Protecting the Space Shuttle from Meteoroids and Orbital Debris

Committee on Space Shuttle Meteoroid/Debris Risk Management

Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Cover Illustration: The large picture of the shuttle orbiter was taken from the Mir space station during shuttle mission STS-71 in July 1995. The inset is a scanning electron micrograph of a 0.6 mm diameter crater found on the Solar Maximum Mission Satellite, which was recovered from space in April 1994 by the crew of shuttle mission STS-41C. Source: NASA.

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Preface

In 1983, three days into my first shuttle mission, I noticed a small pit in one of the windows of the crew cabin. Spectrographic analysis of the residue left in this tiny pit revealed the presence of titanium and aluminum, suggesting that the orbiter had been hit by a chip of paint that had flaked off of some unknown spacecraft or rocket body. This was one of the first indications that orbital debris might pose a hazard to the space shuttle.

By 1995, the number of reported window impacts had increased dramatically, and the debris hazard had forced planners to modify plans for shuttle mission STS-73. In September 1995, the space shuttle program manager established a Space Shuttle Meteoroid and Debris Damage Team to review the environment modeling and orbiter modeling, to assess the potential for damage from meteoroids and orbital debris, and to "recommend concepts and methods to reduce risk to critical orbiter areas" (Holloway, 1995).

In 1995 and 1996, significant impacts occurred on the orbiter's payload bay door and rudder speed brake, as well as on the tethered satellite pallet. In May 1996, the manager of the space shuttle program established interim guidelines to "minimize the time spent in sensitive attitudes, minimizing the probability of orbital debris impact to the wing leading edge and orbiter radiators." He further stated that "mission planning and design should be implemented with the objective of not exceeding a probability of critical penetration of 1/200 while also minimizing the exposure of the orbiter radiators to orbital debris as much as possible" (Holloway, 1996).

The allowable risk of 1/200 means that the hazard from meteoroids and orbital debris is, on some missions, the single greatest threat to the shuttle and crew, slightly larger than the hazard from ascent. To gain an independent, outside assessment of the threat, and of measures to address it, the National Aeronautics and Space Administration (NASA) asked the National Research Council (NRC) to review the space shuttle program's strategy for assessing and mitigating the threat posed by meteoroids and orbital debris. In response, the NRC formed the Committee on Space Shuttle Meteoroid/Debris Risk Management, under the auspices of the Aeronautics and Space Engineering Board. (The charge to the committee is contained in Appendix A.) The committee met in April and June of 1997 to receive briefings from NASA and NASA contractors and to deliberate on findings and recommendations. This report is the product of those meetings and of additional data gathering, writing, and discussion during the summer and fall of 1997.

The committee concurs that the threat to the shuttle from meteoroids and orbital debris is real, although the magnitude of the threat and the resulting hazard are not clear. In recent years, researchers have greatly improved models of the debris environment and conducted numerous tests and studies to assess the damage caused by the impact of meteoroids and orbital debris, but no end-to-end assessment has been made of the orbiter's survivability in the face of the meteoroid and debris hazard.

Such an assessment is needed, and needed soon. Until the magnitude of the threat—and the uncertainty of the threat assessment—are better known, program managers and mission planners will be forced to balance crew safety against cost and mission goals based on very incomplete information. The assessment will have other benefits as well—improvements in NASA's environment and impact models will benefit space activities worldwide.

NASA has developed a world-class center of expertise on the meteoroid and orbital debris hazard. Many experts from NASA and NASA contractors briefed the committee and provided us with information essential to this study. The committee thanks them for their professional and candid presentations. I extend my warm thanks to Dr. Bill Heiser, NRC Aeronautics and Space Engineering Board liaison to this project, for his active participation, his counsel, and his insightful critique of our process and text. In closing, I want to thank the members of the committee personally for their time and effort on the study and on writing this report, as well as Paul Shawcross, the study director, for his tireless efforts in bringing this project to fruition.

RICK HAUCK
Committee Chair

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Have I not walked without an upward look
Of caution under stars that very well
Might not have missed me when they shot and fell?
It was a risk I had to take—and took.

"Bravado"
Robert Frost

Executive Summary

The shuttle orbiter has been struck many times by small meteoroids and orbital debris, but it has not yet been damaged severely. Because it was not designed with the meteoroid and orbital debris hazard in mind, however, some orbiter components are at risk of being damaged by meteoroids or debris. This damage can range from damage that does not affect a mission but increases refurbishment costs (such as pitting of window surfaces) to damage that could force the crew to abort a mission (such as penetration of a radiator pipe) to damage that would prevent the orbiter from successfully returning to Earth (such as a large hole in the leading edge of a wing) to damage that would rapidly result in the loss of life or the vehicle (such as a collision with a large fragment from the breakup of a spacecraft). Astronauts conducting extravehicular activities are also at risk from meteoroids and orbital debris.

RISK MANAGEMENT STRATEGY

A National Aeronautics and Space Administration (NASA) guideline states that the risk of critical failure (i.e., penetration of the orbiter that results in the loss of vehicle or loss of life) from the impact of a meteoroid or orbital debris should not exceed 1/200 for a particular mission. This compares to the median calculated risk of critical failure of 1/248 for the shuttle's launch and ascent to orbit. Compared to the efforts NASA has made to reduce other risks to the shuttle, the efforts made to understand and reduce the risk from meteoroids and debris has been small. NASA should consider changing the 1/200 guideline to reduce the maximum allowable risk from meteoroids and orbital debris.

NASA has not conducted a systematic assessment of the survivability of the shuttle with respect to the meteoroid and orbital debris hazard. Similar analyses, however, have been conducted by the U.S. Department of Defense (DOD) to assess aircraft survivability. NASA should improve its approach to calculating the risk to the shuttle from meteoroids and orbital debris by establishing a survivability assessment process and conducting an end-to-end survivability assessment of the entire shuttle orbiter—including all subsystems and components—against the hazard. The assessment should be integrated with assessments of other hazards, such as the risk during ascent and reentry, to create a complete, integrated, peer-reviewed probabilistic risk assessment for the shuttle.

NASA should also continue its efforts to assess in detail the vulnerability of areas of the shuttle orbiter that they predict to be most likely to experience critical damage, mission-limiting damage, or damage requiring costly repairs. This information should be used to refine assessments of the overall risk to the shuttle, to determine which areas require more protection, and to determine whether operational and procedural modifications can decrease the risk.

TOOLS FOR RISK ASSESSMENT

NASA uses computer models to assess risks and guide its efforts to protect the shuttle from meteoroids and orbital debris. A model of the meteoroid and orbital debris environment (ORDEM96) is used as input for a threat assessment model (BUMPER) to predict the magnitude of the risk to the shuttle from meteoroids and orbital debris.

ORDEM96 is arguably the best available model of the debris environment, and BUMPER is probably the best available model for orbital debris risk assessment. However, both models incorporate a number of simplifying assumptions, and the magnitude of uncertainty in their predictions has not been well characterized. NASA should strive to refine BUMPER and ORDEM96 so that their results include appropriate error bars and associated confidence levels. To begin this process, NASA should analyze the sensitivity of the output of both models to changes in the various input parameters.

Because the data are limited and the population of debris smaller than about 5 mm in diameter varies widely, ORDEM96's predictions of debris fluxes for individual shuttle missions may be highly inaccurate. To predict the short-term hazard to the orbiter from orbital debris more accurately, NASA should expand its data gathering and modeling efforts to better understand the sources (e.g., solid rocket motors and debris wakes) of the sub-5 mm debris population in the shuttle's orbital regime.

COLLISION AVOIDANCE

The DOD Space Surveillance Network (SSN) warns the space shuttle program of possible close conjunctions with cataloged orbiting objects. But probably more than 95 percent of the objects that could cause critical damage to the orbiter are not cataloged because they are too small to be reliably detected by SSN sensors.

The capabilities of the SSN to support NASA's efforts for collision avoidance are eroding, and until recently, NASA had issued no requirements that might have helped to halt this erosion. NASA and the DOD should work together to satisfy these requirements, to identify impending changes to the SSN that will affect debris tracking, and to identify changes that would improve the SSN's ability to track smaller objects that pose a hazard to crewed spacecraft.

Once NASA has received a warning of an upcoming close conjunction, it must decide whether to maneuver the shuttle to avoid a collision. Two flight rules (A4.1.3-6 and C4.3.2-1) that are relevant to this decision appear to place mission success ahead of flight safety. NASA should re-examine these rules and consider restating them to establish when a maneuver is mandatory for safety reasons. NASA plans to use a new probability-based approach to determine when a collision avoidance maneuver is necessary, but the collision avoidance data currently provided by the SSN is not accurate enough for this new approach to be effective.

RISK MITIGATION

The space shuttle program has developed operational procedures, and is about to implement hardware modifications, to improve the survivability of the shuttle orbiter and crew in the face of the meteoroid and orbital debris hazard. In the future, however, when the orbiter is supporting the International Space Station, many of the operational techniques developed to improve the orbiter's survivability will not be employed because the shuttle's freedom to maneuver and control its attitude will be constrained to satisfy requirements for space station power, thermal conditions, and attitude control. The effect of these restrictions on the shuttle's survivability should be reassessed.

NASA plans to modify the orbiter's radiators and wing insulation to reduce the risk of early mission termination and critical failure. These modifications appear to be positive steps that will have a minimal negative impact on the program. NASA should continue to investigate potential modifications to the orbiter to improve its survivability against meteoroids and orbital debris. NASA should also reconsider conducting on-orbit surveys to detect exterior impact damage and repair it as necessary.

1

Introduction

In the 1970s, when the space shuttle was being developed, orbital debris was not recognized as a significant threat to spacecraft. During the 1980s and 1990s, however, extensive data gathering and analysis greatly improved understanding of this growing hazard. The National Aeronautics and Space Administration's (NASA) models of the space environment now suggest that meteoroids and orbital debris pose a significant threat to the shuttle orbiter.

The shuttle orbiter has already been struck many times by small meteoroids and orbital debris, but it has not been damaged severely (although NASA now replaces pitted orbiter windows after most flights). The potential exists, however, for more serious damage. Objects ranging from paint chips to fragments of exploded rocket upper stages to intact spacecraft orbit through the regions in which

BOX 1-1
Meteoroids and Orbital Debris

Meteoroids are created from the breakup of asteroids and comets. They orbit the Sun and rain steadily on the Earth and on objects in Earth orbit.

Orbital debris is human-generated and orbits the Earth. All nonfunctional objects in Earth orbit are considered to be debris (NRC, 1995). This debris can be anything from a piece of paint that has flaked off of a rocket or a spacecraft to fragments of an exploded rocket upper stage to an entire derelict spacecraft.

the shuttle operates. The speed at which objects in low Earth orbit (LEO) can collide makes these objects dangerous—at typical impact velocities of 10 kilometers per second (km/s), even millimeter-sized objects can cause considerable damage. Only the very largest objects are tracked and monitored from Earth; the locations and trajectories of the vast majority are unknown.

Because it was designed to be launched into space and return safely to Earth 100 times, the shuttle orbiter is fairly rugged. However, because it was not designed with the meteoroid and orbital debris hazard in mind, some orbiter components are vulnerable to impact damage. This can include damage that does not affect a mission but increases refurbishment costs (such as damage to window surfaces); damage that might force the crew to abort a mission (such as the penetration of a radiator pipe); damage that would prevent the orbiter from successfully returning to Earth (such as a large hole in the leading edge of a wing or the nose cap); and damage that would result in the loss of life or the vehicle (such as a collision with a large fragment from the breakup of a spacecraft).

For years, the space shuttle program has had the ability to move the orbiter out of the path of pieces of debris that are large enough to be tracked by ground-based sensors. More recently, the shuttle program office has planned missions so that, whenever possible, the orbiter maintains orientations that protect its most vulnerable components from the greater part of the meteoroid and orbital debris flux. In the near future, the program plans to shield some of the orbiter's most vulnerable components against meteoroids and orbital debris.

BOX 1-2
High-Speed Collisions

The shuttle orbiter circles the Earth at a velocity of about 7.5 kilometers per second (about 17,000 miles per hour) a few hundred kilometers above the surface of the Earth. Its orbit is inclined to the equator, usually by 28.5 degrees (for maximum payload mass) or 51.6 degrees (typically to rendezvous with a space station).

Debris orbits the Earth in a tremendous variety of circular and elliptical orbits at different altitudes and with different inclinations. When the orbiter's trajectory intersects the orbit of a piece of debris, the two objects are generally heading in different directions at high relative velocities.

When the shuttle is in a 51.6 degree inclination 400 kilometer altitude orbit, NASA's model of the debris environment predicts an average collision velocity of 9 kilometers per second for orbital debris with a diameter of 1 centimeter or more.

In this report, the committee examines NASA's strategy for protecting the shuttle orbiter from meteoroids and debris and recommends new strategies where appropriate. Chapter 2 examines the hazard to the orbiter and crew from meteoroids and orbital debris. Chapter 3 reviews the shuttle program's risk assessment and risk management strategies, and Chapter 4 looks at the tools NASA uses to assess the risk. Chapter 5 explores the use of collision warning and avoidance systems, and Chapter 6 describes steps that can be taken to improve the shuttle's survivability.

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NRC (National Research Council). 1995. Orbital Debris: A Technical Assessment. Committee on Space Debris, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

2

Risk to the Orbiter and Crew

The risk to the space shuttle orbiter from meteoroids and orbital debris can be broken down into two elements: the probability that the space shuttle orbiter or crew will be struck (susceptibility), and the probability that an impact will affect the mission (vulnerability). The orbiter's survivability is best understood as a combination of susceptibility and vulnerability. Figure 2-1 shows a step-by-step process that can be used to determine the orbiter's survivability in the meteoroid and orbital debris environment.

This chapter first examines the orbiter's susceptibility to impacts from meteoroids and orbital debris. This is followed by a discussion of the damaging effects of hypervelocity impacts, an overview of the orbiter design, and a preliminary assessment of the potential vulnerability of various elements of the orbiter. The chapter concludes with an assessment of the survivability of shuttle crew members conducting extravehicular activities (EVAs).

ORBITER SUSCEPTIBILITY

The probability that the orbiter will collide with meteoroids or orbital debris can be estimated by multiplying the flux of meteoroids and orbital debris by the relevant exposed surface of the shuttle orbiter and the duration of the exposure. Table 2-1 uses NASA's meteoroid model and computer-based orbital debris environment model for spacecraft design and observations in low Earth orbit (ORDEM96) to predict the number of collisions with objects of various sizes during a single shuttle mission and during the lifetime of the shuttle fleet. (The accuracy of ORDEM96 predictions is discussed in Chapter 4.)

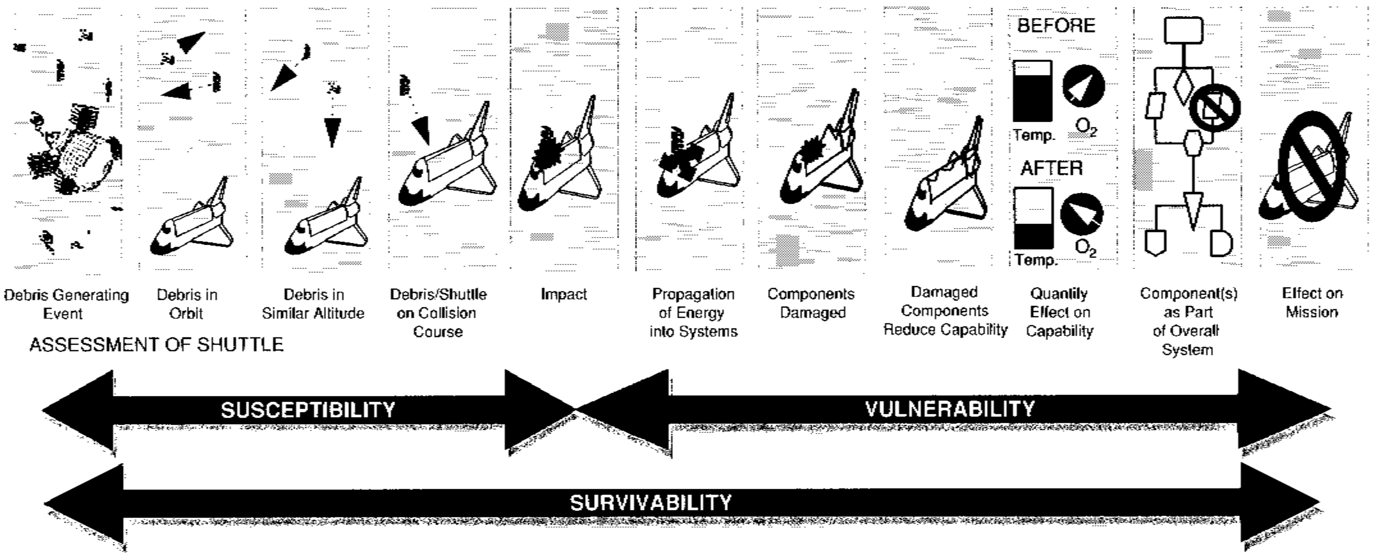

FIGURE 2-1 Survivability analysis.

TABLE 2-1 Predicted Number of Impacts on Orbiter (1997 environment, 400 km altitude, 51.6 degree inclination orbit)

Diameter of Meteoroid or Debris	10-day Mission	400 10-day Missions
> 0.04 mm	700	300,000
> 0.1 mm	100	40,000
> 0.5 mm	1	400
> 1 mm	0.09	35
> 2 mm	0.008	3
> 3 mm	0.002	0.8
> 5 mm	0.0005	0.2
> 10 centimeters	0.000004	0.002

The flux of meteoroids at shuttle altitudes is comparable to the flux of debris for particles between 0.01 mm and 1 mm in diameter. Above and below this size range, debris are normally more populous than meteoroids. Figure 2-2 compares the modeled flux of meteoroids and debris at the altitude at which the orbiter will visit the International Space Station (ISS).

Once a meteoroid or piece of debris has struck the orbiter, the amount of damage it does depends in large part on the impactor's composition and velocity, as well as on the composition and thickness of the components that were struck. Meteoroids are typically silica-based, with mass densities on the order of 0.5 grams per cubic centimeter (g/cm^3), although meteoroids less than 1 mm in diameter are generally considered to have average densities on the order of 1 to 2 g/cm^3. Meteoroids are believed to impact Earth-orbiting objects at average velocities of 19 km/s, although impact velocities can be as high as 70 km/s. Orbital debris can be composed of a variety of materials, such as paint, aluminum, steel, and composites. Steel fragments may have densities of 8 g/cm^3, but the densities of paint and composites are more comparable to meteoroids. Aluminum, which is the most common material used in spacecraft, has a density of 2.7 g/cm^3. The collision velocities of orbiting objects average about 10 km/s at the shuttle's altitude and inclinations.

Because of the different characteristics of meteoroids and orbital debris, they will cause different amounts of damage. On average, the impact velocity of meteoroids is twice the impact velocity of debris, but meteoroids are less dense. Meteoroids typically also have lower yield strengths, and the speed of sound in meteoroids is lower than in typical debris. Orbital debris typically causes significantly more damage to a given surface or component than similar-sized meteoroids, primarily because denser objects that are less dispersed by a high-velocity initial impact are better able to punch through spacecraft surfaces and components.

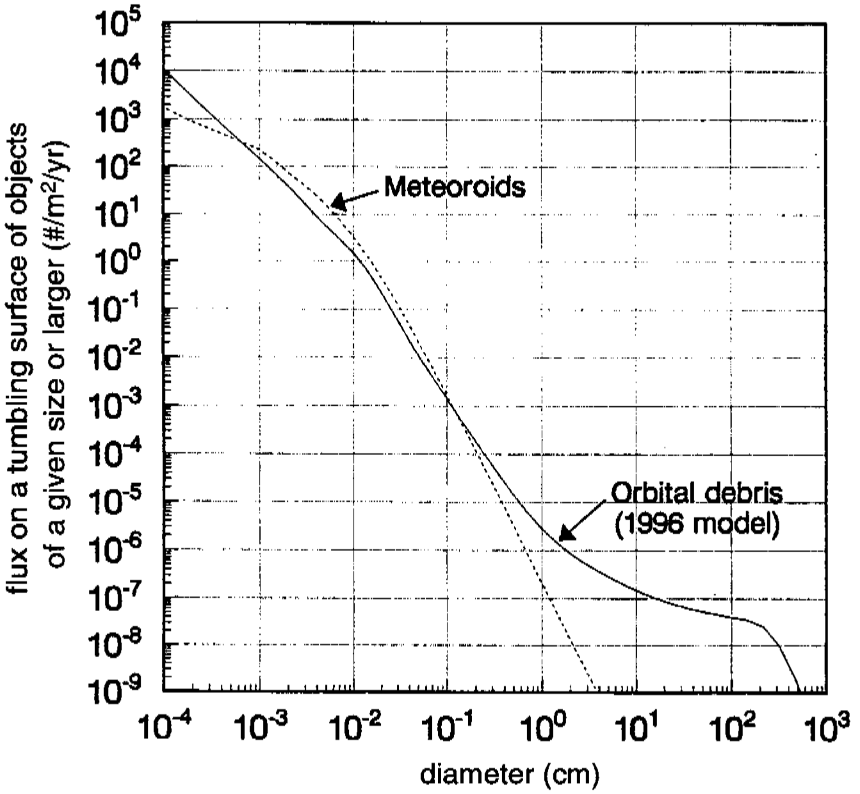

FIGURE 2-2 Comparison of meteoroid and debris flux in ISS orbit. Source: NASA.

An object striking a spacecraft at 10 km/s can cause several types of damage. Impacts can crater or perforate surfaces, create petaled holes and cracks, or cause the back surfaces of walls to spall, sending material from the back of the wall into the spacecraft. If an object penetrates the wall of a spacecraft, its remnants (often fragmented or liquefied) will travel into the spacecraft and be deposited over an area significantly larger than the impact hole. The momentum of the impact can cause impulsive damage, including bending and buckling of structural components and the transmission of a traveling shock wave through the spacecraft's structure and components (NRC, 1995). Depending on the size of the hole and the amount of energy released into a pressurized area (such as the shuttle crew cabin or a Spacelab module) a variety of phenomena could occur, including a strong acoustic shock wave, an intense flash of light that could temporarily incapacitate crew members, and a decrease in air pressure, which could cause rapid changes in temperature, an internal fog, and the eventual depressurization of the module (NRC, 1997; Serrano et al., 1996).

ORBITER DESIGN

During the 1970s, when the orbiter was being designed and qualified for space flight, the threat from orbital debris was not considered to be significant. The only entry in the orbiter vehicle specifications that referred to impact damage was intended to minimize low energy—up to about 0.008 joules—dings and dents in the external thermal protection tiles. (By comparison, a 1 mm aluminum sphere impacting at 9 km/s has a kinetic energy of about 57 joules.)

The orbiter was designed to operate for 100 missions and was qualified by tests and analyses for 400 missions. The space shuttle orbiter subsystems were designed and located to minimize the likelihood that a single failure would cause or coincide with secondary damage to redundant systems. For example, major electrical buses and their associated wiring are separated to a large extent. Although NASA has analyzed the potential for losses from fire, shortcircuits, explosions of high-energy systems, and mishaps during processing of some critical redundant systems that are not physically separated (Rogers, 1994), the threat from penetrating meteoroids and orbital debris, which could result in much different damage propagation processes, was not considered.

Thermal Protection System

One notable nonredundant orbiter system is the thermal protection system (TPS). The external surface of the orbiter's primary structure is protected from the heat of ascent and reentry by the TPS. The orbiter's TPS is a passive, reusable system consisting of various materials applied to the external surface to keep the outer skin within acceptable temperature limits during reentry. For the aluminum materials that are used extensively on the outer skins, this limit is 177°C.

The TPS on the lower surface of the orbiter consists of low-density ceramic materials (designed to survive temperatures up to 1260°C) installed in 15 cm by 15 cm blocks of varying thicknesses (2.5 to 11.5 cm), commonly called "tiles." The TPS on the orbiter's upper surfaces consists of several materials: tiles, fabric and batting blankets, and Nomex felt, depending on the anticipated temperature environment. The leading edges of the wing and the nose cap are designed to survive the hottest temperatures (up to 1650°C). These areas are protected by a reinforced carbon-carbon (RCC) material. Although the tiles were not designed to protect against meteoroids and orbital debris, testing has demonstrated that they perform this task four to five times more effectively per unit mass than single walls of aluminum (Christiansen, 1997).

Orbiter Primary Structure

The orbiter primary structure is the other major nonredundant orbiter system. Its major elements are shown in Figure 2-3. The total cross-sectional area exposed to the meteoroid and debris flux is 1,035 square meters (m^2).

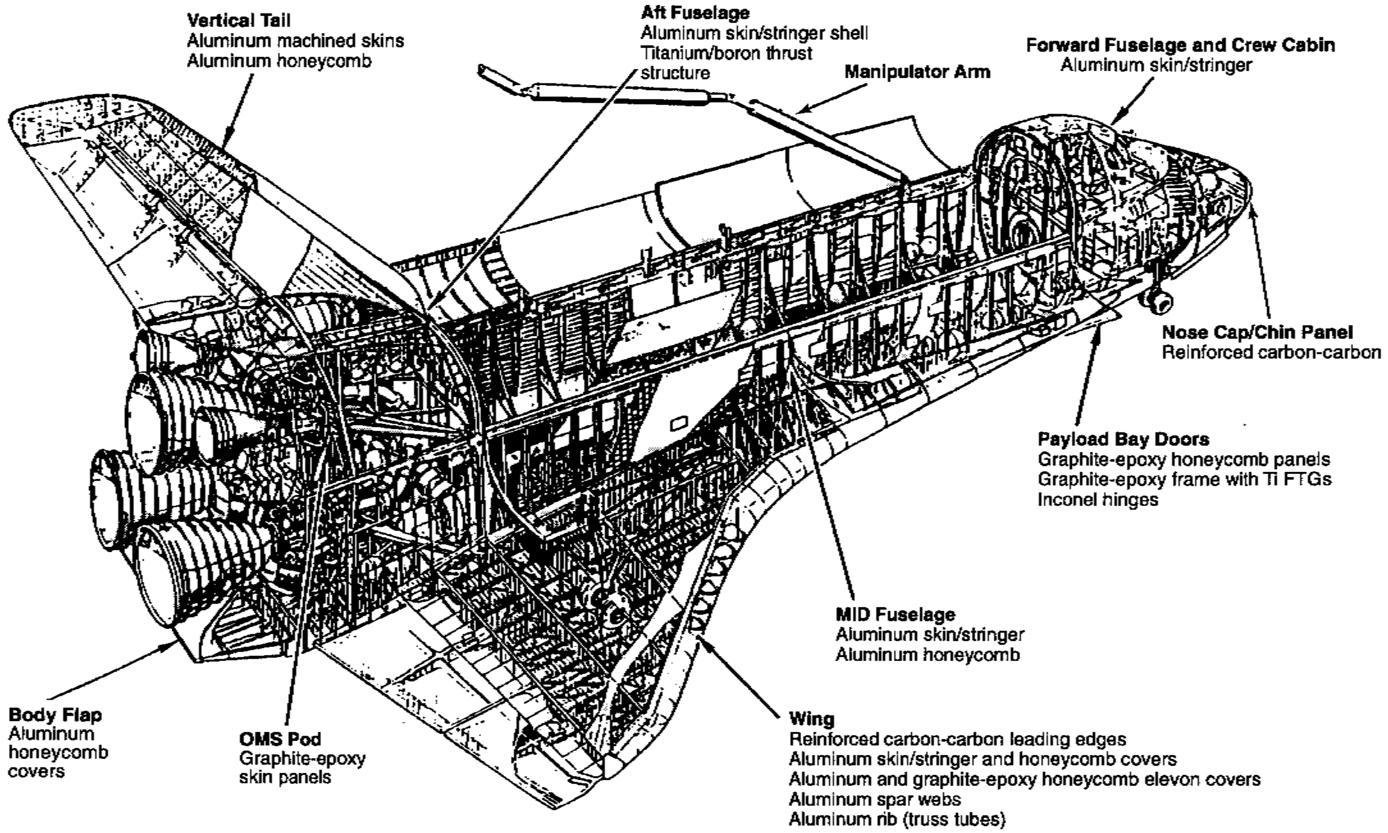

FIGURE 2-3 Orbiter primary structure. Source: NASA.

The crew module is a separate pressurized structure suspended by links within the forward fuselage structure. This design provides multiple barriers against penetration by meteoroids or orbital debris from most directions except through the crew module aft bulkhead. The aft bulkhead constitutes the forward boundary of the payload bay and, unlike the rest of the crew module, is not shielded by an outer shell. To support missions to the ISS, however, three of the four orbiters will be outfitted with an external airlock that will provide some shielding of the crew compartment aft bulkhead from impacts by meteoroids or orbital debris. The crew module has 11 windows, each made up of primary alumino-silicate and redundant silica pressure panes. Nine windows have additional outer fused-silica "thermal" panes (Smith, 1995).

The majority of orbiter subsystems that do not need to be in the crew compartment are located along the fore-aft axis, as shown in Figure 2-4. Among the components on this axis are tanks of liquid oxygen, liquid hydrogen, and pressurized gases, as well as hydraulic lines running forward to the nose gear well for lowering, braking, and steering the nose wheel. Most of the components located in the mid-fuselage are located below a payload bay liner, which covers the major frames. When the payload bay doors are open on orbit, the sill longerons and cable trays, which run the full length of both sides, still provide some measure of protection for the pressure vessels and other components below them. Payloads carried in the payload bay can also provide shielding for these areas. TPS tiles and aluminum skin stringer panels provide protection from below.

The payload bay doors are built of graphite-epoxy and are opened for payload operations on orbit. Attached to these doors, and exposed to the meteoroid and orbital debris environment, are the radiators of the active thermal control system. These radiators are constructed of aluminum honeycomb material, with internal lines that carry a freon coolant fluid from the heat exchangers.

The orbiter wing structures are generally devoid of any internal systems hardware, except for the main landing gear wells and the hydraulic and electrical lines that run outboard to the 11 hydraulic actuators along the inside of the rear wing spar. The leading edge of each wing is comprised of 22 panels of RCC material.

The orbital maneuvering system (OMS) pods are installed atop the aft fuselage astride the vertical tail. They contain both the OMS and the aft reaction control systems, as well as their components and propellant tanks. The graphite-epoxy skin panels are covered by a combination of TPS tiles and blankets. The exposed area of the pods is small, so their susceptibility to the impacts of meteoroids and orbital debris is relatively low.

The aft fuselage contains the members of the thrust structure for the space shuttle main engines, the myriad lines and valves of the main propulsion system, the auxiliary power units, and components of several other subsystems. The primary structure of the aft fuselage is comprised of aluminum skin and stringer panels and frames. The vertical tail and OMS pods shield the top portion of the aft fuselage. The massive primary thrust structure and propulsion system feedlines

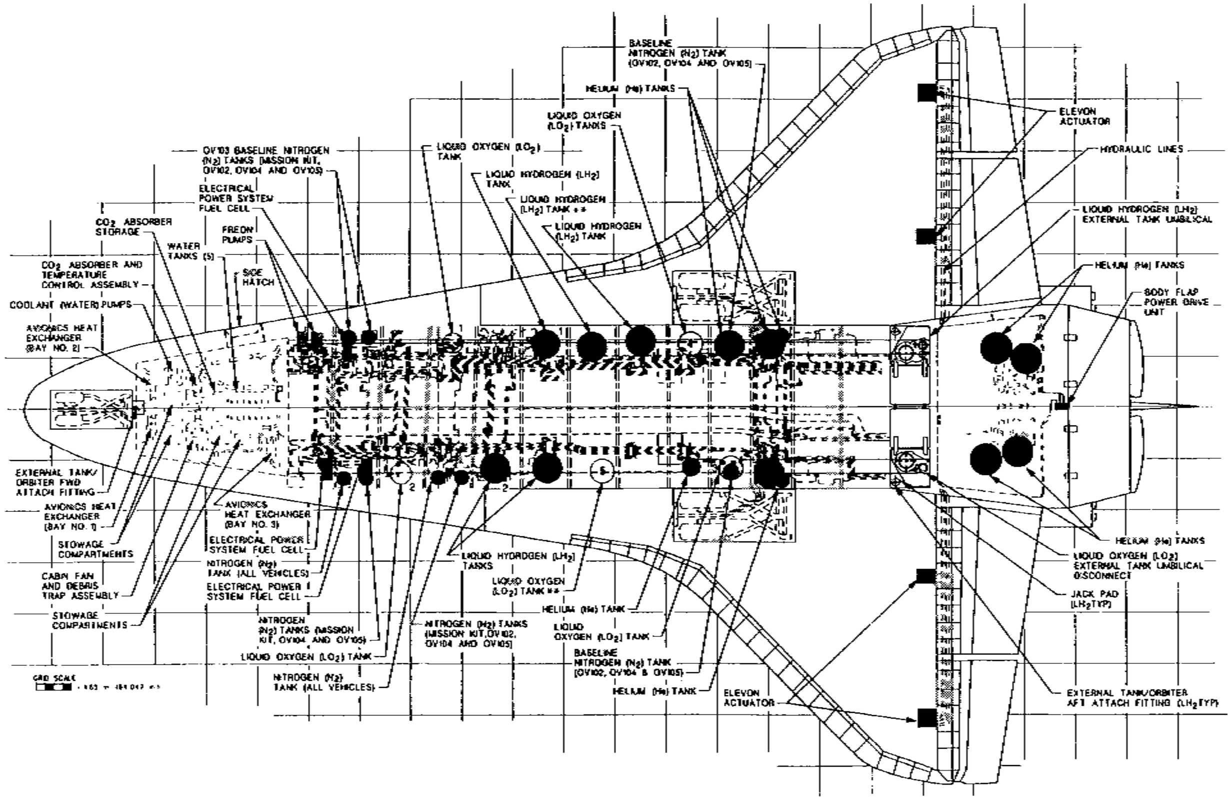

FIGURE 2-4 Orbiter systems concentrated along the fore-aft axis. Source: NASA.

(filled with inert helium on orbit and not needed for reentry) provide some internal shielding for subsystem components. The main engine nozzles and the thermal shields mounted around them to protect equipment in the aft bay from radiant heating and low pressure backflow during space shuttle main engine operations provide additional protection.

The body flap is an aluminum structure with no internal systems. It is shielded from the top by the main rocket nozzles and has thick TPS tiles on its lower surface. The vertical tail is an aluminum structure consisting of the primary fin structural box and the moveable rudder/speed brake panels. These are relatively robust structural components with a small exposed area covered by thick TPS tiles and insulation blankets.

ORBITER VULNERABILITY

The damage caused by a particular impactor depends largely on the location of the impact. Table 2-2 summarizes the damage thresholds for several key components of the orbiter. Calculating the minimum diameter of an impactor that would cause each effect requires making numerous assumptions about impactor composition, shape, and velocity, impact angle, and exact impact location; nevertheless, the table illustrates the range of potential impactors that could damage the orbiter.

The impacts shown in Table 2-2, as well as impacts not included in the table, could cause damage ranging from minor pitting, which would require increased maintenance, to loss of life or loss of the orbiter.

Critical and Near-Critical Damage

There are a number of different mechanisms by which meteoroid and orbital debris could cause critical failure (i.e., involving loss of life or the orbiter). Any

TABLE 2-2 Damage Thresholds for Orbiter Components

Effect on the Orbiter	Minimum Diameter of Debris
Require replacement of window	0.04 mm
Penetrate a space suit	0.1 mm
Penetrate radiator tubes	0.5 mm
Penetrate leading edge of a wing or damage payload bay	1 mm
Penetrate crew cabin aft bulkhead	2 mm
Penetrate thermal protection system tiles	3 to 5 mm
Penetrate crew cabin (average surface)	5 mm
Collision avoidance possible if object is cataloged	10 *cm*

Source: NASA, 1997b

impact that causes structural failure and rapid decompression of the crew module, for example, would be critical. An impact that penetrates the primary structure and explosively ruptures an internal pressure vessel could also be critical. Impacts that penetrate the leading edge of a wing or the lower surfaces of the wing or the fuselage might not be immediately critical—or even detected—but the consequent thermal heating on reentry could have a "blow torch" effect inside the wing that causes loss of flight control or failure of the primary structure resulting in the loss of the vehicle. Major damage to the control surfaces or the hydraulic systems that operate them could result in critical failure during reentry, approach, and landing.

Lesser damage could be survivable but might have a significant impact on the cost and schedule of the shuttle program. For example, an impact on the leading edge of a wing that caused a small hole could result in heating of the wing's inner structure during reentry that might not cause the wing to fail but would require that a substantial portion of the wing skin, ribs, and spars be replaced. The repair could take 18 to 24 months and could cost as much as $25 million to $40 million (Boeing Space Systems Division, 1997). In addition to the cost, prolonged repairs could have a ripple effect on operations and scheduled modifications of the remaining orbiter fleet, especially if the repairs must be done during ISS assembly.

Mission-Limiting Damage

Impacts of meteoroids and orbital debris could also cause a mission to be terminated early. An impact that penetrates a freon coolant line in the radiators on the payload bay doors, for example, would leave only one operational coolant loop. The remaining loop could perform satisfactorily under reduced power conditions, but, because of the absence of further redundancy in the coolant system, the shuttle flight rules require that the orbiter terminate its mission activities and make the earliest possible return to the primary landing site. A noncatastrophic penetration of a pressurized volume, such as the crew cabin or a Spacelab, would also probably result in early termination of the mission.

Other Damage

Damage from meteoroids and orbital debris impacts could also be costly to repair, even if it is not critical or mission-limiting. Orbiter external surfaces, for example, have experienced impacts from particles on every shuttle mission. Inspections of the windows after each flight have revealed pits that were caused by impacts in orbit. The outer thermal panes of the crew cabin windows have sustained one or more impact pits greater than 0.25 mm in diameter on most flights. Almost 300 pits were reported between 1981 and 1996, and 55 windows were replaced (NASA, 1997b). Windows are replaced based on the design stress conditions and the location and depth of pits.

Close inspections of the radiators and other exposed surfaces also show minor punctures and evidence of spallation. The TPS has been struck by meteoroids and orbital debris, but reentry heating and localized deformations around the damage have made it difficult to differentiate damage from meteoroids and orbital debris from damage suffered during ascent. All surface damage adds to the workload during turnaround operations to prepare the vehicle for the next flight.

EXTRAVEHICULAR ACTIVITY

Astronauts performing tasks outside the orbiter are also at risk from meteoroids and orbital debris. The most vulnerable parts of the EVA mobility unit (EMU) are the soft areas of the space suit, the arms, gloves, and lower torso. (NASA calculates that the harder areas of the space suit contribute less than 10 percent of the overall risk.) The soft areas of the suit are constructed of multiple layers of abrasion and thermal protection material and a single pressure bladder.

The secondary oxygen pack on the EMU is sized to provide astronauts with a 30 minute supply of oxygen in case of a 4 mm puncture in the space suit. Presumably, this would be sufficient time for an injured astronaut to be assisted back to the pressurized crew compartment. NASA estimates that a 2 mm diameter particle could cause a 4 mm hole, and a 0.1 mm particle could cause a minute puncture. The degree of damage from these impacts has not yet been assessed in detail, but NASA now has a trauma physician on staff to examine the issue (Heflin, 1997).

NASA's calculations of the risk to two astronauts on the end of the orbiter mechanical arm during a six-hour EVA (with no shielding by the structure) are summarized in Table 2-3. The predictions for 180 EVAs are also shown as an example of what the risks might be during the years of ISS operations (Heflin, 1997).

A three-phase study is under way to characterize the vulnerability of the EMU to meteoroids and orbital debris better. The last phase of the study, scheduled to be completed in October 1997, is intended to determine improvements in crew safety that can be realized through practical enhancements to the EMU. A comparable study is in progress for the Russian Orlan EVA suit, which will be used by U.S. astronauts during some cooperative space activities.

TABLE 2-3 Risk during EVA

	6-Hour EVA	180 EVAs
Probability of no penetration	99.98% (1/4,800)	92.7% (1/14)
Probability of no critical penetration (hole > 4 mm)	99.997% (1/31,000)	98.9% (1/91)

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3

Risk Management Strategy

CURRENT APPROACH

Overall Guidelines for Risk

The most recent integrated probabilistic risk assessment (PRA) for the entire space transportation system, which was conducted in 1995, concluded that the median overall risk of critical failure for a shuttle mission is 1/145 (SAIC, 1995). The median risk of critical failure for the ascent phase alone was calculated to be 1/248, with a risk of 1/118 at the 95 percent confidence level. The study produced an overall median risk of critical failure for each shuttle mission of 1/131, with a 95 percent confidence value of 1/76. The effects of meteoroids and orbital debris were not included in this study.

Following the PRA, however, an interim guideline was established by the shuttle program office establishing an acceptable level of critical risk from the meteoroid and orbital debris hazard. This guideline stated that the risk of critical failure from a meteoroid or orbital debris impact should never exceed 1/200 for a particular mission. (One in 200 was equal to the worst predicted risk of a critical penetration for a single shuttle mission to date [Austin, 1997].) Adding the maximum 1/200 risk of critical failure from meteoroids and orbital debris to the other risks of catastrophic failure increases the overall median predicted risk of catastrophic failure for a shuttle mission from 1/131 to 1/84.

At the same time, the maximum acceptable predicted risk for damage from meteoroid and orbital debris that would cause termination of a mission was set at 1/60. This criterion was based on an analysis that a risk value of 1/60 was achievable during worst-case docking and mated operations with the Russian space station Mir. Radiator damage was the only mission-limiting damage considered in this analysis (Austin, 1997). The 1/60 criterion has been exceeded on subsequent missions to accommodate Mir operations (Loftus, 1997).

The shuttle program has not established a guideline for the maximum acceptable risk that the orbiter windows or other systems will have to be repaired following a mission. The program has accepted that damage to the crew cabin windows will require that, on average, one window will have to be replaced after each flight.

Assessing Risks for Individual Shuttle Missions

Preflight meteoroid and orbital debris risk assessments for the space shuttle were first conducted in 1993 and are now conducted routinely prior to every shuttle mission. Figure 3-1 is a schematic diagram of the various steps involved in calculating the risk from meteoroids and orbital debris. These risk assessments are based upon an approximation of the altitude and attitude time lines predicted for a shuttle mission. The orbital debris environment model (ORDEM96) and the meteoroid model are combined with a model of the orbiter (BUMPER) to evaluate risks for each mission. (These models are described in detail in Chapter 4.)

For each orbiter mission, an initial risk assessment is presented at the cargo integration review (CIR), which typically takes place approximately 12 months before launch. This gives mission planners enough time to minimize the time the orbiter will spend in high-risk attitudes (Brekke, 1997). Specific risks evaluated for each flight profile include the probability of critical penetration, the probability of penetration of a radiator tube, and the probability of window replacement. When a risk assessment indicates that the risks of a proposed mission profile exceed accepted limits, changes are implemented iteratively until an acceptable level of risk is reached.

Refining Risk Assessments

Until 1995, models of the orbiter's ability to survive the impacts of meteoroids and orbital debris incorporated extremely conservative failure criteria. For example, the pre-1995 criteria assumed that any penetration of the bottom side of the leading edge RCC elements of a wing, of the wings themselves, or of the wing elevons would be critical. Considerable analyses by NASA and the orbiter manufacturer, Boeing North American Reusable Space Systems, however, have significantly improved the understanding of which penetrations could be critical (Hasselbeck et al., 1997).

NASA and Boeing North American first identified the RCC leading edge of a wing, the rest of the wing, and the elevons as the areas of the orbiter that appeared to pose the highest risks for critical failure. Next, detailed analyses and limited testing of the effects of impacts were conducted on these areas. The analyses examined the immediate effect of an impact (e.g., the hole and associated

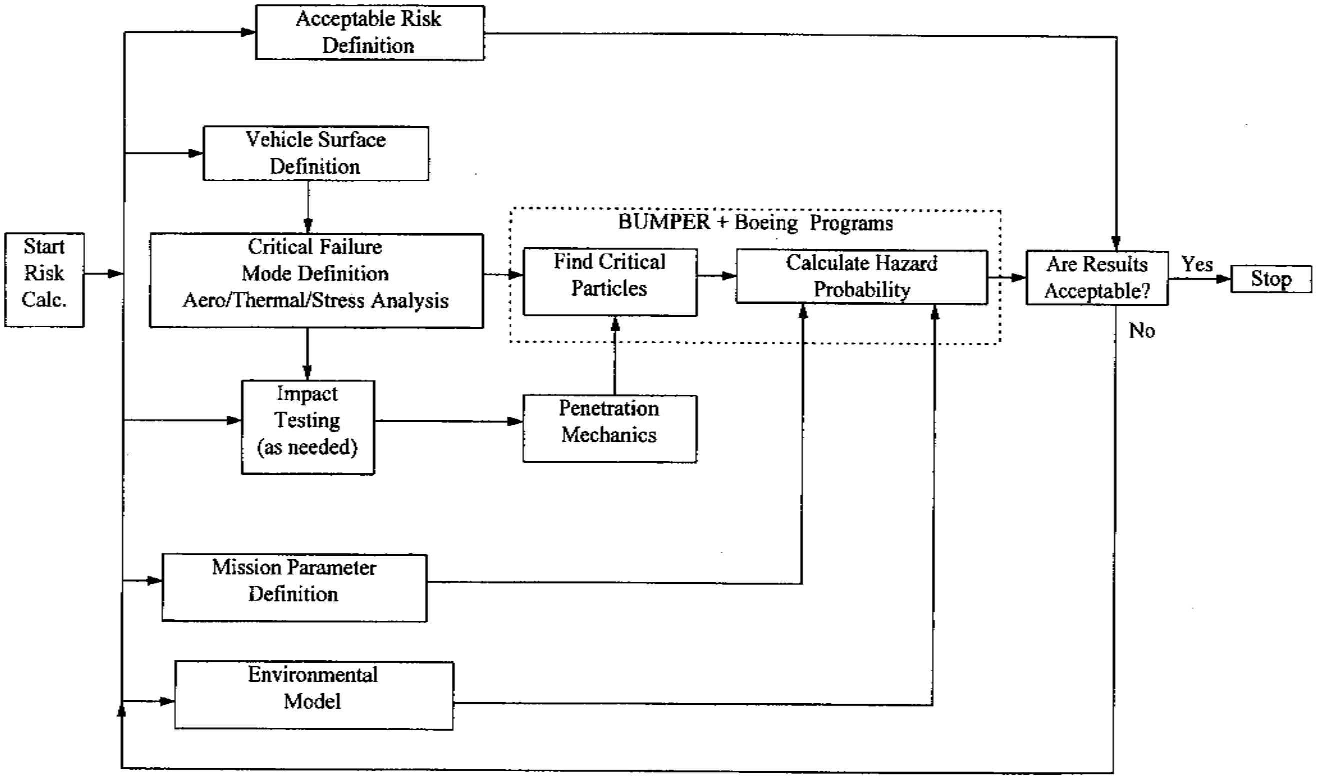

FIGURE 3-1 On-orbit impact analysis methodology. Source: Boeing North American, Inc.

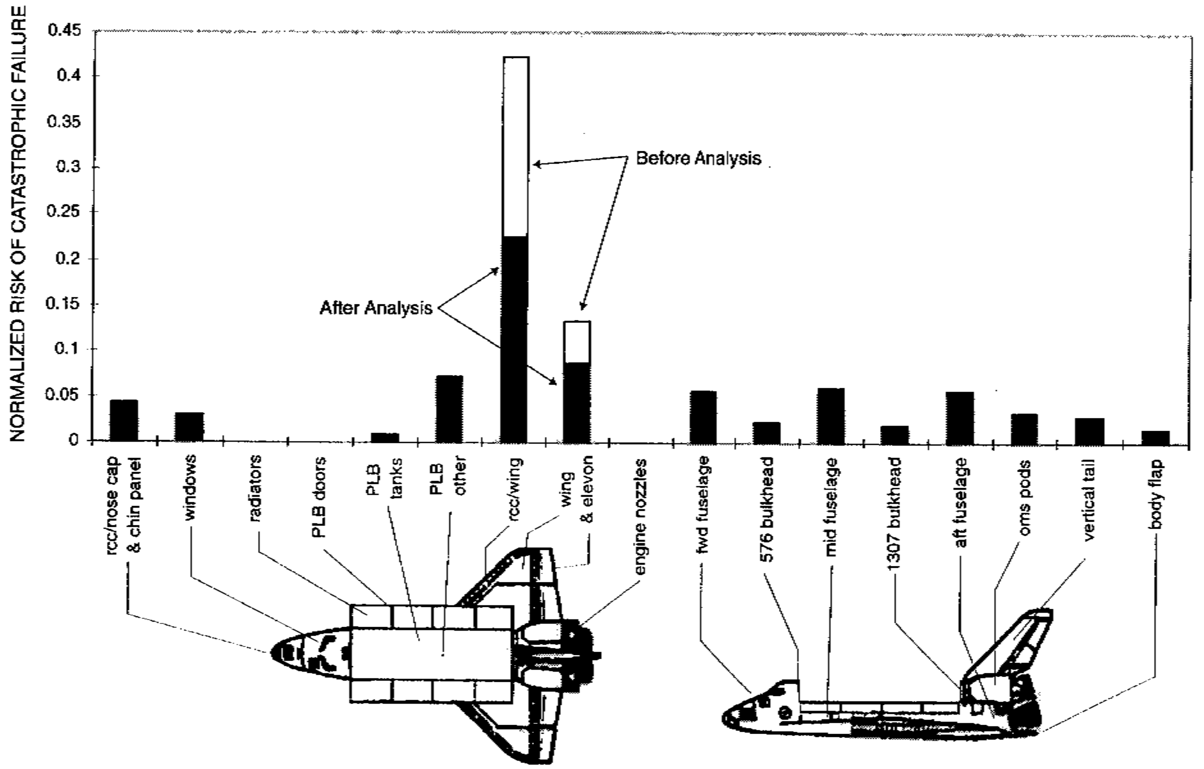

FIGURE 3-2 Relative critical risks for orbiter components after refinement of critical failure limits. The flux is considered to be omnidirectional. The normalized risk from all components before refinement of critical failure limits totals 1.0. Source: Boeing North American, Inc.

structural damage), as well as the effects of reentry heating and pressure (e.g., hole enlargement and overheating of structural members). The analyses then determined the size of a hole from an initial impact that could be sustained and not result in loss due to the effects of reentry heating or structural stress during descent maneuvers and landing. Figure 3-2 shows the predicted relative risk (before and after these analyses) that, on a given mission, various orbiter components will be struck by meteoroids and debris and damaged to such a degree that the orbiter or crew will be lost.

ANALYSIS AND FINDINGS

Guidelines for Overall Risk

The PRA performed in 1995, which calculated the median risk of critical damage during a shuttle mission to be 1/145, did not include orbital debris in its calculations. For some missions, adding the risk from meteoroids and orbital debris nearly doubles the overall risk. Table 3-1 shows predicted risks with and without the meteoroid and debris risk, using NASA's guideline for maximum critical risk from meteoroids and orbital debris of 1/200. (The median and mean risks are noted to establish a baseline uncertainty of about 7 percent.) If the maximum allowable risk from meteoroids and debris is included in the calculations, the total risk of critical failure for a shuttle mission increases from about 1/140 to about 1/80. The increase in risk appears difficult to justify, given that orbiters cost billions of dollars and that the loss of an orbiter or crew would probably leave the nation's human space program in disarray.

Earlier predictions of the risk of catastrophic failure due to meteoroids and debris may have been somewhat overstated because they incorporated conservative predictions of whether a given impact would cause a catastrophic failure. These predictions, however, are becoming less conservative as the understanding of the effects of impacts on different shuttle areas improves. Whether the risk of catastrophic failure due to meteoroids and debris is 1/200 or 1/400, however,

TABLE 3-1 Total Calculated Risk of Critical Failure

		Ascent		Reentry		Meteoroids and Debris		Total
Without meteoroids and debris risk	median	1/248	+	1/350	+	n/a	=	1/145
	mean	1/219	+	1/326	+	n/a	=	1/131
With meteoroid and debris risk of 1/200	median	1/248	+	1/350	+	1/200	=	1/84
	mean	1/219	+	1/326	+	1/200	=	1/79

NASA appears to have put much less effort into understanding and reducing this risk than other comparable risks (such as the risk of catastrophic failure of the space shuttle main engine).

In addition to being allowed to be the largest single critical risk factor, the hazard of meteoroids and orbital debris is also allowed to be the single largest mission-limiting risk factor. The maximum allowable risk that meteoroids and orbital debris will force an early end to a particular shuttle mission has been set at 1/60. The second largest risk, an external hydrazine leak in the high-energy auxiliary power unit system, is believed to be about 1/1,300 (Williams, 1997).

Finding. Meteoroids and orbital debris are currently allowed to pose the largest single risk of both critical failure and early termination of a shuttle mission. Compared to the effort NASA has expended to reduce other risks to the shuttle, the effort spent to understand and reduce the risk from meteoroids and debris appears small.

An integrated PRA of the shuttle that includes the meteoroid and orbital debris hazard has not been conducted. If such an analysis were conducted, and if standardized probability, consequence, and probability-consequence terms were implemented across the full spectrum of risk families, NASA could better understand and weigh the risks from meteoroids and orbital debris against other risks to the shuttle. Incorporating error propagation schemes into this analysis would further enhance the utility of the results.

Assessing Risks for Individual Shuttle Missions

The overall survivability of a system can be determined through a series of steps combining the susceptibility of the system (the probability of being hit) with the vulnerability of the system (the probability that a hit will cause significant damage) (see Figure 2-1). NASA has already put the basic elements for this kind of analysis in place. The ORDEM96 model can provide information about susceptibility, and the BUMPER model can provide part of the assessment of vulnerability.

However, a complete assessment of the vulnerability of the shuttle to meteoroids and orbital debris has not been conducted. Currently, there is no standard terminology or process that covers the major components of the shuttle meteoroid and debris risk assessment process, and no end-to-end sensitivity analysis has been conducted of environmental effects (i.e., ORDEM96), impact effects (i.e., BUMPER), and failure criteria (i.e., input from the Shuttle Program Office). Because mission managers cannot weigh the accuracy of the data, they must make trade-offs between safety and mission goals based on incomplete information.

To rectify this situation, NASA will have to conduct an in-depth survivability assessment for the shuttle orbiter, focusing on vulnerability as it relates to the meteoroid and orbital debris hazard; the results will have to include applicable ranges and associated confidence levels. This assessment would provide shuttle program managers with a complete picture of the potential risks for specific missions and would make it easier for NASA to determine which areas of the orbiter require better protection.

A valuable component of the survivability assessment would be an end-to-end sensitivity analysis to determine the impact of uncertainties and variabilities in parameters for each of the three components of the current risk assessment process: ORDEM96 (e.g., size distribution, ballistic coefficient, lifetime, atmospheric density profile, etc.), BUMPER (e.g., velocity effects, shape effects, density profile, etc.), and failure criteria (e.g., conservative estimates of damage effects, etc.). The results would be most useful if they included applicable ranges and associated confidence levels.

NASA may find the methodology used by the Department of Defense (DOD) for aircraft survivability studies (Ball, 1985) helpful. The DOD aircraft vulnerability process passes "shotlines" through aircraft to determine which components could be hit by various impactors at various velocities. The process takes into account shielding of critical components by less critical components that may not be necessary for continued flight. The process also allows the DOD to determine whether redundant components are adequately separated or if one impact could damage both redundant systems. "Damage modes and effects" analyses are conducted to determine whether critical components or subsystems could be rendered inoperable by various impactors at various velocities. "Failure modes and effects" analyses are used to determine which components and subsystems are critical to continued flight. In other words, the DOD uses a systematic process that determines the contributions of all components and subsystems to the vulnerability of the total system.

Finding. NASA has not conducted an end-to-end assessment of the survivability of the shuttle with respect to the meteoroid and orbital debris hazard. Similar analyses, however, have been conducted by the DOD to assess aircraft survivability.

Refining Risk Assessments

The in-depth analyses conducted by NASA and Boeing North American Reusable Space Systems to characterize the risk of critical penetration of the orbiter wings and elevons have provided mission planners with more complete information about potential risks to the orbiter. The analyses have also provided valuable input into decisions on whether to modify existing hardware to provide better protection from the impact of meteoroids and orbital debris.

Analyses like these have not yet been performed for other orbiter components or systems. For example, the risk from meteoroids or debris to redundant systems that are not physically separated has not yet been assessed. Analyses of this type could also be used to refine assessments of the risk of critical failure, mission-limiting damage, and damage requiring repairs to determine which areas of the shuttle require more protection and to determine whether operational and procedural modifications could decrease the risk.

RECOMMENDATIONS

Recommendation 1. NASA should reevaluate the current guideline that allows the shuttle to experience a 1/200 probability per mission of critical failure from the impact of meteoroids or orbital debris. A lower allowable risk appears to be more appropriate.

Recommendation 2. NASA should establish a survivability assessment process and conduct a systematic survivability assessment of the entire shuttle orbiter—including all subsystems and components—against the meteoroid and debris hazard. The assessment should be integrated with assessments of the risk from other on-orbit hazards, as well as the risk from ascent and reentry, to create a complete, integrated, peer-reviewed PRA for the shuttle.

Recommendation 3. NASA should continue to assess in detail the vulnerability of areas of the shuttle orbiter that are predicted to contribute most to the overall risk of critical failure, mission-limiting damage, and damage requiring repair.

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4

Tools for Risk Assessment

CURRENT APPROACH

Models of the Meteoroid and Orbital Debris Environment

NASA uses ORDEM96 as an input to its assessment of the risk to the shuttle orbiter from debris. ORDEM96 predicts the impact flux and velocity distribution of debris in a prescribed orbit (Kessler et al., 1996). ORDEM96 is the latest in a series of NASA models of the orbital debris environment developed since 1989 as user-friendly tools for spacecraft designers. ORDEM96 is not a conservative model. It attempts to describe the debris environment as accurately as possible (Johnson, 1997).

ORDEM96, although still semi-empirical, is significantly more complex than previous models. It divides the debris population into six source components (intact objects, large fragments, small fragments, sodium/potassium droplets, paint flakes, and aluminum oxide particles). These objects are divided into six inclination bands and two eccentricity families. The population of each source component in each representative orbit varies with altitude according to a formula based on both data and analysis.

The data used to develop and validate ORDEM96 were gathered from a wide variety of sources, including the United States Space Command Satellite Catalog, radar sampling of the LEO environment by the Haystack and Goldstone radars, and samples of materials returned from space. Analytic derivations are used to estimate populations of debris that are difficult to measure. For example, NASA's EVOLVE model (Reynolds, 1991) is used to predict the population of smaller fragments from breakups.

The ORDEM96 model relies largely on internal NASA verification and validation to ensure that it operates as intended. Because it is primarily an empirical curve fit of data, NASA compares new data with ORDEM96 predictions. If the two correlate well, no changes are made. If sufficient new data indicate that the model is incorrectly predicting the environment, the model may be modified. ORDEM96 underwent an international peer review before it was released but has not been subject to formal verification and validation (NASA, 1996).

Because ORDEM96 is empirically derived, it can be modified whenever a significant breakup occurs. Before each shuttle mission, an evaluation is made of the effects of recent breakups. The effects of breakups that might affect the orbiter's environment are added to the output of ORDEM96 for predictions of the debris environment for the mission. The breakup of a Pegasus rocket upper stage in June 1996, which produced several hundred fragments detectable by the SSN, is an example (Johnson, 1997).

The meteoroid model used by the shuttle program consists of a flux model (Grün et al., 1985) and a velocity model (Erickson, 1968; Kessler, 1969). Both are well accepted and widely used. The effects of normal, annual meteor showers are incorporated into the model, but rare meteor storms that occur when the Earth passes through a particularly dense portion of a comet dust trail are not. NASA, however, evaluates threats from meteor showers and storms before every shuttle mission and has delayed two missions to avoid potential hazards from meteor showers. NASA does not plan to fly the shuttle during future meteor storms. NASA is currently developing a new meteoroid model that includes the background environment as well as the effects of meteor showers and meteor storms.

BUMPER

The primary tool for preflight risk assessment and damage prediction from meteoroids and orbital debris is the BUMPER computer code. This code has been used since 1990 to assess the risks to the orbiter from meteoroids and orbital debris. BUMPER's configuration is controlled by the Space Shuttle Requirements Control Board. The NASA Johnson Space Center Space and Life Sciences Directorate maintains the model and determines when updates are warranted (Christiansen, 1997). Recent updates have included new failure criteria and the incorporation of ORDEM96 (Zhang and Prior, 1996).

BUMPER employs a finite element model to represent the geometry of the orbiter and various mission components. This model contains more than 25,000 elements and includes the effects of shadowing some orbiter elements by others. On average, each element in the model measures 25 cm on a side. The size of the elements varies with location on the orbiter: the areas most vulnerable to critical penetrations are modeled using the smallest elements. The model divides the orbiter into 57 different regions (excluding payloads) to describe different materials, configurations, and failure criteria. BUMPER's finite element model library also contains models for a variety of payloads, including single and double Spacehabs, Spacelab, and the extended-duration orbiter pallet.

For each shuttle mission, BUMPER calculates two quantities. The first is the probability of impact, which is based on the expected meteoroid and orbital debris environment, the spacecraft configuration, and the mission profile. The second calculation is the probability of critical penetration and failure, given a particular impact on the orbiter. This is based on the geometry of the orbiter and its critical subsystems, empirically-derived equations governing damage levels and ballistic limits for various orbiter components and materials, and quantified, impact-based, failure criteria for the orbiter systems and components. Because BUMPER cannot evaluate the damage to orbiter components and systems caused by a given penetration, conservative assessments of a penetration causing critical damage are used unless a detailed study (such as the ones described in Chapter 3) of a particular area has been conducted, in which case the results of the study are used to set failure criteria.

High speed impact tests that simulate the impact of orbital debris have been used in the development of the damage predictor and ballistic limit equations in BUMPER for various orbiter materials and component configurations. Equations for materials and configurations not tested are pieced together from empirically-based equations. BUMPER calculations assume that the impactors are aluminum spheres, and all tests are performed with aluminum impactors. Using a single type of impactor simplifies the interpretation of test results and makes assessing the effects of different impact conditions easier.

ANALYSIS AND FINDINGS

ORDEM96

NASA has been, and continues to be, a leader in the development of models of the space environment. A substantial portion of the analyses of the meteoroid and debris environment performed over the last 30 years has been conducted by NASA scientists. The product of the analyses, ORDEM96, is generally considered to be one of the best, if not the best, current model of the debris environment. A 1996 peer review of ORDEM96 revealed minimal dissent (Johnson, 1997). Peer review appears to be an appropriate approach to verifying the relatively simple empirical ORDEM96 model, and a formal independent verification and validation of the model does not appear to be necessary at this time.

The ORDEM96 model, however, is based on limited data and analyses, and its predictions include a high level of uncertainty. The only debris population that is well understood is the tracked population—objects larger than about 10 to 30 cm in diameter. All other population estimates are based on in-situ data gathered intermittently and supplemented by analysis.

Areas where uncertainty compromises the accuracy in ORDEM96 include the conversions of measurements (either remote observations or returned samples) into population characteristics, orbital lifetimes (which are dependent on ballistic coefficients, solar activity, solar-lunar perturbations, and solar radiation pressure), and gaps—temporal, spatial, and object size—in the data (such as the almost complete lack of data on the population of debris with diameters from 0.5 to 2 mm). The use of models to estimate the amount of debris from breakups and releases of small debris also increase uncertainty. Estimates of the future rate of debris production obviously add to the uncertainty. No attempt has been made to quantify the effects of all of the uncertainties on ORDEM96's predictions.

After each shuttle mission, the number of impacts found on shuttle surfaces is compared to pre-flight predictions (which use ORDEM96 flux data as an input). To date, pre-flight predictions of required window replacements appear to be fairly close to the observed results, but the very small amount of data gathered to date on millimeter-sized impactors suggests that the model may be underpredicting the flux in that size range (Levin et al., 1997). Because of the high level of uncertainty in the model and the dynamic nature of the debris environment, these results are still preliminary. Continued comparison of pre-flight predictions to post-flight damage assessments, however, appear to be warranted.

Finding. The ORDEM96 model is arguably the best available model of the debris environment. However, the model is based upon limited data and numerous assumptions. The magnitude of uncertainty in the model's predictions is not known.

Population Variability over Time

Atmospheric drag and other factors cause debris—particularly smaller debris—to rain through the orbiter's altitude regime (300 to 450 km) for relatively short periods of time. Figure 4-1 shows estimates of particle lifetimes (by diameter) as a function of solar activity. The figure shows that millimeter-sized particles will stay in the 300 to 450 km range for a few months at most and that particles 0.04 mm in diameter will stay in orbiter altitudes only for days or weeks.

Basic sampling theory dictates that an accurate description of the dynamics of a certain size of debris in a certain altitude regime requires that the sampling rate be at least twice as fast as the debris will be cleansed from that region. For example, during periods of high solar activity, sampling would have to be done about once a week to produce an accurate assessment of the population of millimeter-sized debris. Although this is currently fiscally infeasible, it does indicate what would be required for an accurate representation of the natural variability in population estimates.

ORDEM96 averages all of its predictions over at least one year and, therefore, does not account for natural variability in the debris environment although it makes some adjustments for changes in solar activity. Thus, for short duration

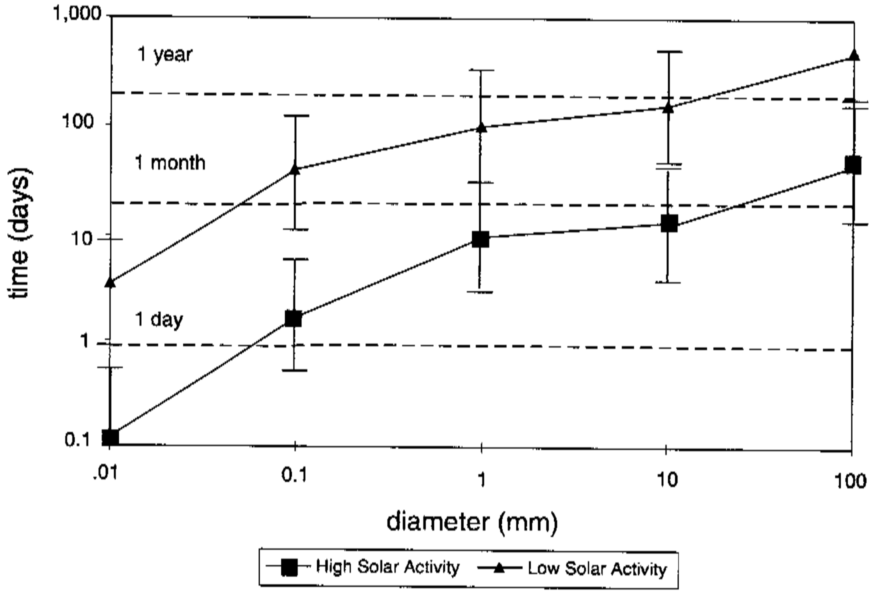

FIGURE 4-1 Particle lifetime as a function of diameter and solar activity.

missions, the actual flux may vary greatly from the ORDEM96 predictions. (This is not to imply a deficiency in ORDEM96 but to sound a cautionary note about interpreting its results.)

Finding. Because of limited data and the natural variability in the population of debris smaller than about 5 mm in diameter, ORDEM96 predictions of debris fluxes for individual shuttle missions may be highly inaccurate.

Improving ORDEM96

To predict the hazard from debris accurately throughout a shuttle mission, NASA needs either to develop spatially and temporally dependent analytic models for debris smaller than 5 mm in diameter or to greatly increase its ability to gather data about this population. Both of these approaches are promising, but the benefits of each must still be weighed against the costs.

The Haystack radar measurement (Stansbery et al., 1996; Settecerri et al., 1997) that investigated the presence of space-borne sodium potassium droplets is an example of the sampling quality and rate that would improve the understanding of the production and removal of millimeter-sized debris. By increasing the sensitivity of ground-based radars, NASA may be able to sample the population down to 2 mm in diameter, although the cost could be prohibitive. With a sufficient sampling rate and rapid data analysis, short-term predictions of the flux of particles in this size range could be made.

At the same time, or as a less expensive alternative, NASA could focus on improving the understanding of sources of debris less than 5 mm in diameter at orbiter altitudes. One of these sources is solid rocket motor firings, which project a variety of aluminum oxide particles into elliptical orbits as they boost spacecraft into higher orbits. Because of their elliptical orbits and high ballistic coefficients, the movement of these particles is difficult to model.

A second major source of debris less than 5 mm in diameter are debris wakes, which are even more difficult to model. Debris wakes are created by the release of debris from a spacecraft by nonenergetic means (typically as external surfaces deteriorate over time and slough off debris). Deterioration is caused by a number of mechanisms, including atomic oxygen erosion of surface materials, thermal cycling, ultraviolet radiation that causes embrittlement, particulate impacts that produce ejecta, and spacecraft operations that release foreign material. All of these release mechanisms create debris wakes that vary with the size, age, and orbit of the object producing the wake, as well as the construction and composition of its external surfaces (in particular, the type of paint).

Finding. Predicting the short-term hazard to individual shuttle missions from orbital debris more accurately would require a greatly improved capability to sample the population of sub-5 mm debris and/or improved models of the sources and orbital behavior of sub-5 mm debris.

ORDEM96 currently does not include information about debris shape or composition although the amount of damage caused by a collision is strongly affected by the shape and composition of the impactor. But debris shape and density are difficult to model for most types of debris. Given the large uncertainties inherent in both NASA's environment and penetration models (Johnson, 1997), it is not clear that shape or density information would significantly improve current damage predictions. However, NASA will need more information about the shape and composition of debris for more accurate, end-to-end meteoroid and orbital debris risk assessments for the shuttle.

BUMPER

Although BUMPER has not undergone formal, external, independent validation and verification, it has been reviewed by many of its users since 1989. Problems in the code or output are forwarded by users to NASA for review and possible action. BUMPER predictions have been shown to compare well with those of ESABASE (the European Space Agency equivalent of BUMPER), SURVIVE (Lockheed Martin), and SD-SURF (Lockheed Martin). BUMPER predictions are also regularly compared with inspections of the surfaces of returned spacecraft, including the shuttle orbiter (NASA, 1997).

Impactor Size, Shape, and Velocity

BUMPER uses solid spherical aluminum projectiles to simulate the impacts of orbital debris. However, testing and analyses in the last 30 years have shown that the damage caused by the impact of non-aluminum and nonspherical projectiles is decidedly different from the damage caused by spherical aluminum projectiles with the same impact energy. Hence, BUMPER's predictions may dramatically overestimate or underestimate damage to the shuttle orbiter from on-orbit impacts by orbital debris particles, which are usually not spherical and are usually not composed of aluminum. For example, NASA estimates that if 30 percent of debris were plastic, 30 percent were steel, and 40 percent were aluminum, the penetration risk would increase by 80 percent (Christiansen, 1997).

The impact velocities of orbital debris are expected to average about 10 km/s, but routine testing using light gas guns cannot exceed impact speeds of approximately 7 km/s. Therefore, all of the equations developed for and used by BUMPER are strictly valid only up to 7 km/s. However, a complete risk assessment requires obtaining the impact responses of materials and configurations at impact velocities of more than 7 km/s. NASA believes its analytical model for extending the ballistic limit curves above 7 km/s is conservative. Although this conservatism may be appropriate for safety reasons, it may unduly restrict operational flexibility (see discussion in Chapter 3).

NASA has performed some initial impact tests at 11 km/s using an inhibited shaped charge launcher (ISCL), and additional tests are planned for 1998. The ISCL can generate impact test results at velocities higher than conventional light gas guns, but the projectile in an ISCL test (a hollow cylinder) differs from the solid sphere typically used in light gas gun testing. NASA has performed an initial study to try to correlate the 11 km/s hollow cylinder data and the 7 km/s or less solid sphere data (Christiansen, 1997). Preliminary results suggest that BUMPER may indeed be conservative at high velocities, but the results are, at best, very limited and inconclusive.

Finding. BUMPER is probably the best available model for orbital debris risk assessment and damage prediction for the orbiter. However, it incorporates a number of simplifying assumptions, as well as a limited set of empirically-derived ballistic limit equations, and the magnitude of uncertainty in its predictions has not been well characterized.

Improving BUMPER

NASA could take two approaches to making the BUMPER model more useful for shuttle mission planners and program managers. First, more extensive data collection and analyses could reduce uncertainties in BUMPER predictions. The effects of non-aluminum and nonspherical projectiles on orbiter materials and configurations, for example, could be systematically characterized and the equations in BUMPER revised accordingly. NASA could also try to improve its understanding of impacts at velocities above 7 km/s, perhaps by better establishing the relationship between its sub-7 km/s tests and its 11 km/s hollow cylinder tests, or by working with other organizations that conduct high-velocity impact tests and simulations.

A second approach would be to characterize the uncertainties in BUMPER predictions more accurately. BUMPER currently does not provide users with error bars or confidence intervals. Such information, however, could be invaluable to those making decisions based upon BUMPER predictions. A sensitivity analysis of BUMPER results to various input parameters could help NASA determine which parts of the model to refine in order to reduce the uncertainties of BUMPER calculations of mission risk most effectively. A rigorous peer review process, including some form of independent validation and verification, could also increase user confidence in the model's results.

RECOMMENDATIONS

Recommendation 4. NASA should increase its data gathering and modeling efforts to improve understanding of the sources (e.g., solid rocket motors and debris wakes) of the sub-5 mm debris population in the shuttle's orbital regime.

Recommendation 5. NASA should try to refine BUMPER and ORDEM96 so that their results include appropriate error bars and associated confidence levels. To begin with, NASA should analyze the sensitivity of the output of both models to changes in input parameters.

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5

Collision Avoidance

CURRENT APPROACH

Collision Warning Capabilities

The DOD SSN warns the space shuttle program of possible close conjunctions with cataloged orbiting objects. The SSN is composed of ground-based radars, electro-optical sensors, and command and control systems that detect, track, and catalog man-made objects in Earth orbit. The SSN uses ground-based sensors to collect data on orbiting objects. The data are used to estimate the positions and trajectories (called orbital element sets) of objects. The element sets can then be used to predict whether a close approach or collision may occur.

The SSN can only warn about collisions with objects identified in their satellite catalog. The current SSN catalog of tracked objects includes essentially all objects larger than 100 cm in diameter in low Earth orbit, and about 95 percent of objects larger than 30 cm in diameter. Although some objects as small as 10 cm are also included, from 15 and 50 percent of objects between 10 cm and 20 cm may be missing. Virtually no objects smaller than 10 cm in diameter are included in the catalog (Kessler, 1996; Lord, 1996).

The U.S. Space Command's Space Control Center (SCC) notifies NASA flight controllers when it predicts close conjunctions between the orbiter and cataloged objects. The information is used to determine if a launch should be delayed or an orbiting vehicle should be maneuvered to avoid a possible collision.

Prelaunch Warnings

Two different prelaunch warnings are used to protect the orbiter from collisions with objects shortly after launch. The SCC (using data from the SSN) determines whether any cataloged objects are predicted to enter an area around the orbiter (called an alert box) with dimensions approximately 5 km radially, 25 km along the track of the orbiter (either leading or trailing), and 5 km out of the orbital plane during the first two hours of the mission (Flight Rule A4.1.1-3). The Eastern Range is responsible for notifying NASA if the orbiter will enter a 50 km × 200 km × 50 km region around another crewed vehicle during the first orbit after a launch (Flight Rule A2.1.1-1.).

If either of these warnings indicates a possible collision, the launch is usually delayed until the next even minute. Additional analyses are requested using the new launch time, and further holds may be ordered. To date, two shuttle launches have been delayed to avoid potential collisions with orbiting objects (Reeves, 1997).

On-Orbit Operations

When the shuttle orbiter is in orbit, the SCC screens the entire satellite catalog for objects that could approach the orbiter within a 5 km × 25 km × 5 km alert box at any time during the mission. The SSN is tasked with providing more intensive tracking of the approximately one to two objects per day that penetrate this box. The objects are then reassessed using a more accurate and computationally intense "special perturbations" algorithm to determine if any will come within a "maneuver box" of 2 km radially, 5 km along the orbiter's track, and 2 km out of plane. (The alert and maneuver boxes are shown in Figure 5-1.) The large box size relative to the size of the orbiter is necessary because the current and future positions of tracked objects are not known precisely. The accuracy of the special perturbations algorithm is obviously dependent on the availability of accurate sensor data.

Information about potential close conjunctions is passed to NASA flight controllers who apply Flight Rule A4.1.3-6 (see Box 5-1), which stipulates that a maneuver be performed "if the maneuver does not compromise either primary payload or mission objectives." Like all flight rules, this one can be superseded by real-time decisions.

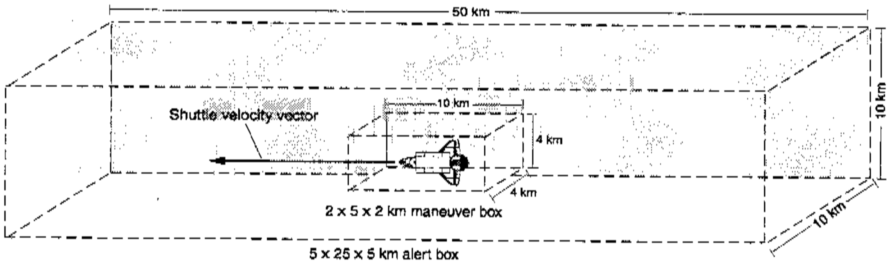

FIGURE 5-1 The space shuttle alert and maneuver boxes.

BOX 5-1
NASA Flight Rule A4.1.3-6

A collision avoidance maneuver will be performed for a conjunction predicted by the United States Space Command if the predicted miss distance is less than 2 km radially, 5 km down track, and 2 km out-of-plane and if the maneuver does not compromise either primary payload or mission objectives. Propellant redlines will not be budgeted for any potential maneuvers.

If NASA flight controllers decide a maneuver is necessary, the orbiter uses its on-board propulsion system to execute the maneuver. On average, the orbiter changes its velocity by about 30 cm/s to avoid a collision, which requires the expenditure of about 11 to 14 kg of propellant (Loftus, 1997). Between shuttle missions STS-26 and STS-82, the orbiter logged approximately 527 days of on-orbit operations. During that time, nine cataloged objects penetrated the 2 km × 5 km × 2 km box. In five of these nine cases, avoidance maneuvers were not performed because they would have interfered with primary mission objectives. In the other four cases, evasive maneuvers were performed by the shuttle. On two other occasions, maneuvers were performed when penetrations of the larger 5 km × 25 km × 5 km alert box, but not the 2 km × 5 km × 2 km maneuver box, were predicted (NASA, 1997).

Proposed New Collision Warning Technique

The current technique for determining the threat of collision between the orbiter and a tracked object does not directly take into consideration the geometry of the conjunction or uncertainties about the position of either the orbiter or the other object. In the future, NASA plans to switch from this deterministic approach to avoiding collisions to a probability-based approach, which will be used for ISS operations.

The new method is based on the probability of collision (P_c), which is defined as the probability that an object will penetrate a sphere around the spacecraft. The calculation of P_c is based on the uncertainties of the positions of the spacecraft and the other object at conjunction and the geometry of the predicted conjunction.

In this probability-based approach, the U.S. Space Command's computation of misses between orbits (COMBO) program will be run with current data for all cataloged objects for 72 hours into the future. The SSN will increase the frequency of tracking observations for each object COMBO indicates will penetrate the 5 km × 25 km × 5 km alert box, thus increasing the accuracy of position estimates. After processing the updated tracking data, COMBO will be run again in the "special perturbations" mode. If the conjunction is still within the alert box, an alert warning will be sent to NASA, along with the updated vectors and covariances for each object and the ISS at conjunction. (Covariances represent the uncertainty in the element sets of the ISS and conjuncting object.) The SCC will continue tracking these objects more intensively and send the updated vectors and covariances to NASA.

NASA will use these data to calculate P_c. If P_c exceeds a predetermined threshold, called the yellow threshold, the flight director will consider ordering a collision avoidance maneuver. If P_c exceeds a higher threshold, called the red threshold, the flight director will order a collision avoidance maneuver.

ANALYSIS AND FINDINGS

Catalog Completeness

The SSN can only observe objects with radar cross-sections on the order of tens of square centimeters. As a result, the Satellite Catalog does not include many objects that could seriously damage the orbiter. The full extent and quantity of the uncataloged population is not known. As shown in Table 2-1, however, NASA's ORDEM96 model predicts that the probability that the shuttle will collide with a trackable object (i.e., greater than 10 to 30 cm in diameter) if no collision avoidance maneuvers are performed is less than 0.5 percent over the design life of the shuttle fleet (.002 impacts per 400 10-day missions). The probability of impact with an object that is untrackable with current sensors but still able to cause critical damage to parts of the orbiter (i.e., objects 5 mm to 10 cm in diameter) is closer to 20 percent (0.2 impacts over 400 10-day missions). Thus, according to NASA estimates, more than 95 percent of the objects that can cause critical damage to the orbiter are not being tracked or cataloged.

Finding. Warnings of collision are provided only for cataloged objects. NASA estimates that more than 95 percent of the objects that could cause critical damage to the orbiter are not being tracked or cataloged.

NASA/DOD Cooperation

The current methodology for providing collision warnings to the orbiter requires coordination between NASA and the DOD SSN. Although the Memorandum of Agreement between United States Space Command and Johnson Space Center for Space Control Operations Relationship, Space Shuttle Program Support, and International Space Station Program Support (USSPACECOM and JSC, 1996) addresses requirements in a general fashion, it does not state requirements for the timeliness of warnings, minimum object size, or the accuracy or uncertainty of predictions. In August 1997, NASA levied more detailed requirements on the SSN, but the SSN may be unable to meet these requirements.

In the absence of specific requirements, budget limitations have forced the DOD to reduce the number of ground-based sensors that supply most of the information about debris at orbiter operational altitudes. Since 1989, the number of radar sensors in the SSN has been reduced from 19 to 13, and no new radar sensors have been added, although upgrades have been made at a few sites. Plans for new or upgraded SSN sensors do not include requirements that would improve debris tracking. Unless action is taken, the SSN's ability to provide collision warnings to the shuttle will probably diminish.

Finding. The capabilities of the SSN to provide collision warnings to NASA are eroding. Until recently, NASA had not issued requirements that might have helped to halt this erosion.

New Approach to Collision Warnings

The planned use of covariance data should help NASA make better decisions about collision avoidance maneuvers and reduce the number of unnecessary maneuvers. NASA is now waiting for the U.S. Air Force to complete development of covariance matrices. The covariance data will also be used for the ISS, for which it will be needed by late 1998.

NASA has recently specified the level of accuracy it requires for covariance or state vector uncertainties at conjunction. The method the SSN currently uses to compute a covariance does not represent uncertainty in the state vectors accurately enough to calculate P_c accurately at the orbiter's operational altitude, where the major uncertainty is atmospheric drag. Inaccurate calculations of P_c could result in the orbiter performing unnecessary maneuvers or not performing necessary maneuvers. Current work (Barker, 1996, 1997) for the Air Force will greatly improve the computation of covariance but will not incorporate the uncertainty in atmospheric drag.

Finding. NASA plans to use a new probability-based approach to determine when a collision avoidance maneuver is necessary, but the collision avoidance data currently provided by the SSN is not accurate enough for the new approach to be effective

NASA Flight Rules for Collision Avoidance

In deciding whether to make a collision avoidance maneuver, NASA flight controllers assess whether the maneuver would compromise primary payload or mission objectives. The current wording of Flight Rule A4.1.3-6. suggests that a very close conjunction of the orbiter and a large, well tracked object could occur without requiring a maneuver. Unlike the vast majority of flight rules, which place safety first and then allow exceptions in limited cases, this flight rule places mission needs first and requires those who provide the collision warning to prove that action needs to be taken.

Future shuttle missions that support the ISS will have a limited ability to maneuver. NASA Flight Rule C4.3.2-1, Space Station Translation Maneuvers During Joint Shuttle Operations, states that debris avoidance maneuvers will not be performed during docked operations. In addition, NASA reports that maneuvers will probably not be performed when the orbiter is undocked but is involved in assembly operations (Reeves, 1997).

Finding. NASA Flight Rules A4.1.3-6 and C4.3.2-1 appear to place mission success ahead of flight safety. The mechanism for making trade-offs between success and safety is not explicit.

RECOMMENDATIONS

Recommendation 6. NASA has recently documented and provided collision avoidance requirements to the DOD. NASA and the DOD should work to satisfy these requirements, to identify impending changes to the SSN that will affect debris tracking, and to identify changes that would improve the SSN's ability to track smaller objects that pose a hazard for crewed spacecraft.

Recommendation 7. NASA should re-examine Flight Rules A4.1.3-6 and C4.3.2-1 and consider restating them to establish when a maneuver is mandatory for safety reasons.

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6

Risk Mitigation

The space shuttle program has developed operational procedures and is about to implement hardware modifications to improve the survivability of the shuttle orbiter and crew in the face of the meteoroid and orbital debris hazard. Additional operational procedures and hardware modifications have the potential to further improve the orbiter's survivability.

CURRENT APPROACH

Constraining On-Orbit Attitude

Because of the geometry of orbital conjunctions, the shuttle orbiter's forward-facing (in the direction of the orbiter's velocity vector) surfaces will be subject to the great majority of collisions with orbital debris. Therefore, the orbiter's attitude relative to the orbital vector will have a major influence on the effects of impacts of meteoroids and orbital debris. One of the most significant factors in window replacement, for example, is the length of time that windows face in the direction of the velocity vector (Smith, 1995). Figure 6-1 shows how the orbiter's attitude affects the predicted number of window replacements, and Figure 6-2 shows how the assessed risk of critical penetration (a penetration anywhere on the orbiter that could result in the loss of the orbiter or crew) varies with orbiter orientation. Developers of orbiter attitude time lines take into consideration the possibility of critical damage, damage that would force early termination of a mission, and damage to orbiter windows, and balance the potential for damage against the need to accomplish mission objectives.

Shuttle Flight Rule A2.1.3-32 states that the preferred attitude for orbiter

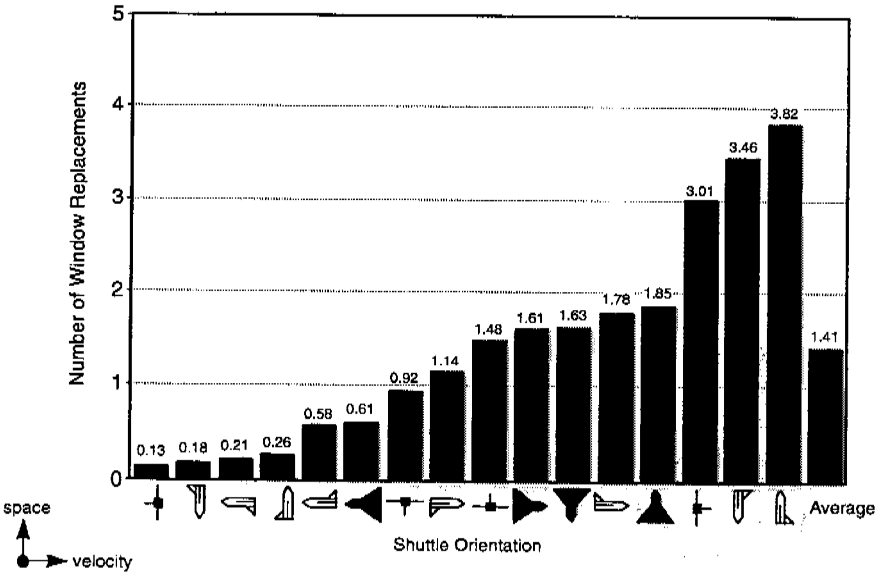


FIGURE 6-1 Window replacements vs. shuttle orientation (BUMPER prediction for 10-day mission, 400 km altitude, 51.6 degree inclination, 1996 environment). The three orientations that place the top of the orbiter in the direction of the velocity vector are most likely to cause window damage because the two overhead windows are exposed, as well as the six forward-facing windows. Source: NASA.

operations is with the payload bay pointing down (toward the Earth) and the nose not pointing forward. Exposure time with the payload bay pointing forward and with the nose pointing forward while the payload bay points up or out of plane is kept to a minimum. If other attitudes are required by payload or orbiter requirements, they will be used. The flight rules are primarily designed to protect the orbiter windows and radiators (for which the hazard is 16 times greater when the payload bay points forward than when it points down) (Reeves, 1997). Although orientations that present the maximum risk of critical penetration are not prohibited, the shuttle program's maximum allowable critical risk of 1/200 might force mission planners to minimize flight time in those attitudes.

Extravehicular Activity

Operational procedures planned to reduce the risk to astronauts performing EVAs include avoiding EVAs when meteor storms or showers or conjunctions with cataloged debris are predicted. Whenever possible, EVAs are performed in locations that are shaded by the orbiter or (in the future) by elements of the ISS

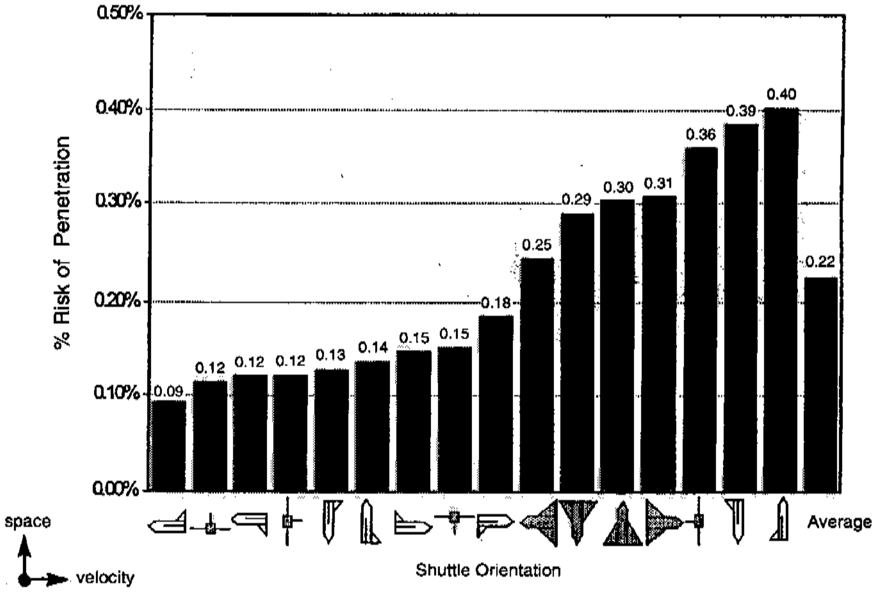


FIGURE 6-2 Critical penetration risk vs. shuttle orientation (BUMPER prediction for 10-day mission, 400 km altitude, 51.6 degree inclination, 1996 environment). Source: NASA.

(Heflin, 1997). NASA considered developing a portable shield to protect astronauts during ISS assembly operations, but that option was determined to be impractical (Simonds and Julian, 1997).

Damage Control and Repair

NASA has developed damage control procedures for the shuttle crew in the event that a pressurized compartment is penetrated. Access to the pressure hull in the orbiter cabin, the Spacelab, and the Spacehab in most cases requires removing racks and storage lockers, which will take significant time and effort. NASA estimates that about 60 percent of the interior of the pressure vessel would be accessible in 30 minutes to two hours, the next 20 percent in two to three hours, and the last 20 percent in more than three hours (Combs, 1997). Given these constraints, NASA has focused on expediting reentry in the event that a pressurized compartment is penetrated.

If the crew detects a penetration of the crew cabin that they believe does not require immediate reentry, they will first attempt to locate the hole. If the hole is accessible, they will attempt to repair it with an epoxy material or sealing tape, which are carried on all flights (Reeves, 1997). The limiting consumable in the event of a leak is the on-board nitrogen gas (N_2) supply. The N_2 supply was designed to provide 165 minutes of pressure in the event of a half-inch diameter hole. An emergency reentry could be initiated within 20 minutes if the shuttle is not docked, 90 minutes if it is docked with Mir, and five hours if it is docked with the ISS. The shuttle takes approximately 60 minutes to land after reentry is initiated.

In the case of a penetration of the Spacehab or Spacelab, the crew would first isolate the damaged module and then decide whether to terminate the mission. If the penetration is not too large and if damaging effects of penetration, such as light flashes and pressure pulses, do not delay their response, the large volume of the Spacelab and the Spacehab provides reasonable time for the crew to evacuate the damaged area (Loftus, 1997a).

Hardware Modifications

To date, the only authorized hardware modifications to the orbiter specifically designed to mitigate the risk from meteoroid and orbital debris are modifications to the radiators in the payload bay doors and the insulation inside the leading edge of the wing. The radiator modifications will reduce the risk that the freon coolant loops will be penetrated by meteoroids or orbital debris, which would force the orbiter to return to Earth. As shown in Figure 6-3, strips of aluminum

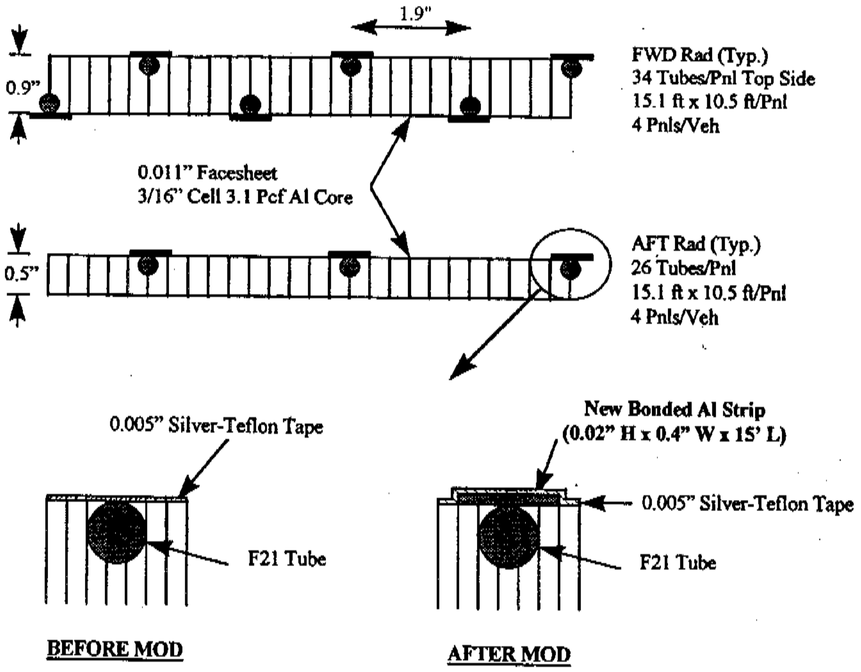


FIGURE 6-3 Modification of radiator tube shielding. Source: NASA.

tape 0.02 inches thick will be added to the length of the coolant loop. In addition, NASA has authorized installation of an isolation valve at the radiator freon inlet and a check valve at the radiator outlet to isolate a leak and limit the loss of freon. The crew will have to close the valves when a caution and warning alarm signals that a change in freon pressure has been detected. An automated system to close the valves is currently under review. The modifications, which will add 30 kg to the orbiter's mass, are scheduled to be installed on all four orbiters during routine maintenance between February 1998 and February 1999 (Ouellette, 1997).

The modifications to the RCC leading edge of the wing will be made in the region of the wing where the shock wave from the nose of the vehicle and the shock wave from the wing intersect during reentry. Existing insulation inside the wing could not tolerate the heating rates and heating loads from the plasma flow that would result from a penetration of the wing in this area. Several layers of Nextel, a high-temperature ceramic fiber, are being added behind the current insulation. This modification should allow the orbiter to maintain structural integrity during a reentry with a 0.63 cm diameter penetration in the lower side of the RCC. The modification, which will add approximately 77 kg to the orbiter's mass, will be installed during planned modification periods and inspection cycles (Loftus, 1997b).

ANALYSIS AND FINDINGS

Constraining On-Orbit Attitude

By constraining the on-orbit attitude of the shuttle orbiter, NASA can significantly reduce the risk of significant damage. One issue with the current approach is that it forces mission planners to make trade-offs between (1) protecting the crew cabin windows, (2) reducing the probability that the mission will have to end early, and (3) minimizing the risk of critical damage. During some Mir missions, for example, attitudes chosen to reduce the predicted risk to the radiators have increased the predicted risk of a critical impact. Without a mechanism for making trade-offs, NASA runs the risk of treating minor hazards that are well known (e.g., window pitting) as more important than more serious hazards that have not yet damaged the orbiter.

When ISS operations begin, NASA plans to constrain shuttle attitudes to satisfy ISS power, thermal, and attitude control requirements, rather than to minimize risks from meteoroids and orbital debris (Reeves, 1997). The planned configuration for docking the orbiter to the completed ISS, for example, leaves the orbiter in an orientation that maximizes the predicted risk of critical penetration. Missions to the ISS will also limit mission planners' ability to modify the launch schedule or orbital altitude to reduce the risk from meteoroids and orbital debris.

Finding. During the ISS era, the orbiter will be unable to use some current operational techniques to improve its survivability in the face of meteoroids and orbital debris.

Damage Control and Repair

NASA has developed procedures to detect, locate, and repair small punctures in the orbiter crew cabin. However, no in-flight procedures have been developed to detect, locate, and repair punctures elsewhere on the vehicle. This capability could be very useful because many of the orbiter's potential failure modes caused by meteoroid or debris impact may not be critical immediately but could become critical during reentry. If they could be detected and repaired in orbit, the risk of critical failure could be significantly reduced.

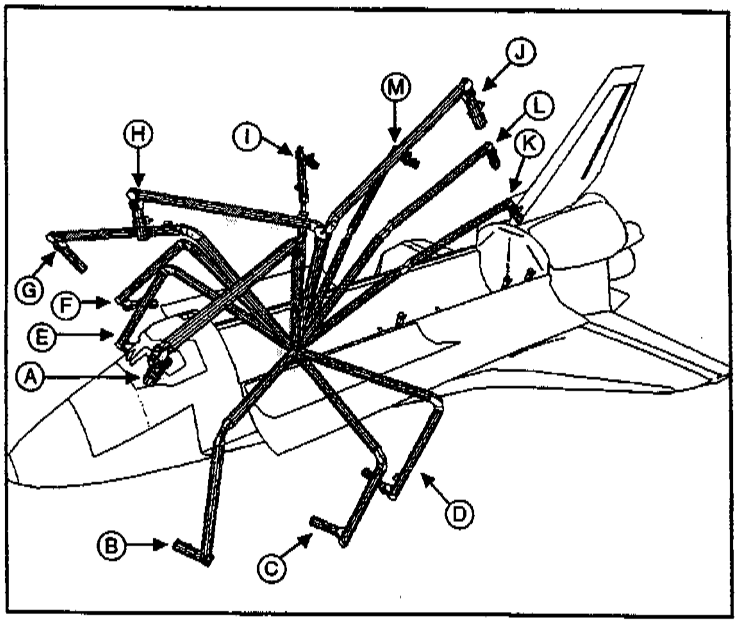
On most missions, significant damage from meteoroids and orbital debris could be located without an EVA. Large portions of the orbiter's critical areas can be surveyed for impact damage with the remote manipulator system (RMS) cameras, if the RMS is on board (80 to 90 percent of planned missions). Figure 6-4 shows how the RMS could be used to survey the orbiter for damage. NASA is also considering stationing free-flying monitor robots at the ISS; these would be able to examine a shuttle docked at the station.

Repairing significant damage from meteoroids or orbital debris outside the pressurized area might also be feasible although it would require at least one EVA. Before the first shuttle flight, NASA developed a spray can foam-in-place ablative material to repair damaged or lost TPS tiles. The hardware was never carried on the orbiter because of NASA's confidence that the TPS would perform effectively, but it could be used to repair damage from meteoroids or debris on the TPS. Repairs to other orbiter elements might also be possible, although effective repair of the RCC leading edges would be very difficult because the repairs would have to survive exposure to very high temperatures during reentry.

NASA's guideline that sets the maximum allowable risk of sustaining a critical penetration during a given mission suggests that one or two critical penetrations will occur during the 400 mission life cycle of the orbiter fleet (as of September 1997, 87 shuttle missions have been flown). In deciding how to allocate the finite resources of dollars, crew training time, and on-orbit operations time, NASA must determine whether in-orbit detection and repair of penetrations by meteoroids and debris outside the pressurized compartments are feasible and worthwhile.

Hardware Modifications

The planned modifications to the payload bay door radiators and to the wing leading edge insulation appear to be positive steps that will have minimal negative effects on the overall program. NASA estimates that the modification to the



A - PORT SIDE, ORBITER NOSE
B - ORBITER UNDERBODY
C - NOSE AND MAIN LANDING GEAR DOORS
D - ORBITER MIDBODY AND VENT DOORS
E - STBD SIDE, WING LEADING EDGE TO NOSE
F - STBD SIDE, UNDERBODY WING TO NOSE WITH STOWED MPM
G - STBD SIDE, NOSE
H - TOP SIDE, NOSE AND OVHD WINDOWS
I - TOP VIEW, STBD WING
J - TOP VIEW, PORT WING
K - PORT, OMS POD AND VERT TAIL
L - PORT, LEAD EDGE VERT TAIL
M - STBD SIDE, LEAD EDGE VERT TAIL AND OMS POD

FIGURE 6-4 Use of remote manipulator system to survey orbiter for damage. Source: NASA.

radiator will reduce the worst case risk of early mission termination by approximately a factor of 10. The proposed solution appears to be fairly simple to implement and can be accomplished in a relatively short time. The design modification to prevent melting or overheating of critical structural components inside the leading edge of a wing that has been perforated by a meteoroid or orbital debris should reduce the probability of critical failure and require only a minor increase in vehicle mass.

Finding. NASA plans to modify the orbiter radiators and wing insulation to reduce the risk of early mission termination and critical failure. These modifications appear to be positive steps that will have a minimal negative effect on the program.

In Chapter 3, the committee suggested that NASA should continue to assess the potential of various hardware modifications to improve the survivability of the orbiter in the face of the meteoroid and orbital debris hazard. This assessment could also be used to determine future hardware modifications. Although deciding which areas should be assessed in detail will require further analysis, NASA may wish to consider the following areas:

- wing locations that contain multiple hydraulic and electrical lines vital for elevon motion and flight control
- additional modifications inside the leading edges of wings and wing areas
- payload bay pressurized modules, such as the Spacehab and Spacelab modules
- pressure vessels in the payload bay, including those on the extended duration module
- a replacement for the current payload bay liner and multilayer insulation that would provide better protection of the multiple components and pressure vessels in the orbiter mid-body
- design options to replace existing insulation blankets with materials that provide better protection from meteoroids and orbital debris
- reinforcement materials on the aft bulkhead of the cabin to provide more robust protection from meteoroids and orbital debris
- relocation of redundant systems that may be vulnerable to the impact of meteoroids and debris

RECOMMENDATIONS

Recommendation 8. NASA should assess the effect of plans for the ISS era that will render the shuttle unable to use some current operational techniques to protect the vehicle from meteoroids and orbital debris.

Recommendation 9. NASA should reconsider conducting on-orbit surveys of the orbiter exterior to detect impact damage and repair it if necessary.

Recommendation 10. NASA should investigate additional modifications to the orbiter to improve its survivability.

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Acronyms

COMBO	computation of misses between orbits
DOD	U.S. Department of Defense
EMU	extravehicular activity mobility unit
EVA	extravehicular activity
ISCL	inhibited shaped charge launcher
ISS	International Space Station
LEO	low Earth orbit
NASA	National Aeronautics and Space Administration
ORDEM96	Orbital Debris Environment Model for Spacecraft Design and Observations in Low Earth Orbit
P_c	probability of collision
RCC	reinforced carbon-carbon composite
RMS	remote manipulator system
SSN	Space Surveillance Network
TPS	thermal protection system
USSPACECOM	United States Space Command

APPENDICES

APPENDIX
A
Statement of Task

Drawing upon available data and analyses, including information presented by NASA and other agencies, the committee will assess the space shuttle program's strategy for assessing and mitigating the threat posed by the meteoroid or orbital debris environment and recommend alternative strategies where appropriate. Specifically, the committee will review and assess:

- the meteoroid/debris environment model used by the space shuttle program
- current techniques for pre-flight prediction of meteoroid and debris damage to the shuttle (taking into account the actual damage seen on past shuttle missions)
- current techniques for characterizing the potential for loss of the crew or the shuttle due to meteoroid or debris impacts
- the ability of the current Space Shuttle shielding and operational approaches to protect the space shuttle from meteoroids and debris impacts
- proposed design modifications to reduce the hazard to the shuttle from meteoroids and debris
- operational procedures and hardware to reduce the hazard to the shuttle and its crew in the case of damaging meteoroid or debris impacts
- the space shuttle program's approach to collision avoidance
- the need for additional data on the meteoroid/debris environment in the shuttle orbit, and appropriate measures to gather that data

APPENDIX B

Biographical Sketches of Committee Members

Frederick H. Hauck (chair), is president and chief executive officer of AXA Space (formerly INTEC), a company that specializes in providing insurance for launching and operating space systems. Before coming to AXA Space, Mr. Hauck was director of the Navy Space Systems Division in the Office of the Chief of Naval Operations. Before that, Mr. Hauck was a test pilot and a member of the astronaut corps. As an astronaut, he flew in space three times and was commander of the first shuttle flight after the Challenger accident. He has been a member or chair of numerous panels and advisory groups on national and international space activities. Mr. Hauck has received two Defense Distinguished Service Medals, the National Aeronautics and Space Administration (NASA) Distinguished Service Medal, the Distinguished Flying Cross, the Presidential Cost Saving Commendation, and many other honors and awards. He holds degrees in physics and nuclear engineering from Tufts University and the Massachusetts Institute of Technology.

Kyle T. Alfriend is a professor and head of the Aerospace Engineering Department at Texas A&M University. Previously, he headed research centers and laboratories at the Naval Postgraduate School, the General Research Corporation, and the Naval Research Laboratory. Dr. Alfriend is a recognized expert in astrodynamics and has chaired the American Institute of Aeronautics and Astronautics (AIAA) Astrodynamics Technical Committee. He has worked on orbital debris for several years and has developed algorithms both for estimating the probability of collisions between space objects and for estimating the space object population from sample radar measurements. He is a fellow of the AIAA and the American Astronautical Society. Dr. Alfriend holds degrees in engineering mechanics from Virginia Polytechnic Institute and State University and from Stanford University.

Dale B. Atkinson is a consultant on survivability issues. For 34 years, he worked for the U.S. Department of Defense (DOD) and was one of the founders of the aircraft survivability discipline. He retired from the Office of the Secretary of Defense in 1992. Before working on aircraft survivability, he was involved in some of the first attempts by the U.S. Air Force to protect spacecraft from meteoroids. He is an associate fellow of the AIAA and the recipient of the first AIAA Survivability Award. Mr. Atkinson holds degrees in aeronautical engineering and national resources from the University of Kansas and George Washington University.

Dale R. Atkinson is chief executive officer of POD Associates, Inc., which specializes in impact physics analyses and impact survivability and safety for spacecraft, aircraft, vehicles, and ships. Mr. Atkinson has worked on various aspects of modeling, analyzing, and monitoring the meteoroid and debris environments, their effects on systems, and potential mitigation techniques. He has also worked on analyzing the results from the Long-Duration Exposure Facility (LDEF) spacecraft, advised the White House National Space Council on orbital debris from 1991 to 1993, was the Ballistic Missile Defense Organization's expert on orbital debris and micrometeoroid survivability technologies, and served as a member of the National Research Council (NRC) Committee on Space Debris and the Committee on Space Station Meteoroid/Debris Risk Management. Mr. Atkinson holds degrees in aerospace engineering from the University of Arizona.

G. Taft DeVere is an analyst at the Space Warfare Center. Until January 1997, he was a member of the technical staff at SenCom Corporation, where he was technical lead for U.S. Department of Defense orbital debris data collection campaigns. Previously, Mr. DeVere worked at Teledyne Brown Engineering and Nichols Research Corporation, where he led studies of the Space Surveillance Network's sensors, command center, and debris analysis. Before that, he was a captain in the U.S. Air Force and worked on a wide variety of space observation and analysis activities. He holds degrees in physics and space operations from the University of Massachusetts and from Webster University.

Donald H. Emero is a retired vice president of Rockwell's Space Systems Division. Mr. Emero held a variety of positions in the space shuttle program and was the chief engineer for space shuttle orbiter production and operations from 1989 to 1993. In this position, he headed numerous teams to resolve complex problems with the shuttle. Mr. Emero has been awarded the NASA Distinguished Public Service Medal and the National Management Association's Gold Knight of Management, and he is an associate fellow of the AIAA. Mr. Emero holds two degrees in civil engineering from the University of Massachusetts.

George J. Gleghorn is a retired vice president and chief engineer of TRW's Space and Technology Group. He was the chair of the NRC Committee on Space

Debris and the Committee on Space Station Meteoroid/Debris Risk Management. He is also a member of NASA's Aerospace Safety Advisory Panel. Dr. Gleghorn is a fellow of the AIAA and was elected to the National Academy of Engineering for his "contributions to the development of advanced scientific and communications spacecraft and the technology of spacecraft systems engineering." He holds degrees in electrical engineering from the University of Colorado and the California Institute of Technology.

Darren S. McKnight is vice president of Titan Research and Technology. He has co-authored two books and written more than 40 technical articles on orbital debris and was the founder and editor of a newsletter, the Orbital Debris Monitor. Dr. McKnight previously worked at Logicon RDA and Kaman Sciences Corporation on kinetic energy weapons lethality, simulation, orbital debris, and space environmental effects. Before that, he was a professor of physics at the Air Force Academy. Dr. McKnight holds degrees in engineering from the University of New Mexico, the Air Force Academy, and the University of Colorado.

William P. Schonberg is professor and chair of the Civil and Environmental Engineering Department at the University of Alabama in Huntsville. Dr. Schonberg has published more than 30 journal articles and has presented more than 35 papers on shock physics, hypervelocity impacts, and penetration mechanics. The results of his research have been applied to a wide variety of engineering problems, most notably the development of orbital debris protection systems for spacecraft—including the International Space Station—in low Earth orbit. Dr. Schonberg holds degrees in civil engineering from Princeton University and Northwestern University.