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Paper Session II-A - Meteoroid and Orbital Debris Protection for the International Space Station Alpha

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ABSTRACT

The potential for collisions with natural particles (meteoroids) at relative velocities up to 72 km/sec (155,000 mph) has historically been a design consideration for spacecraft. The deposition of man-made particles, referred to as orbital debris, into orbit around the Earth presented an even more severe hypervelocity impact problem for spacecraft designers. This paper examines the threat to the International Space Station Alpha (ISSA) imposed by the meteoroid/orbital debris (M/OD) environment and the risk management approaches implemented to mitigate the threat.

The ISSA program has established a balanced strategy for managing the risks associated with the M/OD threat based on the following three principles: 1) maximize design protection by implementing state-of-the-art shielding, 2) track and avoid the larger objects, and 3) minimize residual risk by implementing risk control and abatement features and procedures.

Even though NASA is using effective hardware and operational risk mitigation approaches, there remains a residual risk of a penetrating impact. Due to weight, volume, and funding constraints, a gap exists between the passive protection (shielding) capability and active protection (collision avoidance) lower particle size tracking limits. Fortunately, the estimated number of impacts per year decreases exponentially as the size of the particle increases. With the implemented design and planned operational measures, the resulting residual risk of an impact that could potentially cause severe damage to the station is extremely small. Options are continually being assessed and implemented to reduce the residual risk and increase reliability. Control of the debris threat is being pursued by NASA through international treaties and agreements among all space-faring nations. These agreements refer to guidelines for the design, development and operation of satellites with the intent to reduce the evolving orbital debris environment.

1. INTRODUCTION

The potential for collisions with natural particles (meteoroids) at relative velocities up to 72 km/sec (155,000 mph) has historically been a design consideration for spacecraft. The deposition of man-made particles, referred to as orbital debris, into orbit around the Earth presented an even more severe hypervelocity impact problem for spacecraft designers. This paper examines the threat to the International Space Station Alpha (ISSA) imposed by the meteoroid/orbital debris (M/OD) environment and the risk management approaches implemented to mitigate the threat.

2. CHARACTERIZATION OF THE M/OD THREAT

The flux of M/OD particles that are encountered by an object in low Earth orbit is essentially random but lends itself well to statistical quantification of the number of particles of a given characteristic size that would be encountered by a randomly tumbling flat plate per unit area and time. Flux is defined as number of intercepted objects per unit time and area, typically in terms of per square meter per year. The primary method of characterizing the threat of significant damage to the ISSA operating within the M/OD environment is described in terms of a probability of no penetration (PNP). The PNP function is described as:

$$PNP[d > D_{crit}] = e^{-fat}$$

where

f = penetrating flux, number of particles per square meter per year of diameter d or larger that defeat the shielding (D_{crit})

a = effective area of spacecraft, sq. meters

t = time in space, years.

2.1 Meteoroids

Meteoroids are natural bodies remaining from the formation of the solar system or from collisions of other natural bodies making up the solar system. Nearly all meteoroids originate from comets or asteroids. The meteoroid flux represents at any time a total of about 200 kg of mass within 2000 km of the Earth's surface. Most of this mass is concentrated in 0.1 mm or smaller micrometeoroids.

The precession of the spacecraft's orbit and tilt of the Earth's equatorial plane relative to the ecliptic contribute to making the micrometeoroid environment relatively omnidirectional. The micrometeoroid threat becomes anisotropic relative to the spacecraft moving through the environment with most strikes coming from the direction of motion. Further, shadowing provided by the Earth tends to reduce strikes in the direction of the Earth (nadir).

The meteoroid environment model remains relatively unchanged since its initial documentation in the 1960's. The implemented model is very similar to that used for the design and assessment of Apollo, Skylab, and Shuttle. In discussions with Russian technical experts, the NASA meteoroid model was determined to be very similar to the model that was used for the design of their spacecraft including the currently orbiting MIR. This time proven model is being used for ISSA design.

2.2 Orbital Debris

Man-made orbital debris differs from natural meteoroids because it remains in Earth orbit during its lifetime instead of passing through the space around the Earth. Within 2000 km of the Earth's surface there is an estimated 1.5 to 3 million kg of man-made orbiting objects as of mid 1988. Most of these are in high inclination orbits where they sweep past each other at an average velocity of 10 km/s. About 1500 spent rocket stages, inactive payloads, and a few active payloads account for most of this mass. These objects along with 4500 others totaling about 20,000 kg, are mostly fragments of satellites or other orbiting hardware. Observations indicate a total mass of about 1000 kg for orbital debris with diameters of 1 cm or smaller and about 300 kg for orbital debris sizes smaller than 1 mm. This distribution of mass makes the orbital debris environment more hazardous than the meteoroid environment in most spacecraft applications below 2000 km altitude as is certainly the case for ISSA.

Figure 1 shows the comparison of meteoroid and orbital debris fluxes as a function of size from the environmental model currently baselined for ISSA design. As a result of measurements and analyses of the orbital debris environment conducted over the last three years, revisions to the orbital environment model for the space station are being formulated and are now under review. The measurements and analyses indicate that the flux for orbital debris larger than 0.5 cm at space station altitudes is as much as a factor of two lower than current model predictions.

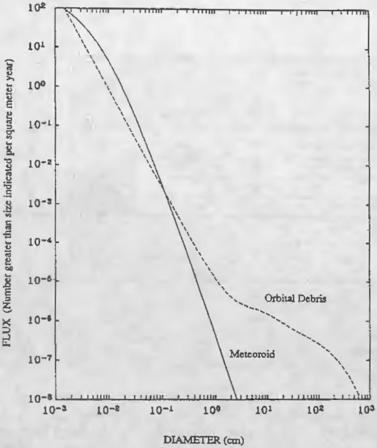

Figure 1. Comparison of Meteoroid and Orbital Debris Flux

3. M/OD PROTECTION AND RISK MANAGEMENT

3.1 Strategic Plan

The ISSA program has established a strategy for managing the risks associated with the M/OD threat based on the following three principles: 1) maximize design protection by implementing state-of-the-art shielding, 2) track and avoid the larger objects, and 3) minimize residual risk by implementing risk control and abatement features and procedures. This three part approach to the strategic plan is related to the small, midrange, and large particle size regimes illustrated in Figure 2.

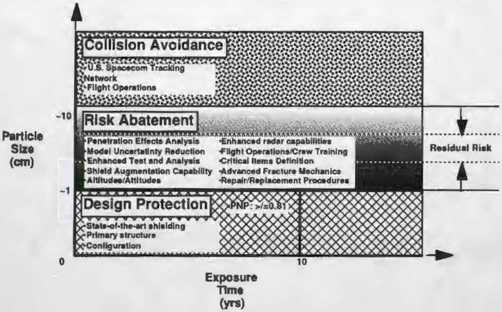

Figure 2. M/OD Strategic Plan

Over 99% of the number of threatening particles are small enough (microscopic to marble size) that the potentially damaging penetrations may be avoided by hardware protection systems (shielding). For this reason, primary emphasis is placed on design protection as the preferred method of risk mitigation. Operational mitigation approaches include scheduled maintenance and repair activities and collision avoidance maneuvers.

Even though NASA is using effective hardware and operational risk mitigation approaches, there remains a residual risk of a penetrating impact. Due to weight, volume, and funding constraints, a gap exists between the passive protection (shielding) capability and active protection (collision avoidance) lower particle size tracking limits. Fortunately, the estimated number of impacts per year decreases exponentially as the size of the particle increases. With the implemented design and planned operational measures, the resulting residual risk of an impact that could potentially cause severe damage to the station is extremely small. Penetration effects analyses examine the potential hazards associated with a penetration of a habitable module or other critical item. These analyses are used to assess the ability of the ISSA to safely perform its mission with a reliability goal of greater than 99.7% per year. Options are continually being assessed and implemented to reduce the residual risk and increase reliability.

3.2 Hardware Design Protection

The hardware design protection strategy consists of dedicated shielding of M/OD critical items. An item is classified as M/OD critical when effects resulting from a penetration could immediately endanger the survivability of the space station or the crew (items primarily consist of the habitable modules). Although all exposed components are subject to M/OD impacts, those which do not impose immediate, time critical hazards to crew or station survival are evaluated and shown to meet against established equipment performance and maintainability criteria.

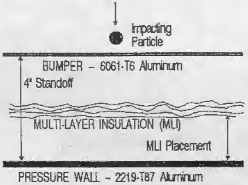

Figure 3. Typical Whipple Shield

The basic shielding techniques utilized on the U.S. habitable modules consists of a thin plate of aluminum with a stand off from the pressure wall (see Figure 3). Known as a "Whipple" shield, this simple but highly effective technique utilizes the outer bumper to break up the impacting particle into smaller pieces thus distributing the impact on the primary wall. Due to the tremendous level of energy dissipated during an impact, characterization of the event is complicated by the transphase/multiphase physical processes and thermodynamics of the events that follow. Hypervelocity impact testing at velocities up to 7 km/s and sophisticated hydrocode analytical simulations are used to characterize the penetration resistance of M/OD shielding.

Recent NASA developments in shield technology have advanced the state-of-the-art in hardware protection systems. Enhanced shielding incorporating intermediate non-metallic layers of Nextel™ (3-M Corp.) and Kevlar™ (DuPont) will be used on the U.S. Hab and Lab modules. The penetration resistance of these shields result in PNP levels of greater than 99.8% per year. Figure 4 is a hydrocode simulation of a "stuffed " Whipple shield stopping a 0.849 cm diameter particle.

Should the M/OD flux levels increase greater than anticipated environment growth during the operational life of the station, the capability to further mitigate the risk is designed into the station. Mounting locations are included in the hardware to allow for on-orbit addition of M/OD shielding.

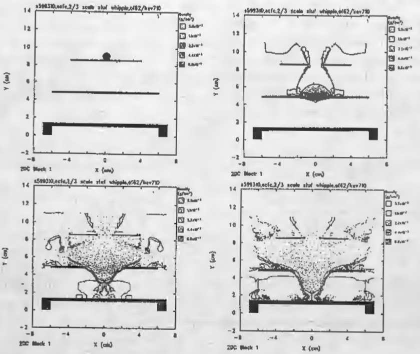

Figure 4. "Stuffed" Whipple Impact Simulation

3.3 Debris Collision Avoidance

Orbital debris is tracked and cataloged by the United States Space Command (USSPACECOM) Space Surveillance Network. Currently USSPACECOM assists NASA by providing information that is used to determine the need for performing debris avoidance maneuvers for the space shuttle orbiter. The ISSA program plans to continue this arrangement and is now developing procedures for executing debris collision avoidance maneuvers.

Utilizing existing network capabilities to track particles down to approximately 10 cm diameter, debris avoidance maneuvers will be executed as required to avoid collisions with the larger objects. Early estimates indicate from 1 to 10 maneuvers per year may be expected. The actual number of maneuvers anticipated in a year is a function of estimated debris flux, relative position uncertainties, and collision probability thresholds yet to be established. These thresholds will be carefully derived to minimize risk of collisions while still permitting the space station to carry out its scientific mission objectives.

3.4 Risk Abatement and Control

Additional measures are being pursued to reduce potential M/OD hazards including: hatch closure protocols to isolate modules in the event of a depressurization, penetration repair procedures, internal spall blankets to minimize effects of debris fragments, advanced test and analysis techniques to reduce uncertainties in the penetration resistance equations, and refined penetration effects analysis. Further, operations procedures may be modified during periods of high flux (i.e., meteor storms).

An integral part of risk management is a long term commitment by NASA to monitor the debris environment over the ISSA operational period accompanied by assessments of the updated environment. Control of the debris threat is being pursued through international treaties and agreements among all space-faring nations. These agreements refer to guidelines for the design, development and operation of satellites with the intent to reduce the evolving orbital debris environment.

4. SUMMARY

Protecting the ISSA from meteoroids and orbital debris is particularly challenging due to its long mission duration and large surface area. A multifaceted strategy and long-term risk management program to achieve safe and reliable operations has been implemented by the ISSA program. The NASA, prime contractor, and international partner team is committed to producing innovative and practical solutions to the M/OD challenge.

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