PROTECTION FROM INDUCED SPACE ENVIRONMENTS EFFECTS ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

The International Space Station (ISS) is the one of largest, most complex multinational scientific project in history and protection from induced space environments effects is critical to its long duration mission as well as to the health of the vehicle and safety of on-orbit operations. This paper discusses some of the unique challenges that were encountered during the design, assembly and operation of the ISS and how they were resolved. Examples are provided to illustrate the issues and the risk mitigation strategies that were developed to resolve these issues. Of particular importance are issues related with the interaction of multiple spacecraft as in the case of ISS and Visiting Vehicles transporting crew, hardware elements, cargo and scientific payloads. These strategies are applicable to the development of future long duration space systems, not only during design, but also during assembly and operation of these systems.

1. ISS INDUCED ENVIRONMENTS

During a typical year of ISS operations, induced environments are produced with thruster operations (reboost and attitude control, and proximity operations of the Space Shuttle Orbiter and Russian, European and Japanese Visiting Vehicles), and operation of vacuum vents, which vent a variety of gases and in some cases liquids to space.

Analyses are conducted to assess induced environments effects on vehicle systems and assets. Analysis results are used to develop risk mitigation and safing constraints to protect the ISS and its science utilization capabilities.

2. THRUSTER OPERATIONS

The bipropellant thrusters used by ISS (for reboost and attitude control), Space Shuttle and other Visiting Vehicles produce contamination and mechanical erosion on exposed surfaces which can impact optical properties and performance of systems such as the ISS solar arrays and robotic cameras, as well as introduce hazards to Extra-Vehicular Activity (EVA).

During 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 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. The origin of the particles, which can range from 1 to 100µm 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. 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.

The thruster plume particle flux is based on a semi-empirical model for the plume centerline of a Space Shuttle Orbiter primary reaction control system thruster. 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. [1, 2]

A SPIFEX aluminum witness coupon, which was plumed by the space shuttle reaction control system thrusters, is shown in Fig. 1. The figure shows plume particle pits in the range of 1–10µm, though pits as large as 40µmhave 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.

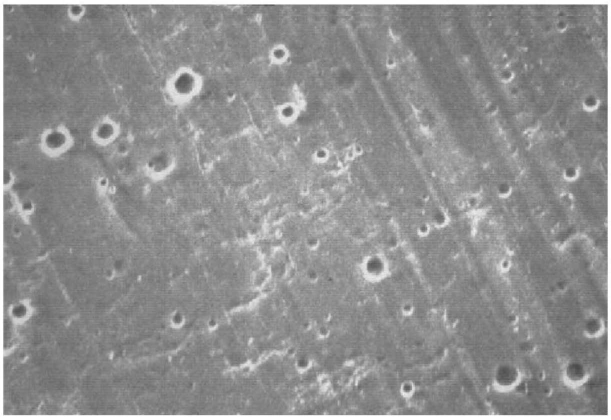

Figure 1. Plume particle impact features on SPIFEX witness aluminium coupon

3. PROTECTION FROM THRUSTER OPERATIONS

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. Optically sensitive surfaces on the ISS can be damaged (or eroded) when impacted by high-velocity droplets/particles from unburned and partially burned liquid propellant present in bipropellant thruster plumes.

Sensitive surfaces that may see a great number of thruster firings during ISS operations include the ISS photovoltaic (PV) solar arrays, the active thermal control system (ATCS) radiators and robotic cameras on the Space Station Remote Manipulator System (SSRMS) and truss mounted cameras. Fig. 2 identifies ISS solar arrays and active thermal system radiator surfaces for the 15A assembly stage.

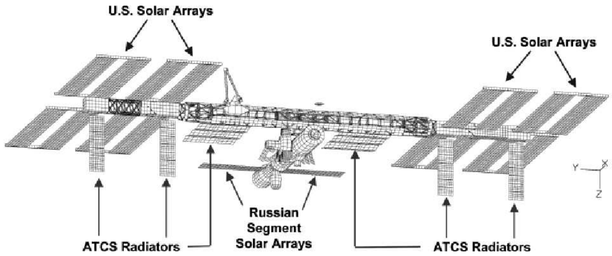

Figure 2. Select ISS sensitive surfaces for the 15A assembly stage

Plume contamination models were developed to support the definition of position and orientation of solar array panels during specific thruster operations. These constraints protect the performance of the ISS electrical power system which is vital to both vehicle and science operations.

3.1. ISS Solar Arrays

Surfaces with thin optical coatings, such as solar arrays and radiators, are of primary concern. Thruster plume induced erosion of sensitive surfaces has been observed on Space Shuttle flight experiments.

The Boeing Space Environments Team in Houston developed an approach to modeling thruster plume-induced erosion of ISS surface materials. The Boeing team 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° off-normal), however, will essentially skid off surfaces without producing any damage. [3]

A mitigation technique was developed to prevent plume erosion of solar array coatings. Before a thruster-firing event, solar arrays may be rotated to a pre-established position that will eliminate plume particle impact damage to the surface. The pre-established 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° off-normal).

Operational constraints for plume erosion mitigation are coordinated with other solar array operational constraints such as power, thermal, and plume-induced structural loads. An integrated operational solution has been implemented to support the ISS assembly flight sequence.

The Boeing Space 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° 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° 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 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° from a plume centerline (or farther) would be nearly free of plume particle impact damage.

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

The implemented mitigation strategy successfully protects the solar arrays from plume induced damage while optimizing the solar arrays' view to the sun.

The thruster induced erosion events of concern for ISS solar arrays 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.

For Progress on DC1 nadir roll control firings, allowable solar array •/• angle pairs to mitigate erosion were defined per the mitigation criteria. These •/• 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. 3. It should be noted that allowable solar array •/• angle pairs are shown in gray.

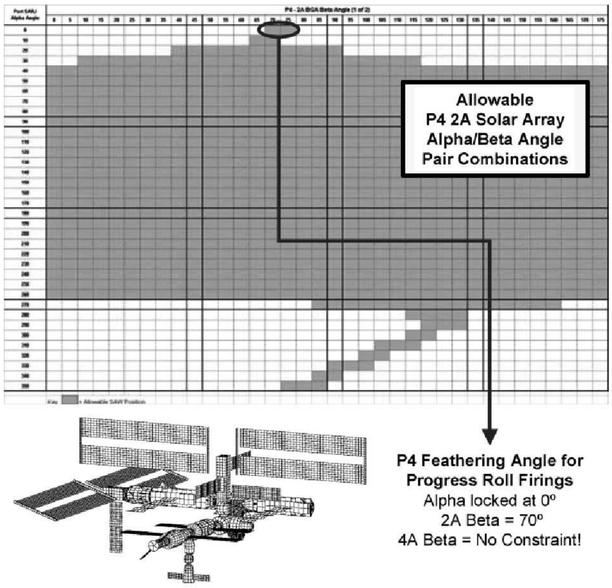

Figure 3. P4-2A allowable feathering angles for Progress on DC1 nadir roll control thruster firings

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 •/• 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 •/• 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. 4. By comparison to Fig. 3 (the •/• 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.

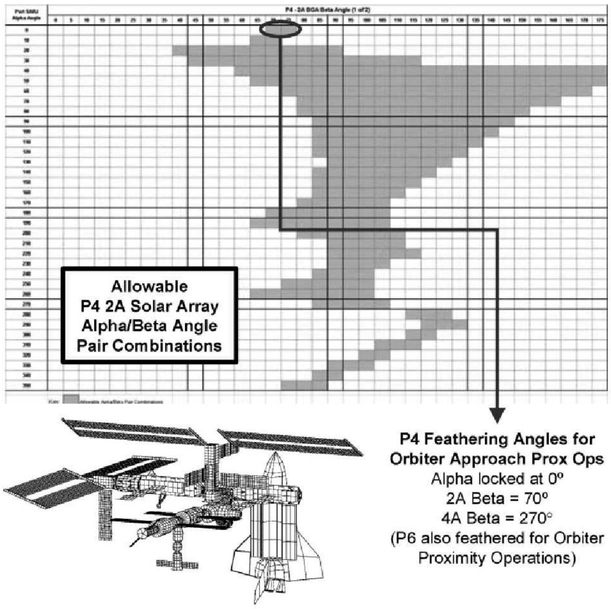

Figure 4. P4-2A allowable feathering angles for Orbiter approach to ISS (with Progress on SM aft and Progress on DC1 nadir attitude control)

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 •/• combinations for allowable solar array positions are prepared for various thruster firing events (Figs. 3 and 4). 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.

3.2. ISS Cameras

ISS robotic arm camera assets, which are essential to the vehicle, are also protected from thruster induced erosion and contamination through modeling and development of Keep-Out Zones (KOZs) for camera operations.

Simulations of visiting vehicle approach to and separation from ISS are used in the development of erosion planes (contour plots) that are used in the definition of KOZs for ISS robotic camera assets. These KOZs are used to protect SSRMS and truss mounted robotic cameras from incursions into regions with potentially high erosion fluxes.

An erosion plane plot for a Russian vehicle approach to the ISS MRM1 nadir docking port in shown in Fig. 5.

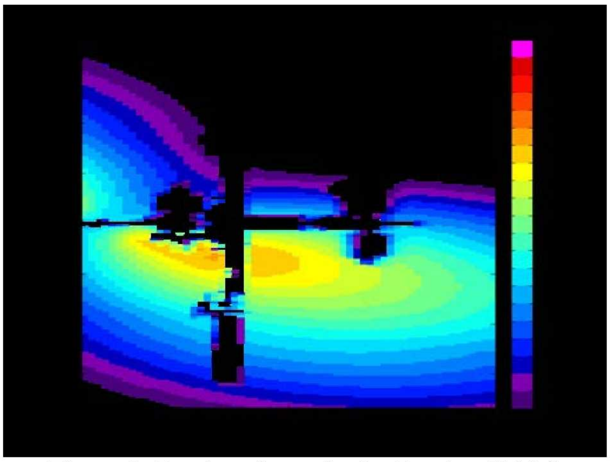

Figure 5. Erosion plane plot for Russian Vehicle approach to the ISS MRM1 nadir docking port

This strategy has been proven to be successful as robotic camera assets continue to operate without degradation from erosion effects while being used to monitor approach of automated vehicles to ISS

3.3. EVA Hazards from Plume Contamination

Thruster induced contamination also produces hazards to extra-vehicular activity (EVA) as the fuel/oxidizer reaction products contain toxic byproducts (Fuel/Oxidizer Reaction Products or FORP). The Space Environments Team coordinated FORP testing at the NASA White Sands Test Facility in conjunction with coordination with Russia to develop hazard mitigation through Flight Rules defining EVA crew keep-out zones. [4]

The U.S. control moment gyros (CMGs) maintain the vehicle attitude of the International Space Station (ISS) by compensating for disturbances. However, when the docking compartment (DC1) of the ISS, the location of the Russian airlock, is depressurized for extravehicular activities (EVAs), the service module (SM) attitude control thrusters have to fire because the CMGs have an insufficient margin of momentum to compensate for the disturbance and must be desaturated.

The ISS propellant is unsymmetrical dimethylhydrazine (UDMH), and the oxidizer is nitrogen tetroxide (N_2O_4). Thruster firings produce fuel–oxidizer reaction products (FORP) that can contaminate adjacent surfaces around the thrusters. For EVAs on the aft end of the SM of the Russian segment, there is a concern that when EVA crewmembers translate around the FORP-contaminated area they could inadvertently brush against the FORP and transfer some of it to their suits.

FORP is composed of both volatile and non-volatile components. How fast the volatile components leave varies. One of the components present in FORP that represents the greatest toxicological concern to the crew is the potent carcinogen N-nitrosodimethylamine (NDMA). NDMA is volatile; it poses an inhalation concern if it is introduced into the ISS atmosphere. In addition, when other components in the dried FORP, such as dimethylammonium nitrite and nitrate, are reintroduced into a humid environment such as the ISS cabin, NDMA can be formed. So the concern is that when FORP (on the suit) is brought back into the humid environment of the ISS cabin, it can release NDMA into the atmosphere and the crew can be exposed.

Because of the presence of FORP on the SM surfaces adjacent to the roll thrusters and the potential for FORP contamination of the EVA crew, additional EVA constraints were required to be implemented in these areas. The constraints were initially established through a nonconformance report that discussed the removal of the Kromka 1-0 experiment and installation of the Kromka 1-1 experiment and in subsequent ISS program safety review panel discussions.

The EVA constraints were initially developed because the Kromka experiment is in close proximity to the SM thrusters, and the EVA crewmembers would need to enter that area. The constraints included establishing a 1-m keep-out zone (KOZ) around the thrusters for 2.5 h after the last SM thrusters fired before the EVA crewmembers could enter the area, procedures for inspecting the EVA suits before ingress back into the airlock, and procedures for wiping the gloves and suit with towels that are jettisoned to retrograde. Also, once inside the ISS, the EVA gloves are bagged to mitigate any potential risk from FORP. Because EVAs are generally very time-constrained, the ISS program approved a test program at the NASA White Sands Test Facility (WSTF) to obtain FORP test data that could be used to determine whether those EVA constraints could be relaxed.

Owing to the presence of FORP on the SM surfaces adjacent to the roll thrusters observed in Flight 5A and subsequent imaging and the potential for FORP contamination of the EVA crew, additional EVA constraints were required to be implemented in those areas. These EVA constraints were initially implemented through the non-conformance report described earlier. The constraints included establishing a 1-m keep-out zone (KOZ) around the thrusters for a period of time after the last SM thrusters fired before the EVA crewmembers could enter the area, procedures for inspecting the EVA suits before ingress back into the airlock, and procedures for wiping the gloves and suit with towels that are jettisoned to retrograde. Also, once inside the ISS, the EVA gloves are bagged to mitigate any potential risk from FORP.

Prior to an EVA on the Russian segment, the DC1 must be depressurized, because it is used as an airlock. When the DC1 is depressurized, the CMGs' margin of momentum is insufficient to compensate for the disturbance and the service module attitude control thrusters need to fire to desaturate the CMGs. The thruster firings result in FORP contamination of the adjacent SM surfaces.

The FORP contamination of the SM surfaces, the release of NDMA in a humid environment from crew EVA suits if they happen to be contaminated with FORP, and the toxicological risk associated with the NDMA release were calculated. It was determined that the FORP and NDMA evaporate rapidly and that their concentration drops off rapidly with distance from the thrusters. The FORP remaining after 1 h for the nadir (cold side) case was found to be 36% of the initial mass. For the zenith (hot side) case the FORP remaining after 1 h was 22% of the initial mass.

The NASA JSC Toxicology Group found that the highest calculated cancer risk from the projected NDMA concentrations is less than 8.46E□□□ □□□□å#□□ distance 0.08 m from the thrusters). The NASA JSC Toxicology Group, with the concurrence of the National Research Council Spacecraft Maximum Allowable Concentrations (SMAC) Subcommittee, accepts a cancer risk of 1/10,000 (i.e., 1.0E□□□□ IN□ DERIVING□ SMACs on carcinogenic compounds, such as benzene.

Based on the results of tests performed in 2003 and 2004, subsequent analyses, and the NASA JSC Toxicology Group assessment of the risk, it was determined that the constraints could be reduced and the time to remain outside the 1-m KOZ could be reduced to 1 h. The procedures for inspecting the EVA suits and clean-up procedures were retained. The reduction in KOZ time is a significant time savings for EVA planning.

4. THERMO-OPTICAL PROPERTY DEGRADATION

Potential degradation of thermo-optical properties of vehicle systems is carefully evaluated as system failures leading to unplanned EVA R&R are viewed as hazardous. The combined effect of induced contamination and exposure to space environments is modeled and assessed for impacts. Correlations derived from degradation predictions and observed thermal performance have been conducted to assess model applicability. These activities mitigate the risk of system failures due to optical property degradation.

Hardware lifetime is highly dependent on optical properties, which may degrade over time due to space environment effects. Induced effects which can degrade optical properties include molecular deposition due to outgassing and water vent/thruster plume contaminant deposition and erosion. Degradation of optical properties affects the thermal performance and can result in hardware becoming hotter or colder than it was designed for. It can also limit the attitudes that the vehicle can fly or require hardware to be replaced sooner than planned. In some cases, hardware lifetime can actually be extended with improved predictive capability for optical property degradation.

The Boeing ISS Space Environments team has developed and refined models of optical property degradation induced by molecular contamination (i.e. deposition due to material outgassing, venting operations, and thruster firings) as well as exposure to the on-orbit environment. For ISS thermal control surfaces, the models incorporate: molecular contamination effects (actual contaminant deposition predictions vs. design requirements), temporal effects due to solar exposure, and the operational end-of-life assessment.

Several thermal analyses were performed with this model (using as-flown contamination predictions and solar exposure estimates) and yielded lower solar absorptivity degradation predictions. Such results imply enhanced thermal capability and therefore reduced/eliminated thermal constraints for some ISS components. These analyses assumed realistic ESH values calculated by the ISS Passive Thermal Control System (PTCS) team using as-flown and future expected attitudes and durations.

For example, the radiators for the Node1 heat pipe were originally predicted to have a lifetime of 3 years in the nominal ISS attitude. Larger 13-year life radiators were planned as a replacement. By re-examining the original analysis using improved modeling of optical property degradation combined with planned flight attitude/durations, it was determined that the original radiators life could be extended by several years with some attitude constraints as documented in the Flight Rules. This gave the ISS Program more flexibility on the replacement of the PMA1 MDM radiators.

5. VACUUM VENTING

During a typical year, induced environments are produced with the operation of 33 active vacuum vents, which vent a variety of gases, and in some cases liquids, to space.

Vacuum venting of liquid water from the Space Shuttle while mated to ISS, and as required from the U.S. Lab module can produce an orbital recontact hazard since the venting produces a large flux of ice particles that can recontact ISS every half-orbit. The risk of recontact is mitigated through control of vehicle attitude to prevent orbital recontact with ice particles.

5.1. Water dumps

The International Space Station (ISS) and Orbiter dump water overboard into space. The phenomena of water release into a vacuum have been studied for many years. It is known that as the liquid exits the nozzle into the vacuum of space it begins to freeze by radiative and evaporative cooling. It freezes initially on the outer surface of the stream. Then expanding gas bubbles in the stream burst the stream into vapor and small and large liquid/ice particles that can travel in various directions.

When water is dumped overboard, the concern is that direct contact of the liquid/ice particles with ISS hardware can cause mechanical damage to sensitive surfaces due to erosion/pitting of those surfaces. Solar arrays are of particular concern because of the thin optical coatings on the surfaces of the solar cells. Damage to these coatings can cause degradation of the solar cells' optical characteristics that can potentially reduce performance and shorten the life of the solar cells.

To mitigate potential damage from water dumps, a methodology was developed that could be used to develop the constraints needed to protect sensitive ISS surfaces. To develop the methodology, the characteristics of water dumps were studied and the select angles at which the ISS solar arrays can be parked to preclude damage to solar array and radiator surfaces were defined. The select angles were used to develop the constraints needed to mitigate damage. [5]

Operational constraints needed to mitigate damage from liquid/ice particle impacts were developed based on analysis results from Smooth Particle Hydrodynamics (SPH) impact simulations. Although the results did not show any damage to the solar cell, the ultraviolet energy (UVE) protective coating is thin, 43,300 Å. If the coating is damaged it could potentially degrade the performance and lifetime of the solar cell. To be conservative, it was determined that the operational constraint will be not to allow impacts onto the active side of the solar arrays.

The backside of the solar array has a 1300Å SiOx coating to protect the Kapton backing from atomic oxygen erosion. Below the Kapton layer, there are additional layers that, if eroded, will not affect the performance of the solar cell. However, to minimize damage to the solar array, the operational constraint developed for the backside of the solar array is that impacts will be at a shallow angle, less than 15 deg to the surface (or 75 deg from the surface normal).

In addition, to minimize the number of impacts, an operational constraint was developed so that the solar arrays will be rotated to remain outside the impact zone with engineering margin (the 20° half-cone angle cone around the plume centerline). To mitigate damage to the solar array photovoltaic radiators, an operational constraint was developed to keep the radiators away from the plume centerline. The radiators operate cold and cannot be feathered. In addition, the effect of liquid/ice particle impacts on the radiators has not been well defined yet. The constraint is to keep a solar array between the impact zone with engineering margin and the radiator. This operational constraint will allow the radiators no closer than 50–60° from the plume centerline.

5.2. U.S. Lab water dump damage mitigation and operational constraints

Figure 6 shows the field of view from the port-side U.S. Lab condensate water nozzle for ISS assembly complete. The solar arrays are rotated outside of the impact zone with engineering margin and feathered so that impacts from the water dump occur on the backside of the arrays. The Japanese hardware can be seen in the lower right section of the view. This view can be compared with the one shown in Fig. 5a, where the solar array would be impacted.

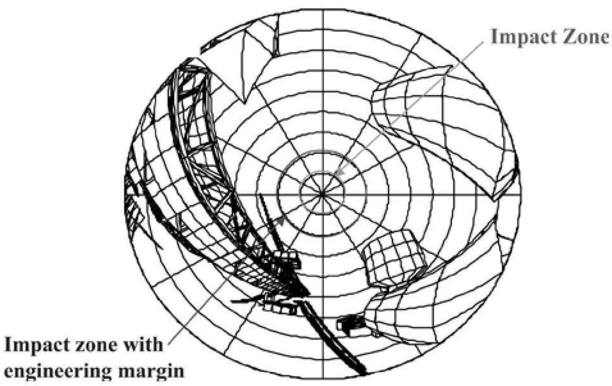

Figure 6. Field-of-view from port-side U.S. Lab condensate water dump nozzle. The solar array is feathered and rotated out of the impact zone with engineering margin.

An example of the allowable feathering angles that will feather the solar array wings (SAWs) so that impacts from the liquid/ice particles occur on the backside of the arrays at a shallow angle is shown in Fig. 7. This table was developed based on the defined constraints. This table gives allowable solar array •/• feathering angle pair combinations that will mitigate damage from U.S. Lab water port side nozzle dumps. The white region represents the allowable SAW positions. In this table, the port-side solar array rotary joint • rotations are defined down the left-hand side of the table.

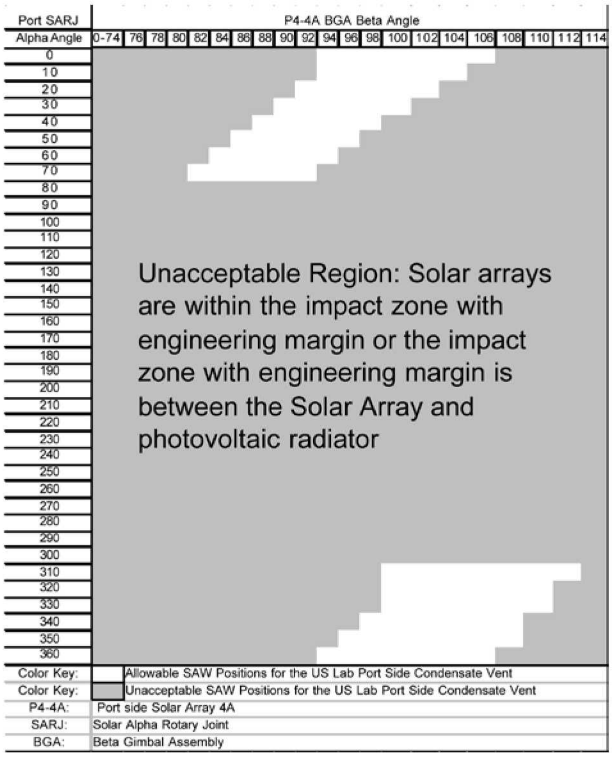

Figure 7. ExampleU.S. Lab port-side condensate water dump allowable solar array feathering angles for the P4-4A solar array wing (SAW)for• gimbal assembly •-rotations from 0 to 238 deg.White zone is allowable SAW positions.

The • gimbal assembly beta rotations from 0 to 114° are defined along the top of the table. The remainder of the • rotation angles, from 114 to 360°, is defined in another table. Similar tables have been developed for U.S. Lab starboard-side nozzle dumps and for orbiter water dumps.

5.3. Orbiter water dump damage mitigation and operational constraints

Figure 8 shows the field of view from the orbiter dump nozzle for a solar array rotated out of the high-impact zone and with the solar array feathered so that impacts are on the backside of the array at a shallow angle. The solar array is feathered so that there are no impacts on the active side of the array and so that impacts on the back of the array are at a shallow angle. This view can be compared with the one shown in Fig. 9 where the solar array would be impacted. The JAXA payload sites can be seen just below the center of the plume. Urine dumping was discontinued with the deployment of the Japanese elements.

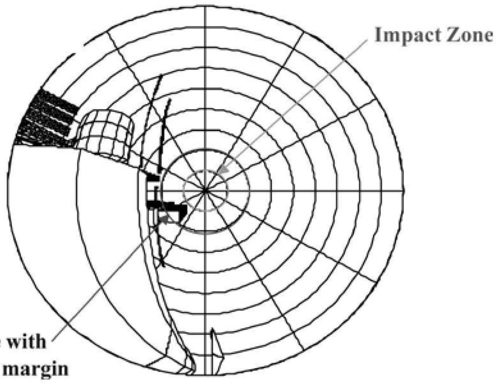

Figure 8. Field of view from orbiter water dump nozzle. The solar array is feathered and rotated out of the impact zone with engineering margin.

Allowable feathering angle •/• pair combinations similar to those discussed earlier for the U.S. Lab condensate water dumps have been developed for orbiter water dumps and incorporated in table format.

This approach is used to develop the constraints needed to mitigate damage to ISS hardware from the U.S. Lab and orbiter water dumps. The results of these studies show that the ISS solar arrays can be parked at select angles during water dump operations that will protect the solar array and radiator surfaces from impact damage.

6. CONCLUSION

This paper discusses some of the unique challenges that were encountered during the design, assembly and operation of the ISS and how successful mitigation strategies were develop to protect the ISS from induced environment effects. Solar arrays are of particular concern because of the thin optical coatings on the surfaces of the cells. Damage to these coatings can cause degradation of the cells' performance and operational lifetime. Examples are provided to illustrate the issues and the risk mitigation strategies that were developed to resolve these issues. These strategies are applicable to the development of future long duration space systems, not only during design, but also during assembly and operation of these systems.

7. References

[1] Soares, C. E., and Mikatarian, R. R., "Thruster Plume Induced Contamination Measurements from the PIC and SPIFEX Flight Experiments," International Symposium on Optical Science and Technology, Vol. 4774-20, Society of Photo-Optical Instrumentation Engineers (International Society for Optical Engineering), Bellingham, WA, 2002.

[2] Larin, M., Lumpkin, F., and Stuart, P., "Modeling Unburned Propellant Droplet Distribution and Velocities in Plumes of Small Bipropellant Thrusters," AIAA Paper 2001-2816, June 2001.

[3] Pankop, C., Alred, J., and Boeder, P. Mitigation of Thruster Plume Erosion of International Space Station Solar Array Coatings. Journal of Spacecraft and Rockets (0022-4650); vol.43 no.3, May – June 2006, p. 545-550.

[4] Schmidl, W.D., et al; "N-Nitrosodimethylamine Release from Fuel Oxidizer Reaction Product Contaminated Extravehicular Activity Suits," Journal of Spacecraft and Rockets, 2006, 0022-4650, vol. 43 no. 3, p.557-564.

[5] Schmidl, W.D., et al, "Mitigating Potential Water Dump Particle Impact Damage to the International Space Station," Journal of Spacecraft and Rockets, 2006, 0022-4650, vol. 43 no. 3, p. 551-556.