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Mitigating Potential Water Dump Particle Impact Damage to the International Space Station

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The International Space Station (ISS) and orbiter dump water overboard. This water is from the ISS condensate system and from the orbiter's fuel cell (supply side) and wastewater (urine and condensate) systems. When water is dumped into a vacuum, some of it flashes into vapor. The expanding vapor bursts the stream into vapor and small and large liquid/ice particles. The large liquid/ice particles are approximately 2 mm in diameter and have nominal velocities of approximately 9.45 m/s (U.S. Lab) and 15.24 m/s (Orbiter). As these liquid/ice particles impact sensitive surfaces, including solar array or radiator surfaces, they may cause mechanical damage due to erosion/pitting. Solar arrays are of particular concern because of the thin optical coatings on the surfaces of the cells. The thickness of these coatings is 43,300 Å. Damage to these coatings can cause degradation of the cells' optical characteristics, which can potentially reduce performance and shorten the life of the cells. To mitigate damage from water dumps, the characteristics of the water dumps were studied and the results used to develop the operational constraints needed to mitigate damage to ISS hardware from U.S. Lab and orbiter water dumps. The characteristics of water dumps and how the operational constraints that were developed mitigate potential damage from water dumps are discussed.

I. Introduction

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.[1–3] Figure 1 shows a schematic of water dumping into a vacuum. 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. The thickness of these coatings is 43,300 Å. 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.

II. Characteristics of Water Dumps

A. U.S. Lab Water Dumps

Condensate is produced aboard the ISS by the thermal heating and cooling system and stored in a tank that must eventually be emptied. The tank is fill restricted to 45.4 kg (60.35% of capacity) to prevent hard-filling the tank and to maximize the tank bellows' life. The U.S. Lab condensate system dumps the excess water at cabin pressure [760 torr (14.7 psi)] and with a mass flow rate that is approximately 18 g/s (spec).

The condensate system dumps the excess water overboard through nozzles located on the U.S. Lab forward end-cone. These nozzles are located on the port-zenith and starboard-nadir sides and have a diameter of 1.4 mm. Each nozzle is preheated to 120°C and heated while dumping to keep ice from forming close to the nozzle exit that could result in clogging the nozzle, forming an icicle, or diverting the dump stream. Figure 2 shows the relative position of the condensate dump nozzles and their direction. The plume from the nozzles is directed 37.4 deg from the zenith and nadir directions of the ISS.

The flight experiment SDTO 16004-A (Station Detailed Test Objective 16004-A), performed on 7 September 2001, was designed to videotape a condensate vent using cameras located on the ISS robotic arm, the space station remote manipulator system, and to measure the characteristics of the U.S. Lab water vents.[4–6] One camera captured images of the port nozzle vent and a second camera captured simultaneous images of the starboard nozzle vent.

SDTO measurements included the plume cone angle, the velocity of the large liquid/ice particles, and the duration of each of the dump phases. Figure 3 shows the distinct phases that were observed in the SDTO video. The phases observed were a startup, steady-state, and shutdown phase. The startup phase occurs when the line valve is opened and the liquid first moves into the lower-pressure environment. The steady-state phase occurs for the majority of the dumping duration. The liquid is confined to a narrow directed cone. It lasts for the remainder of the dump, excluding the startup and shutdown phases. The shutdown phase occurs when gas becomes entrained in the condensate water being dumped. The shutdown phase was also divided into an initial shutdown phase and a sputtering shutdown phase. The initial shutdown phase occurs when gas becomes entrained in the condensate tank and the valve is still open. During the initial shutdown phase the plume cone angle is wider and more diffuse than in the steady-state phase and the flow is continuous. The shutdown sputtering phase occurs after the valve is closed and while the line is being baked out to remove residual liquid/ice from the lines. During the shutdown sputtering phase the plume cone angle is wider and more diffuse than the steady-state phase and the flow is intermittent.

The plume cone angles were measured from the centerline for each of the dump phases. It was observed that the plume had a core region where the majority of the liquid/ice particles were concentrated; however, some particles were also observed outside the core region at high angles from the plume centerline.

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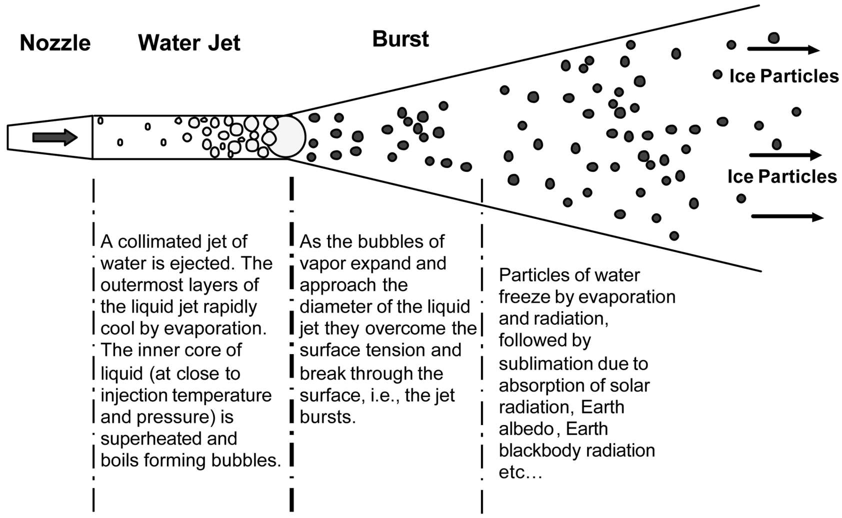


Fig. 1 Schematic of water dumping into a vacuum. The outer layer of water freezes as the inner core of liquid boils and forms bubbles. The expanding bubbles burst the stream into liquid/ice particles.

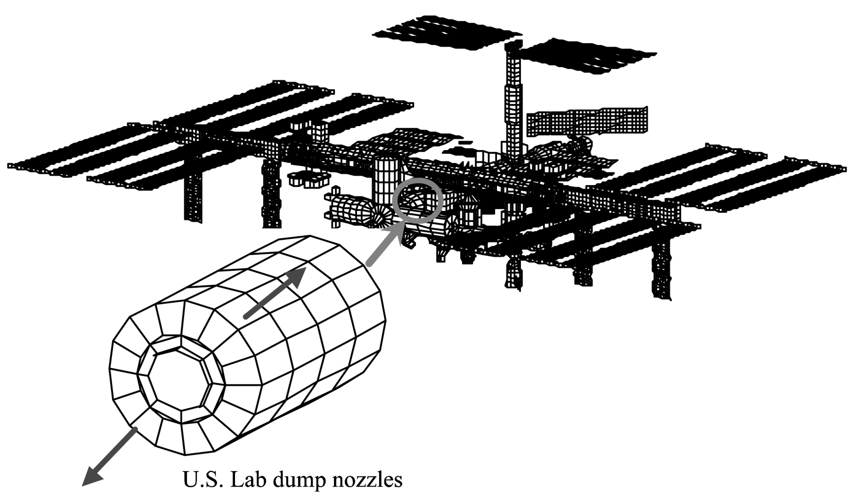
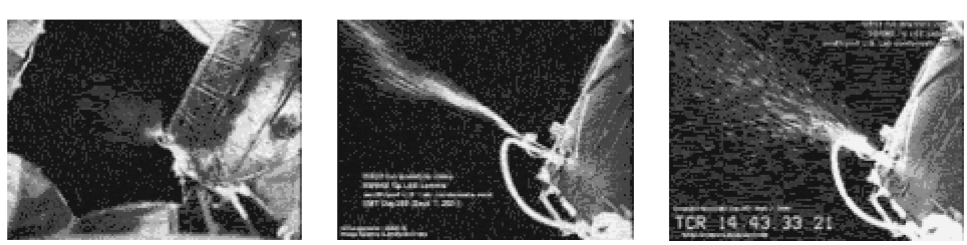


Fig. 2 ISS assembly complete configuration. The arrows indicate the position and direction of the U.S. Lab condensate dump nozzles. The nozzles are located on the starboard-nadir and port-zenith sides of the U.S. Lab.



a) Startup **b) Steady state** **c) Shutdown**

Fig. 3 U.S. Lab water dump video captured during flight experiment SDTO 16004-A. Three phases were observed during the U.S. Lab condensate water dump, a startup, a steady-state, and a shutdown phase. The startup phase lasted ∼36 s, the steady-state phase lasted ∼564 s, and the shutdown phase lasted ∼54 s.

For SDTO 16004-A, ∼145 particles were ejected outside the core region.

In Fig. 3 it can be observed that the steady-state phase has a tight cone. The startup and shutdown phases, at the beginning and end of the dump event, have large cone angles. This is due to the bursting of the dump stream close to the nozzle. The plume cone angle for the steady-state phase was measured to be approximately 10 deg. However, for engineering margin, the plume cone angle for the steady-state phase was defined to be 20 deg. For the startup and shutdown phases, the plume cone angle was defined to be 60 deg.

It can also be seen in Fig. 3b that the steady-state phase has corkscrew-type behavior. This was an interesting and unexpected finding of the SDTO. It has been determined that the likely cause of the behavior is the bends in the piping from the tank to the nozzle exit that induce vorticity in the flow. It can be seen that even with the corkscrew behavior the stream is well contained in a tight cone.

Figure 4 shows the angular distribution function that was developed for each of the phases observed during SDTO 16004-A. For the startup, shutdown initial, and shutdown sputtering phases, the distribution is flat, to account for the larger plume cone angle that was observed. Figure 4b shows the angular distribution function for the steady-state phase. It can be seen that the majority of large particles are concentrated near the plume centerline out to 10 deg. This region is defined as the impact zone. The ISS external contamination team defined the cone out to 20 deg from the plume centerline as the impact zone with engineering margin.

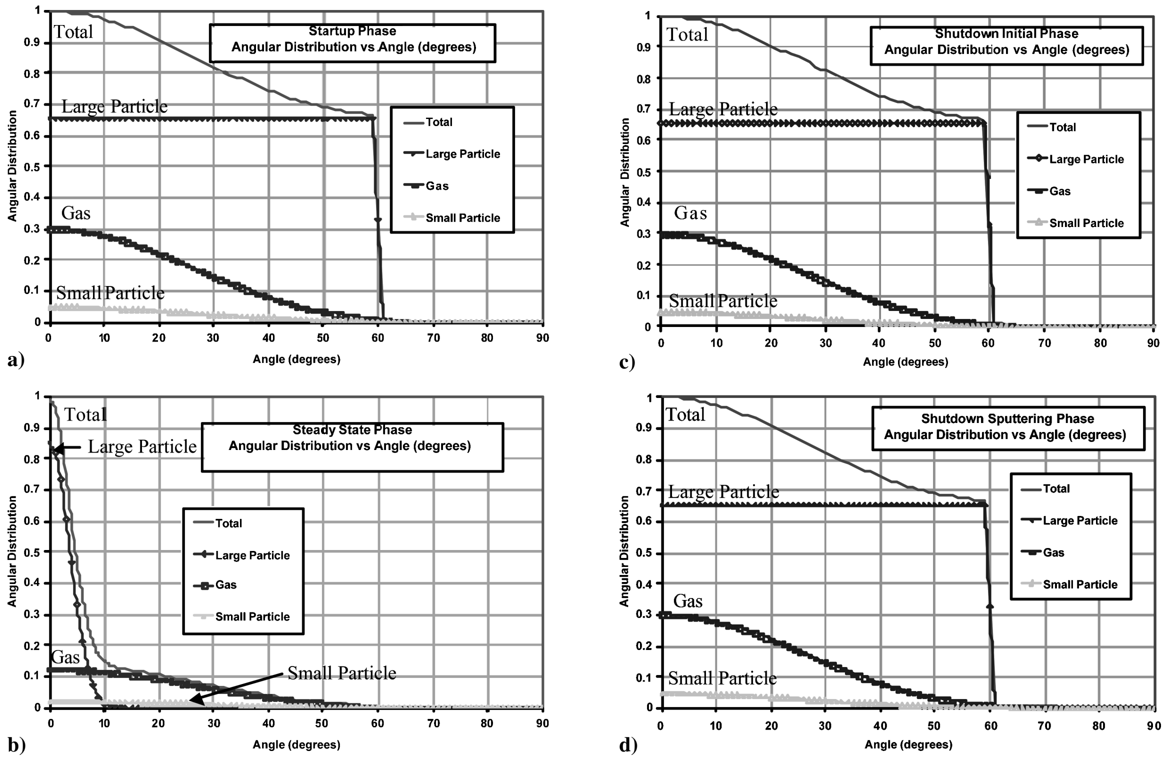


Fig. 4 U.S. Lab water dump cumulative mass fraction distribution: a) startup phase, b) steady-state phase, c) shutdown initial phase, and d) shutdown sputtering phase.

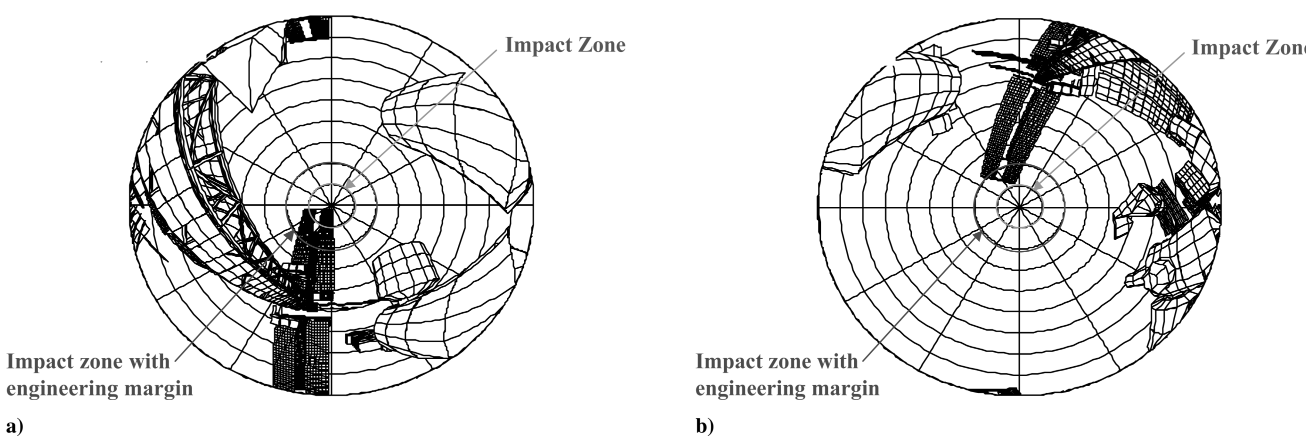


Fig. 5 Field of view from a) port-zenith and b) starboard-nadir U.S. Lab condensate water dump nozzle for complete ISS assembly. It can be seen that if the solar array is not feathered, it will be impacted.

Figures 5a and 5b show hemispherical fisheye fields of views from the port and starboard U.S. Lab condensate water dump nozzles, respectively, for the ISS assembly complete configuration. The center of each view corresponds with the plume centerline of the dump nozzle. The grid on the view is divided so that each circular ring corresponds to 10-deg intervals. So from the centerline to the edge gives a 90-deg view. The 360-deg field of view is also divided into 30-deg sections. In Fig. 5a, the port nozzle view, the Japanese segment hardware can be seen in the lower right-hand section. The ISS port side truss and solar arrays can be seen at the left-hand side of the view. It can be seen that if the solar arrays are not rotated and feathered for the water dump, they could rotate directly into the impact zone with the engineering margin of the water dump. In Fig. 5b, the starboard nozzle view, the European Columbus module can be seen on the upper left-hand side. The ISS starboard side truss and solar arrays can be seen on the upper right-hand side of the view. Once again, if the solar arrays are not rotated and feathered, they could rotate into the impact zone with engineering margin of the water dump.

For each vent phase of SDTO 16004-A, the liquid/ice particle velocities were measured both outside and inside the core region of the plume. For the startup phase, velocities measured outside the 60-deg core region ranged from 1.77 to 4.57 m/s (measured velocities including the core region ranged from 0.85 to 9.33 m/s). For the steady state phase (core region within 20 deg), from the average flow rate and nozzle diameter, the average velocity was determined to be 9.45 m/s. For the initial shutdown phase, measured velocities outside the core region ranged from 0.61 to 1.01 m/s (measured velocities including the core region ranged from 0.61 to 2.44 m/s). For the shutdown sputtering phase, measured velocities outside the 60-deg core region ranged from 0.61 to 1.40 m/s. (Measured velocities including the core region ranged from 0.46 to 2.77 m/s.)

The phase durations for the SDTO 16004-A dump, as shown in Fig. 3, were determined from the video by the NASA Image Science and Analysis Group. The startup phase took approximately 36 s, the initial shutdown phase took approximately 22 s, and the shutdown sputtering phase took approximately 32 s. The steady-state phase lasted for the remainder of the dump, which lasted ~564 s for this experiment (SDTO 16004-A). The steady-state phase duration is solely dependent on the quantity of water dumped, whereas the durations of the other phases (startup, shutdown, shutdown sputtering) are dependent on the characteristics of the piping, valves, and nozzle geometry.

B. Orbiter Water Dumps

The orbiter dumps both waste water (urine and condensate) and supply water. Supply water is generated by the orbiter's fuel cells and is extremely pure, and so it is not a molecular deposition concern. The condensate water is collected from the orbiter cabin and has approximately 0.004% nonvolatile residues in the water. So it does not leave a significant deposit. Pure urine contains approximately 4% residue and is a deposition concern. To protect the solar cells from urine deposits, the solar arrays are feathered so that only the backside is hit. The feathering angles defined to protect against erosion/pitting will also mitigate deposition concerns.

Flight rules are currently in place to minimize urine dumps. To minimize urine dumps, urine, and condensate water are separated, and the condensate water is stored in contingency water containers. Only urine in excess of the tank capacity is dumped overboard. All urine dumping is to be discontinued when the Japanese hardware goes up, because it is in direct line of sight of the orbiter vent nozzles.

Water released from the orbiter is dumped through two nozzles located close to each other on the orbiter's port side and is directed to the port side of ISS. One nozzle is for supply side water and the other is for wastewater. The nozzles are 1.4 mm in diameter. Water released from each nozzle is dumped at 1603.2 torr (31 psia) at 23.7 g/s.

The concern for orbiter water dumps is with sensitive hardware on the port side of ISS. Figure 6 shows a schematic of the direction of the orbiter dump for the ISS assembly complete configuration. It can be seen that hardware on the port side of ISS includes the Japanese hardware, port-side truss, and port-side solar arrays. Figure 7 shows a representative image of the orbiter dumping water. The inset figure was captured from a video of the orbiter water dump for comparison.

The Arnold Engineering Development Center (AEDC) performed ground laboratory tests and measured the characteristics of the orbiter water dump. These measured characteristics include the orbiter water dump plume cone angle, the composition of the plume (the fractions of vapor/ small particles/ large particles), and the velocity of the large particles. The results from the AEDC ground tests were compared with flight images. The results show that the velocity of the particles is nominally 15.24 m/s and the plume cone angle is 10 deg. Based on the data and results, an orbiter dump model was developed by the Boeing external contamination team, the Boeing two-phase water dump plume model for orbiter.[7]

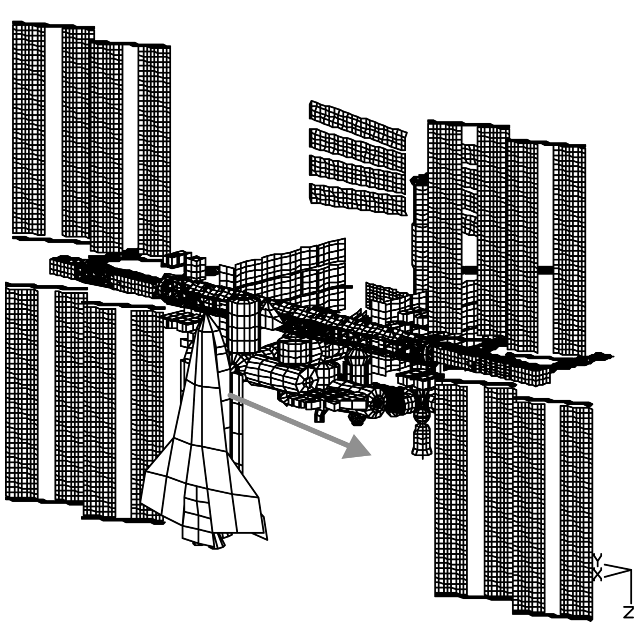


Fig. 6 Orbiter water dump for ISS assembly complete. The orbiter dumps water out to the port side of ISS.

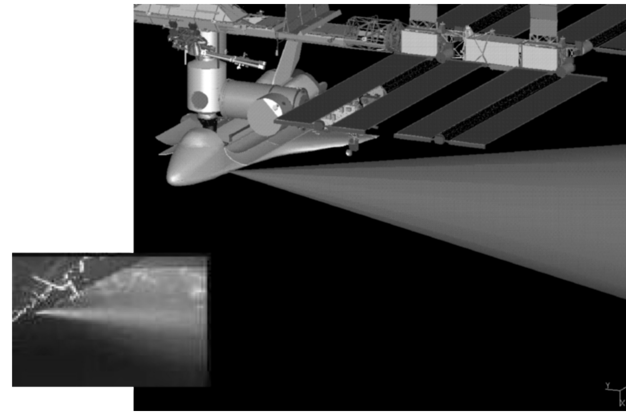


Fig. 7 Representative image of orbiter water dump. The inset image was captured from a video of the orbiter water dump.

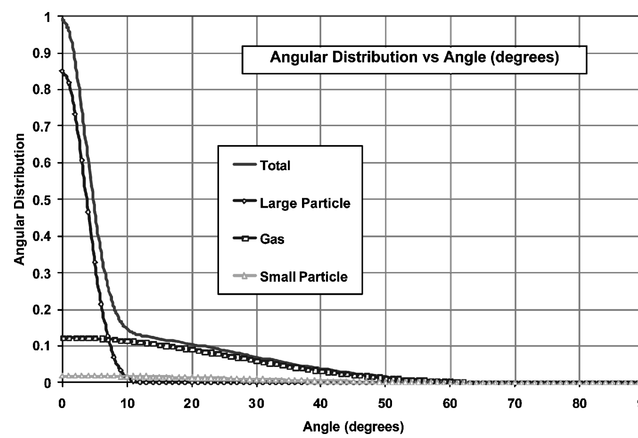


Fig. 8 Boeing two-phase water dump plume model for orbiter. The region from the plume centerline out to 10 deg is defined as the impact zone. The region out to 20 deg is defined as the impact zone with engineering margin.

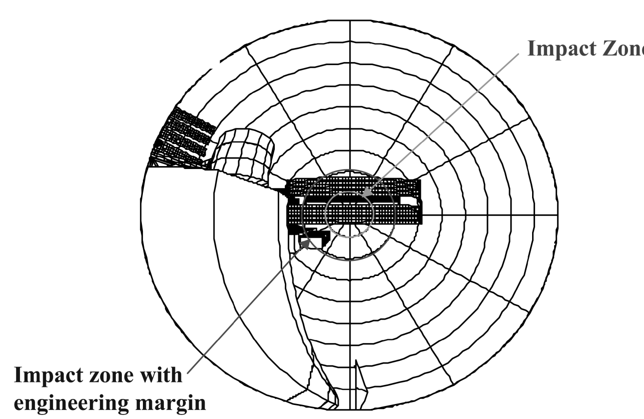


Fig. 9 Field of view from orbiter water dump nozzles for ISS assembly complete. It can be seen that if the solar array is not feathered, it will be impacted broadside.

Figure 8 shows the plume distribution for that model. It can be seen that the majority of large particles are concentrated near the centerline of the plume out to 10 deg. This region is defined as the impact zone. The ISS external contamination team defined the cone out to 20 deg from the plume centerline as the impact zone with engineering margin.

Figure 9 shows the hemispherical fisheye field of view from the orbiter dump nozzles for ISS assembly complete. The orbiter payload bay door can be seen in the lower left-hand side of the image and shields the hardware behind it. Sensitive surfaces of concern are the Japanese Aerospace Exploration Agency (JAXA) payload sites and the P4/P6 radiators and solar arrays. The JAXA payload sites can be seen just below the center of the plume. It can be seen that if the solar array is not feathered, it will be impacted broadside. In this configuration, the radiator is rotated out of the field of view. As will be shown later, the solar arrays should be feathered so that the impacts occur on the backside of the array and at a shallow (15-deg) angle.

III. Damage Mitigation and Operational Constraints

SPHINX is an impact code developed at the Los Alamos National Laboratory.[8–10] SPHINX uses smooth particle hydrodynamics to simulate impact phenomena. SPHINX has been applied in the past to modeling thruster droplet impacts onto sensitive surfaces to develop the appropriate feathering angles for the solar arrays.[7] The results from these studies showed that direct impacts normal to the surface would damage the solar cells. Impacts at a shallow angle to the surface of less than 15 deg (or 75 deg from the surface normal) did not show any damage to the solar cells.

Using these results as a starting point, the operational constraints needed to mitigate damage from liquid/ice particle impacts were developed. 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 1300-Å SiO_x 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 deg/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 deg from the plume centerline.

The operational constraints developed for the U.S. Lab condensate water dumps and orbiter water dumps will be discussed in the next section. These constraints are being incorporated into flight rules.

A. U.S. Lab Water Dump Damage Mitigation and Operational Constraints

Figure 10 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.

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. 11. This table was developed based on the defined constraints. This table gives allowable solar array α/β 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

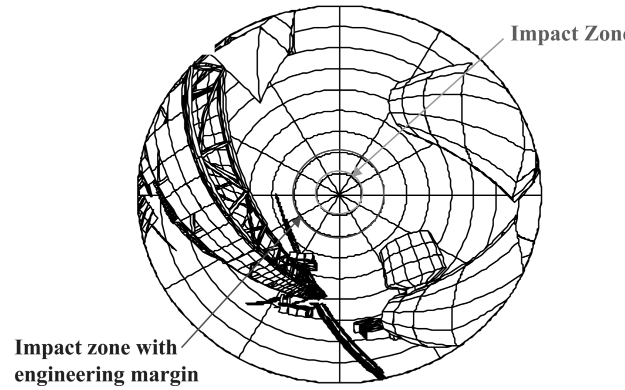


Fig. 10 Field of view from port-side U.S. Lab condensate water dump nozzle for complete ISS assembly. The solar array is feathered and rotated out of the impact zone with engineering margin.

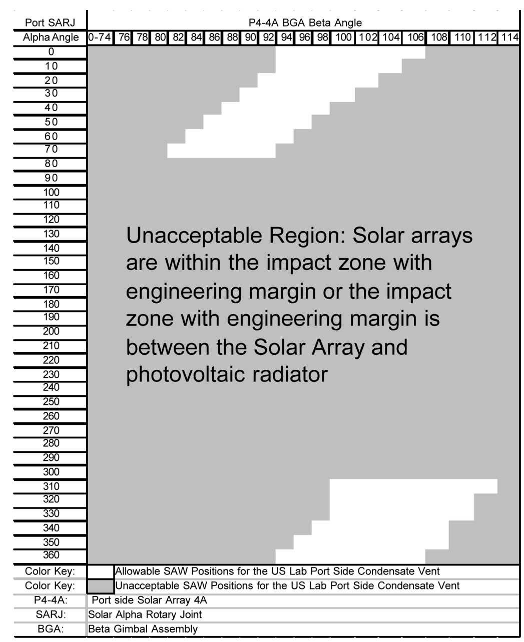


Fig. 11 Example U.S. Lab port-side condensate water dump allowable solar array feathering angles for the P4-4A solar array wing (SAW) for β gimbal assembly β-rotations from 0 to 238 deg. White zone is allowable SAW positions.

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

B. Orbiter Water Dump Damage Mitigation and Operational Constraints

Figure 12 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 will be discontinued when the Japanese hardware goes up on orbit.

Allowable feathering angle α/β 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.

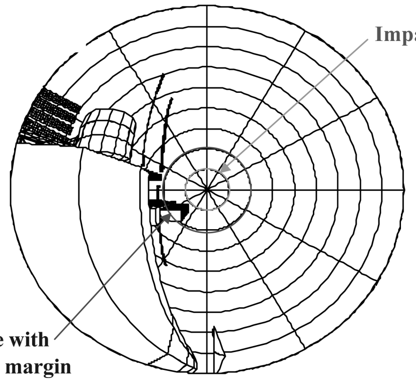


Fig. 12 Field of view from orbiter water dump nozzle for complete ISS assembly. The solar array is feathered and rotated out of the impact zone with engineering margin.

IV. Conclusions

The International Space Station (ISS) and orbiter both dump water overboard into space. The dumped stream bursts into liquid/ice particles. The large liquid/ice particles are approximately 2 mm in diameter and have nominal velocities of approximately 9.45 m/s (U.S. Lab) and 15.24 m/s (orbiter). As these liquid/ice particles impact, they can cause mechanical damage due to erosion/pitting of sensitive surfaces, such as the coatings used on the solar array or radiator surfaces. 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.

To mitigate damage from water dumps, the characteristics of the water dumps were studied. The results were 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 preclude damage to the solar array and radiator surfaces.

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Guest Editor