which minimizes thruster plume erosion during current and future ISS assemblies, was presented. Implementation of these mitigation techniques into ISS program flight rules was discussed, and an overview was presented of ongoing and future analyses and ground-based testing to characterize plume erosion effects.

The Boeing ISS Environments Team pursues these activities to ensure a known environment around the ISS so as to guarantee the success of the ISS as a platform for scientific experiments in low earth orbit.

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