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MICROMETEOROID AND ORBITAL DEBRIS THREAT MITIGATION TECHNIQUES FOR THE SPACE SHUTTLE ORBITER

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ABSTRACT

An overview of significant Micrometeoroid and Orbital Debris (MMOD) impacts on the Payload Bay Door radiators, wing leading edge reinforced carbon-carbon panels and crew module windows will be presented, along with a discussion of the techniques NASA has implemented to reduce the risk from MMOD impacts. The concept of "Late Inspection" of the Nose Cap and Wing leading Edge (WLE) Reinforced Carbon Carbon (RCC) regions will be introduced. An alternative mated attitude with the International Space Station (ISS) on shuttle MMOD risk will also be presented. The significant threat mitigation effect of these two techniques will be demonstrated. The wing leading edge impact detection system, on-orbit repair techniques and disabled vehicle contingency plans will also be discussed.

INTRODUCTION

NASA's Space Shuttle program has completed 123 shuttle flights between 1981 and 2008. Orbiter vehicles have spent nearly 1,167 days in low Earth orbit in altitudes ranging from 220 to 600 kilometers and inclinations between 28.5 and 62 degrees. This paper will document protection upgrades, operational changes, inspection and repair techniques that have served to mitigate risk from MMOD impacts, with emphasis placed on changes taking place since Return to Flight in 2005.

BUMPER-II

BUMPER-II is an MMOD risk analysis program originally developed for the Space Station Freedom Program. Over the years, the capabilities of this engineering analysis tool have been extended to include the Space Shuttle Orbiter, ISS and many other spacecraft. When provided with a vehicle shape, orbit parameters and applicable ballistic limit equations with defined failure criteria, the BUMPER-II code will calculate the MMOD risk for spacecraft in low Earth orbit against a variety of natural and man-made environments. Thousands of hypervelocity impact tests have been performed on representative samples of ISS shields and subsystems, Shuttle thermal protection system (TPS) materials, Extravehicular Mobility Unit (EMU) materials and other spacecraft components to determine MMOD impact parameters at the failure limits of the various subsystems. BUMPER is used to calculate MMOD impact risks to specific Orbiter surfaces. An integrated mission assessment is completed using Poisson statistics and knowledge of the distribution of times spent in each unique Orbiter attitude [1].

MITIGATION HISTORY

Previous shuttle modifications to increase MMOD protection have been discussed by Loftus, et al. [2]. They include improvements to the wing leading edge thermal protection system with Nextel insulation blankets that increase thermal margins of the panel's structural attachment to the wing spar. Another improvement discussed by Loftus involved the installation of aluminum doublers over the coolant tubes in the payload bay door radiators and the addition of isolation valves to prevent excessive loss of coolant in the event of tube leak. These protection upgrades were installed throughout the fleet in the mid 1990's [3]. Operational protocols for collision avoidance maneuvers that were implemented by the Space Shuttle Program in the 1980's are an example of an operational change that mitigated impact risk [4]. Large orbital debris fragments are tracked by the US Space Command's Space Surveillance Network, which communicates possible future conjunctions to the Flight Dynamics Officer in Mission Control Center. Another example of an operational change that reduced MMOD risk was the introduction of a flight rule concerning orbiter attitude. The rule provides guidance on flight attitudes that minimize MMOD risk [4]. In general, the flight rule puts the orbiter in an attitude where the tail is forward and the payload bay faces earth. At the time the flight rule was published, this was considered the minimum risk attitude for critical MMOD damage.

SIGNIFICANT MMOD IMPACTS

One of the earliest documented impacts on the shuttle occurred during the STS-7 mission in 1983 when an orbital debris particle of spacecraft paint produced a 4mm pit in a crew module window [3]. The crew photographed the impact site on orbit.

The STS-50 mission in 1992 spent nearly 10 days in a nose space, payload bay forward attitude during a 16 day Extended Duration Orbiter (EDO) mission. Postflight inspections revealed a 0.57 mm deep crater with a diameter of 7.2 mm x 6.8 mm in window #4 (right hand forward). The damage caused the window to be removed and replaced. The STS-50 mission experienced a large increase in payload bay door radiators impacts when compared to previous missions [6]. The largest radiator impact on STS-50 occurred on left hand forward panel #1. The impact produced a 3.8 mm diameter hole in the thermal control tape and a 1.1 mm diameter hole in the face sheet.

The 16 day STS-73 mission in 1995 carried a United States Microgravity Module (USML) Spacelab module and an EDO cryogenics pallet in the payload bay. The vehicle was oriented with its port wing into the velocity vector for 13 days of the mission, so the port payload door was kept partially closed in order to protect the USML and EDO payloads from MMOD impacts. Post flight inspections revealed a crater in the outside surface of the port payload bay door that was 17 mm in diameter and 6 mm deep. A 1.2 mm long intact fragment of a circuit board was found in the crater [6]. If this orbital debris projectile had impacted a different region of the orbiter, such as the EDO pallet or a wing leading edge RCC panel, it could have caused the loss of the vehicle and crew.

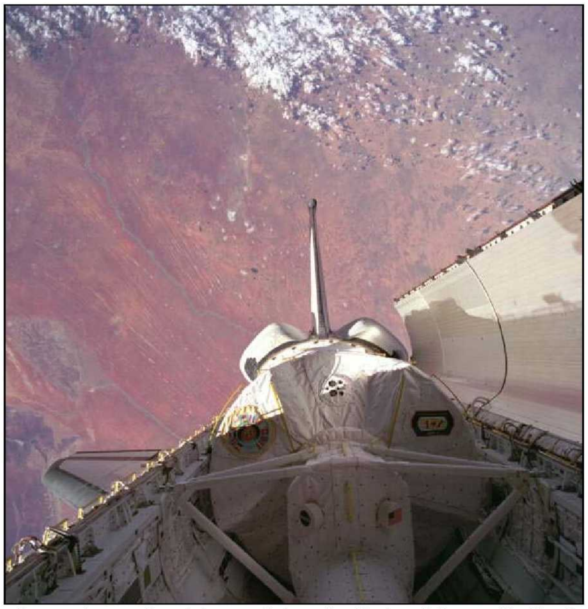

Figure 1. Payload bay of shuttle Columbia on STS-73

After the STS-86 mission in 1997, several significant MMOD impacts were observed on the left hand radiator interconnect lines (Fig. 2). The aluminum tubes carry Freon coolant between the thermal control system radiator panels.

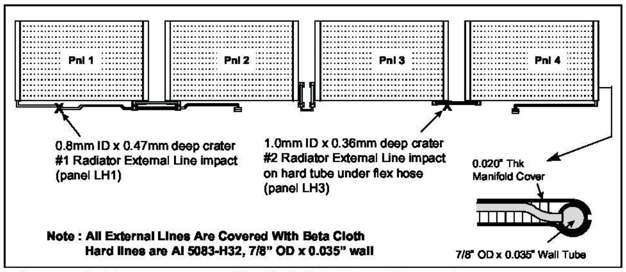

Figure 2. Impacts on STS-86 LH radiator interconnect lines.

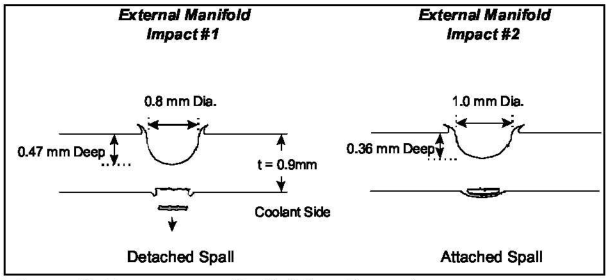

Figure 3. Impacts on STS-86 radiator interconnect lines.

The largest impact, on the external line at panel #1, penetrated just over halfway through the 0.9 mm wall thick coolant tube wall [6]. Post flight inspections determined that the site experienced detached spall on the inside surface of the tube wall, close to a tube perforation (Fig. 3). A tube leak would likely have resulted in a mission abort and possible loss of mission objectives. Post flight analysis indicated that impact #1 was caused by an orbital debris particle of stainless steel, while impact #2 was produced by a micrometeoroid particle. After this mission, an additional layer of beta cloth was added to the external radiator lines on all orbiters [6].

The STS-118 mission in 2007 experienced a large MMOD impact on the left hand #4 radiator. The impact produced a 5.5 mm diameter entry hole in the thermal tape and outer face sheet of the aluminum sandwich panel (Fig. 4). Subsequent inspections revealed a 12 mm x 19 mm exit hole in the inner face sheet of the radiator panel, with two small down stream damage sites on a thermal control system (TCS) blanket under the radiator. The payload bay door under the TCS blanket was not damaged by the impact. Analysis showed that this impact was caused by an orbital debris particle that was rich in Titanium, Zinc and Antimony.

Figure 4. MMOD impacts on STS-118 LH4 radiator.

COLUMBIA ACCIDENT AND AFTERMATH

On February 1, 2003, the Space Shuttle Columbia was destroyed on reentry due to a failure of the TPS. A piece of foam debris punctured an RCC panel on the left wing leading edge and allowed hot plasma from the reentry to enter the wing and break the shuttle apart from within [7].

The Space Shuttle program has made several operational changes since the disaster in an attempt to lower the risk of damage that would cause a loss of the vehicle on reentry.

RCC FAILURE CRITERIA UPDATES

As part of the Shuttle Return-to-Flight effort, the NASA/JSC Hypervelocity Impact Technology Facility performed hypervelocity impact testing and analysis of Shuttle WLE RCC test samples to update threshold failure criteria [8]. After the hypervelocity impact (HVI) tests, the samples were exposed to typical reentry heating conditions at the NASA/JSC Arc-Jet (AJ) Facility to determine the extent of heating induced damage growth. It was found from the HVI/AJ testing that non-penetrating pits would lead to burn-through in some areas of the WLE where burn-through can lead to loss-of-vehicle (LOV) during reentry. Results of the AJ testing on RCC indicated that the WLE failure criteria for LOV should be reduced for MMOD assessments on future missions. Figures 5 and 6 show the WLE and nose cap failure criteria maps before and after the changes.

The reduction in allowable damage increased calculated MMOD risks for future missions [9]. The knowledge of a specific regional vulnerability allowed a strategic response to the risk, which is described in the following sections.

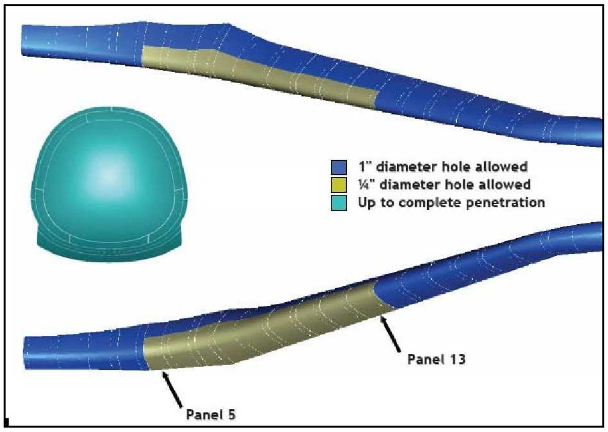

Figure 5. Pre-STS-107 RCC failure criteria map.

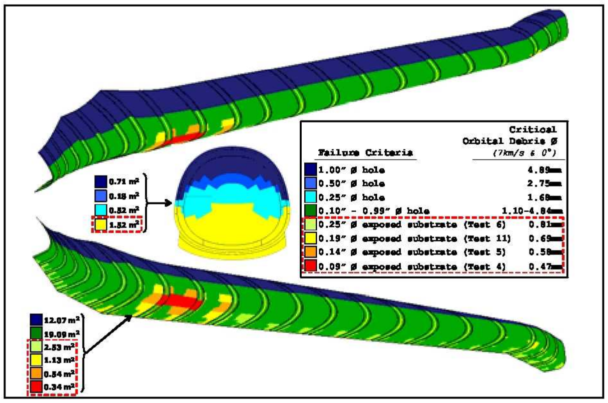

Figure 6. Post-STS-107 RCC failure criteria map.

ORBITER/ISS MATED ATTITUDES

The Shuttle and ISS Programs were able to mitigate a significant portion of the increased MMOD impact risk to the orbiter by changing the orientation of the ISS while the shuttle is docked. The change in orientation – essentially flying the ISS "backwards" – provided incidental shielding to the shuttle as well as directing MMOD sensitive areas of the WLE and nose cap away from the majority of the MMOD particle flux. Figure 7 shows the shuttle-ISS docked attitude before the orientation change, with the belly of the vehicle oriented into the velocity direction of ISS motion and highest MMOD impact flux. The attitude change illustrated in figure 8 orients the bottom of the shuttle in the wake direction of ISS reducing MMOD impacts to the most vulnerable surfaces of the vehicle and improving crew safety and odds of mission success.

Analysis has shown the ISS -XVV docking attitude results in a 3X reduction in overall MMOD mission risk for the orbiter when compared to a mission with equivalent ISS +XVV exposure hours. The revised docking attitude increases the MMOD risk to the upper wing and fuselage TPS, but these areas have a higher damage tolerance for reentry. The new docking attitude produces a higher risk of replacement for crew module windows, which is a cost and schedule issue for the shuttle program. The risk of a payload bay door radiator tube leak is also higher with the new docking attitude. The program impact of a radiator tube leak failure is a potential early mission abort.

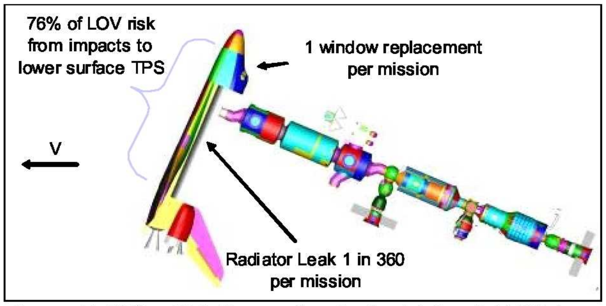

Figure 7. ISS +XVV mated attitude, higher MMOD impact risk to lower TPS

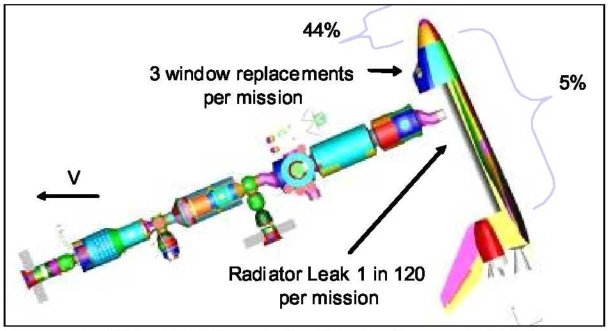

Figure 8. ISS –XVV mated attitude, lower MMOD impact risk to lower TPS, residual risk concentrated on nose cap

ON-ORBIT INSPECTION

Since the STS-114 mission in 2005, in which Discovery made the first flight following the Columbia accident, NASA has implemented several new procedures to verify TPS integrity. Prior to docking with the ISS, Discovery performed a Rendezvous Pitch Maneuver, simply a 360° pitch rotation, allowing high resolution imagery of re-entry critical areas of the vehicle to be acquired by astronauts aboard the ISS.

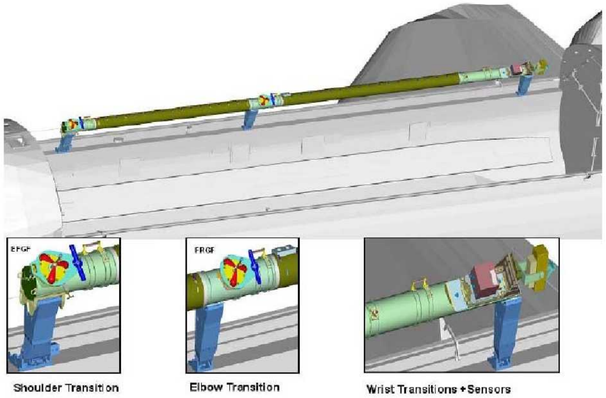

Figure 9. Orbiter Boom Sensor System.

The STS-114 mission also included the 15.2 m long Orbiter Boom Sensor System (OBSS), shown Figure 9. The OBSS, an extension to the Remote Manipulator System (RMS), was used to inspect the orbiter for damage. The Integrated Sensor Inspection System (ISIS) at the end of the OBSS is shown in figure 10. The ISIS consists of two sensor packages. Sensor Package 1 (SP1) includes the Laser Dynamic Range Imager (LDRI) and Intensified Television Camera (ITVC), both mounted on a Pan and Tilt Unit (PTU). The LDRI was primarily used to provide imagery of the wing leading edge and nose cap RCC surfaces. The ITVC was primarily used to collect additional imagery (focused inspections) of RCC areas of interest as identified by a screening team.

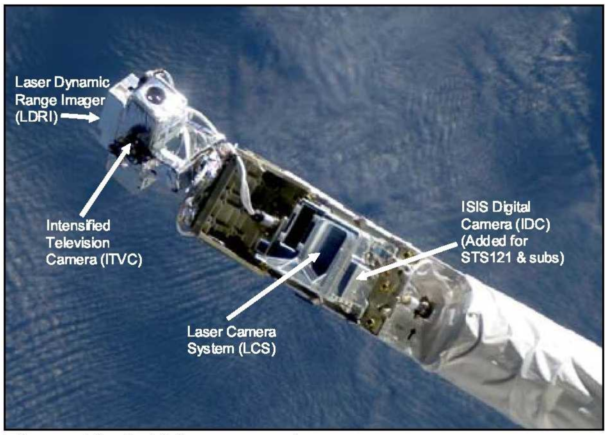

Figure 10. OBSS sensor suite

Sensor Package 2 (SP2), for STS-114, consisted of the Laser Camera System (LCS). The LCS was primarily used for detailed 3D measurements of damaged tile regions. After STS-114, SP2 also includes an ISIS Digital Camera (IDC). The IDC is a higher resolution 2-dimensional digital camera. It is used to collect additional imagery (focused inspections) of RCC areas of interest as identified by screening and damage assessment teams.

The next return to flight mission, STS-121 in 2006, introduced a late inspection procedure. The goal of late inspection is to inspect the Orbiter, as late in the mission as possible, for MMOD damage to RCC surfaces. Typically, the LDRI sensor is used to inspect the RCC surfaces in the same manner as the flight day 2 early inspections. Imagery returned by the sensors is examined for distinct features consistent with MMOD damage. The sensor system can be used to discern impact features as small as 2 mm (0.080 inches).

Analysis has shown that late inspection can mitigate as much as 50% of the critical MMOD risk on a typical shuttle mission. It's possible that improvements in the system discernment level and inspection efficiency could lead to further reductions in MMOD risk.

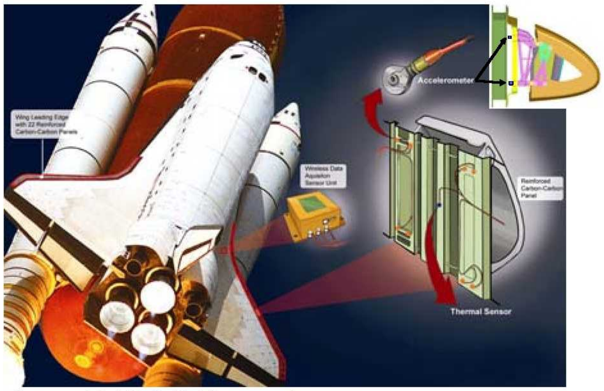

Figure 11. WLEIDS overview

ON-ORBIT DETECTION

The WLEIDS consists of 132 single axis accelerometers mounted along the length of the orbiter's leading edge wing spars (Fig. 11). During launch, the accelerometers collect data at a rate of 20 kHz and store that data onboard for subsequent downlink to Mission Control [10]. Within 6 to 8 hours of launch, summary files containing periodic sub-samples of the data collected by each accelerometer are down linked for analysis to find potential signatures of ascent damage. This analysis must be completed within 24 to 48 hours of the launch so the results can be used to schedule focused inspection using the OBSS sensor. The WLEIDS has some limited capability to detect MMOD impacts to the WLE, and this data may also be used to guide and influence inspection decisions.

ON ORBIT REPAIR

The Shuttle program has manifested two options for on orbit RCC repair. The repair must prevent plasma flow through the damaged RCC. One option is a pre-ceramic polymer designed to repair small cracks and coating losses on the exterior of the RCC panel. The crack repair option uses a pre-ceramic polymer sealant impregnated with carbon-silicon carbide powder, together known as NOAX (Non-Oxide Adhesive eXperimental). It is designed to be applied by an astronaut using a space-adapted caulking gun and putty knife.

The second repair option is designed for the repair of 13 to 100 mm diameter holes in RCC panels. The plug repair consists of a carbon silicon carbide (C-SiC) patch coated with sealant and mechanically attached to the remaining RCC structure with a T-bar attachment mechanism made of TZM (a molybdenum alloy). The plug is a 178 mm diameter, 0.762 mm thick cover plate that are designed to flex up to 6 mm to conform to the shape of the wing leading edge RCC panels, and a hardware attachment mechanism similar to a toggle bolt. If the damage site is less than 25 mm, astronauts would use a special bit to drill out the hole.

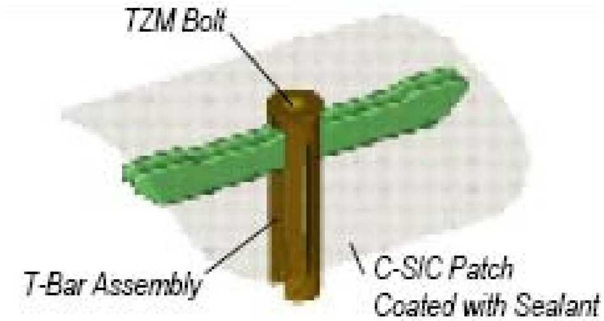

Figure 12. Plug repair concept.

SAFE HAVEN

As a last resort, Contingency Shuttle Crew Support (CSCS), also known as safe haven, would be used to return the crew of a critically damaged Shuttle. If repair operations were determined to be unsuccessful, CSCS could be used to rescue the crew. The CSCS scenario allows the visiting crew of a critically damaged Shuttle to live onboard the Space Station until a rescue Shuttle can be launched. The viability of this option is tied to resource limitation on the ISS and the time required to prepare a rescue vehicle for launch.

SUMMARY

A number of recent shuttle MMOD threat mitigation techniques were presented. Inspection methods include photographic examinations of the thermal protection system with the Rendezvous Pitch Maneuver and the Orbiter Boom Sensor System. Recognition of MMOD impacts with the Wing Leading Edge Impact Detection System was described. Two Wing Leading Edge RCC repair methods were discussed: NOAX repairs, for coating damage and Plug repairs for holes. Operational changes for the flight program include a revised mated attitude when the shuttle is docked to the International Space Station. The Contingency Shuttle Crew Support (Safe Haven) option and Launch on Need (LON) rescue vehicle were presented as a last resort to save the crew of a damaged shuttle.

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