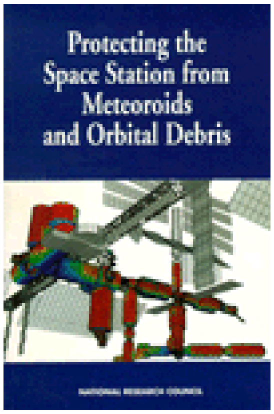

Protecting the Space Station from Meteoroids and Orbital Debris

Committee on International Space Station Meteoroid/Debris Risk Management

ISBN: 0-309-52350-8, 64 pages, 6 x 9, (1997)

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Committee on International Space Station
Meteoroid/Debris Risk Management

Aeronautics and Space Engineering Board

Commission on Engineering and Technical Systems

National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.   1997

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, DC 20418

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Additional copies available for sale from: National Academy Press, 2101 Constitution Avenue, N.W. Box 285, Washington, D.C. 20055. 1-800-624-6242 or 202-334-3313 (in the Washington metropolitan area). http://www.nap.edu

Printed in the United States of America.

Cover Illustration: BUMPER finite element model of the International Space Station. Critical items are colored to represent predicted probability of collision with 1 cm diameter and larger debris. Red represents the highest predicted probability of impact and blue the lowest. Source: NASA.

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Preface

Protecting the International Space Station (ISS) from meteoroid and debris impact poses a unique challenge because of the station's large size, high value, and planned long lifetime. To mitigate the meteoroid and debris hazard, the ISS program has developed a strategy involving shielding, collision avoidance, and damage control. The National Aeronautics and Space Administration (NASA) asked the National Research Council to review this strategy and to recommend changes, where appropriate.

In response, the National Research Council formed the Committee on International Space Station Meteoroid/Debris Risk Management. (The charge to the committee is contained in Appendix A.) The committee found that the meteoroid and debris environment the space station will encounter is increasingly well understood, that the program for shielding ISS modules appears extensive and thorough, and that the development of damage control procedures and hardware has begun. In this report, the committee recommends changes to the ISS meteoroid/debris risk mitigation program that should serve to further strengthen the current program.

Although this report focuses on the shielding, collision avoidance, and damage control measures that the ISS program can take to reduce the hazard posed by meteoroids and debris, it is important to note that the success of these measures will also be affected by the efforts of others to reduce the generation of orbital debris in low Earth orbit. For several years, the United States and other spacefaring nations have been working to reduce the production of new orbital debris. Without continued resolute action to minimize the creation of new debris, the hazard to the ISS could rise considerably over the operational lifetime of the station.

The committee wishes to thank the many experts at NASA, the Air Force Space Command, the U.S. Space Command, the Russian Space Research Center Kosmos, RKK Energia, Boeing, and Lockheed-Martin who briefed the committee and provided background information over the course of the study. I would personally like to thank the members of the committee for their time and effort spent on the study and in writing this report. I am also indebted to Paul Shawcross and his staff at the National Research Council for their hard work and leadership throughout the process.

The recent loss of a stabilizing boom on the French Cerise spacecraft due to a debris impact highlights the threat that meteoroids and debris pose to the ISS. Experts working to protect the ISS clearly understand this threat and the effectiveness of various methods to counter it. It is essential for this understanding—including the recognition of where assumptions are unproved, models are uncertain, and protective measures are limited—to be communicated clearly to the upper management of the program. Better information will result in better decisions, and when a multibillion-dollar facility and human lives may be at stake, every effort must be made to ensure that decision makers are armed with the best information available.

George Gleghorn, *chair*

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The chance of a spacecraft colliding with meteoroids or orbital debris increases with the size of the spacecraft and the time it spends in orbit. The International Space Station (ISS), a multibillion-dollar crewed orbiting laboratory, will be the largest spacecraft ever built and is expected to remain in orbit for at least 15 years. Due to its large size and long operational lifetime, the ISS will face a significant risk of being struck by potentially damaging meteoroids or orbital debris. This report is the National Research Council assessment of ISS program efforts to protect the space station from meteoroids and debris.

Both the overall ISS risk management process (which primarily addresses cost and schedule risks to the program) and the ISS safety office (which focuses on threats to crew safety) monitor and react to the meteoroid and debris hazard. An analysis integration team (AIT) staffed by the National Aeronautics and Space Administration (NASA), Boeing, and the international partners (Canada, Japan, Russia, and the member nations of the European Space Agency) has been established to study the threat from meteoroids and orbital debris, develop and evaluate countermeasures, and provide input to the risk management processes. Although the ISS risk management approach appears sound, the unique nature of the meteoroid and debris hazard has made it difficult for the ISS risk management schemes to properly weigh the risk from meteoroids and debris against other risks to determine whether action should be taken. The ISS program needs to ensure that the findings of the meteoroid and debris AIT are communicated clearly to program managers.

The meteoroid and debris AIT has developed an approach to reduce the hazard posed by meteoroids and debris to the station and crew. The team plans to shield the ISS against smaller objects and to maneuver the ISS to avoid collision with objects large enough to be tracked by ground-based radar. Damage control hardware will be deployed, and procedures will be implemented to mitigate the effects of collisions with objects too small to be tracked by radar and too large to be stopped by the ISS shields.

To provide the information needed for effective risk management, NASA has developed models of the meteoroid and debris environment in the orbit of the ISS. Over the past five years, NASA has done a good job of improving these models by incorporating new data and by making reasonable assumptions about areas where data are sparse. NASA should continue to update these models with new data and analyses and make the models available for peer review. Although recent models of the debris environment differ considerably from older models in a few areas, elements of the ISS program still use the outdated models. This is justifiable in some cases, but the ISS program should strive to ensure that the most recent meteoroid and debris environment models are used wherever possible.

In general, the effort to shield the ISS from meteoroid and debris impact appears extensive and thorough. However, some portions of the ISS, primarily in the Russian segment, are currently expected to be much less well protected from meteoroid and debris impact than other areas. The ISS program must strive to improve shielding for areas of the ISS that do not yet meet requirements. Further efforts to improve coordination with the Russian Space Agency on meteoroid and debris issues should be explored to help ensure that all parts of the ISS are adequately protected.

A shortcoming in ISS shield design is that the shields have been designed to protect the ISS against a hazard considerably different in some respects from that currently expected. Recent models show that debris may strike the ISS at a lower velocity and from a wider range of directions than previously thought. Because the actual environment under which the shields must protect the station is still not well known, future shields should be designed to withstand a broader variety of threats.

The ISS program should initiate an accelerated shield testing program to ensure that the currently planned shield designs are effective against the expected threat and to aid in the design of future shields. Increased emphasis should be placed on the lower velocity regimes and on gaining a better understanding of secondary ejecta. The ability of extravehicular activity suits to protect astronauts in the current predicted environment also should be assessed.

To further improve ISS shielding, NASA should consider upgrading its capability to perform computer-simulated impacts, perhaps by working with other national facilities. In addition, the meteoroid and debris AIT should consider holding a workshop to bring in experts from outside NASA to discuss the use of advanced shielding materials for future ISS shields.

The ISS team has been slow to concentrate on damage control issues, but it has begun to develop hardware and procedures to aid the ISS crew in the event of a serious meteoroid or debris impact. The team has developed a software tool, MSCSurv, to assess the relative merits of various damage control procedures and devices. NASA should continue to refine this program and to update it to reflect failure modes associated with all critical and high-energy systems, toxic gas releases, nonpenetrating impacts, and equipment and system failures caused by impacts.

The ISS program should accelerate its efforts to plan for damage control and repair. As part of this effort, NASA should intensify its work with the Russian Space Agency to identify and resolve differences in damage control hardware and procedures. The program also needs to study the failure modes of shielded pressure walls and to assess the capability of the ISS to continue safe operations with damaged wiring, piping, and other systems.

The ISS program plans to maneuver the space station to avoid debris large enough to be tracked and cataloged by the U.S. Space Surveillance Network (SSN). (Because of the limited maneuvering capability of the ISS, onboard sensors will be ineffective in providing collision avoidance services.) The ISS program expects the SSN to alert the space station several hours in advance when a close encounter is predicted. If it appears that the ISS is in the path of an oncoming object, the station will maneuver out of the way.

The current debris environment model suggests that the ISS can expect to receive about 10 warnings per year that may require an avoidance maneuver. The ISS program should work on reducing the number of false warnings, perhaps by increasing the accuracy of locating threatening objects. The ISS program currently has no plans for maneuvering the station during some phases of the assembly sequence or when the shuttle is docked, due to concerns about the structural integrity of some ISS configurations under acceleration. The ISS program should work to ensure that maneuvering capability is always available.

The risk that the ISS will collide with untracked debris could be lowered if more objects were tracked. The number of objects being tracked could be increased by improving the sensitivity of the tracking radars and by using optical sensors, but this would require significant effort. The future capability of the SSN, however, may actually decrease due to sensor shutdowns or other actions caused by budgetary pressures. NASA should work closely with the SSN at the highest level of authority to determine what support the network will be able to provide the ISS over its lifetime.

1

Introduction

Spacecraft in low Earth orbit (LEO) continually collide with meteoroids passing through near-Earth space and with orbital debris created by human activities in space. The vast majority of these meteoroids and debris are much smaller than a millimeter in diameter and cause little damage. A small fraction of the meteoroid and debris populations, however, are larger and can cause severe damage in a collision with a spacecraft. The chance of impact with larger objects relates directly to the size and orbital lifetime of a spacecraft. The larger the spacecraft and the longer it remains in orbit, the more likely it will collide with potentially damaging objects (NRC, 1995a).

The International Space Station (ISS) will be the largest spacecraft ever built. ISS assembly in LEO is due to begin in late 1997, and the station is expected to remain operational for at least 15 years. When assembly is complete, the multibillion-dollar ISS will have a mass of 419,000 kg, a crew of approximately six researchers, and more than 11,000 m^2 of surface area exposed to the space environment (NRC, 1995b). Figure 1-1 depicts the ISS at the end of its assembly sequence. Due to its large surface area, long functional lifetime, and the potential for a catastrophic outcome from a collision, protecting the ISS from meteoroids and debris poses a unique challenge.

The National Aeronautics and Space Administration (NASA) has been aware of the potential hazard to the space station from meteoroids and debris since the inception of the program (Portree and Loftus, 1993). The agency has addressed the problem by seeking to better understand the meteoroid and debris hazard and by taking steps to protect the space station from the hazard. Both these tasks are formidable.

It is difficult to characterize the hazard posed by meteoroids and debris to the ISS because most of the meteoroids and debris that could harm the space station are small, dark, and fast moving and thus difficult to detect from the Earth. Moreover, the meteoroid and debris environment in the ISS orbit can vary greatly, depending on the state of the solar cycle and the number and severity of recent breakups of orbiting objects. Adequately protecting the ISS from this environment is also challenging because of the uncertainty of the threat and the difficulty of accurately simulating the effects of high-speed meteoroid and debris impacts.

The team building the ISS has developed a strategy to manage the hazard posed by meteoroids and debris to the ISS. To support this strategy, the team has developed models that predict the flux of meteoroids and debris in the ISS orbit. The ISS program uses these models to determine the chances that the station will collide with meteoroids and debris of various sizes. The program plans to reduce the hazard by: (1) shielding elements of the ISS to protect them from impacts with the smallest meteoroids and debris, (2) moving the ISS out of the path of the rare pieces of debris large enough to be tracked by ground-based sensors, and (3) implementing design features and operational procedures to minimize the

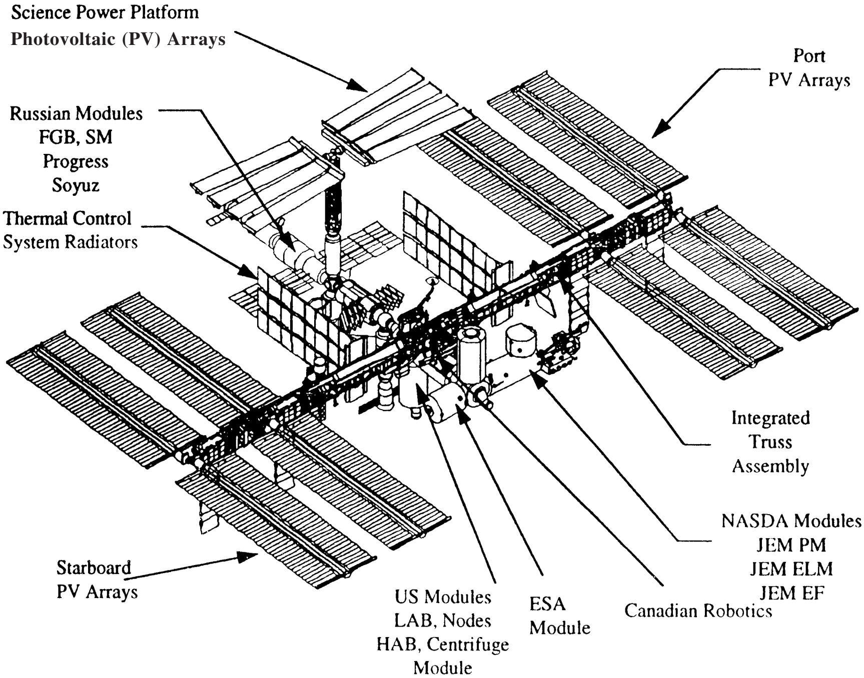


FIGURE 1-1 The International Space Station. Source: NASA.

hazard to the station or crew if the ISS collides with meteoroids or debris too large to be shielded against but too small to be tracked by ground based-sensors.

In this report, the committee examines the ISS program strategy for reducing the hazard of meteoroid and debris impact and recommends alternative strategies where appropriate. Chapter 2 examines the overall ISS meteoroid and debris risk management strategy. Chapter 3 looks at the NASA meteoroid and debris environment models, and Chapter 4 examines the vulnerability of the ISS to impact and the use of protective shields. Chapter 5 addresses methods to reduce the risk to the station and crew in the event of a damaging impact. Finally, Chapter 6 explores the use of collision warning and avoidance systems.

REFERENCES

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

NRC (National Research Council). 1995b. The Capabilities of Space Stations. Committee on Space Station, Aeronautics and Space Engineering Board. Washington, D.C.: National Academy Press.

Portree, D.S.F., and J.P. Loftus, Jr. 1993. Orbital Debris and Near-Earth Environmental Management: A Chronology. NASA Reference Publication 1320. Linthicum Heights, Maryland: NASA Center for Aerospace Information.

2

International Space Station Risk Management Strategy

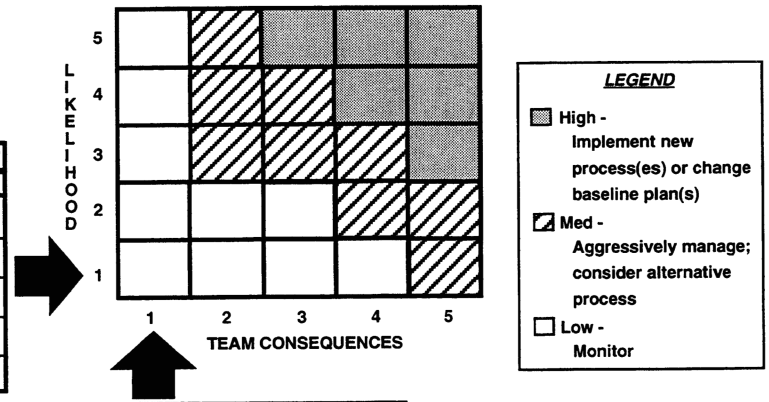
CURRENT PROGRAM

NASA is responsible for establishing risk management policies, goals, and processes for the ISS. These policies, goals, and processes are implemented in detail by the ISS prime contractor (Boeing) and the international partners (Canada, Japan, Russia, and the member nations of the European Space Agency). The ISS risk management process is managed by integrated product teams (IPTs) and analysis integration teams (AITs), jointly staffed by NASA and Boeing (for the U.S. on-orbit segment) or the international partners (for the non-U.S. segments). The teams evaluate risks in terms of likelihood and consequences and qualitatively rank them on a relative scale matrix (shown in Figure 2-1). The consequences can be technical, or they can affect the ISS schedule or cost, although cost and schedule risks dominate the current list of risks. ISS program policy requires that action be taken to change designs, processes, or plans to mitigate the impact that high-risk items (those in the upper right corner of the matrix) could have to the program. The ISS program currently ranks the risk of meteoroid and orbital debris impacts as one of the top 15 risks to the ISS program, although it is not one of the top 10.

The ISS safety office maintains a separate ranking of safety hazards and technical risks. The sixth risk in their ranking is directly related to meteoroids and debris. Box 2-1 shows the August 1996 safety office list of the 10 greatest ISS risks and hazards. Program policy requires a two-failure tolerance level for safety hazards in systems that, by themselves, could cause the loss of the station or crew in the event of a failure. Structural safety hazards are dealt with using safety

Likelihood

What is the likelihood the situation or circumstance will happen?	
Level	Your team's current process . . .
5	... cannot prevent this event, no alternate approaches or processes are available.
4	... cannot prevent this event, but a different approach or process might.
3	... may prevent this event, but additional actions will be required.
2	... is usually sufficient to prevent this type of event.
1	... is sufficient to prevent this event.



Team Consequences

Given the event occurs, what is the magnitude of the impact to your team? . . .					
Level ➡	1	2	3	4	5
Technical	Minimal or No Impact	Mod. Reduction, Same Approach Retained	Mod. Reduction, But Workarounds Available	Major Reduction, But Workarounds Available	Unacceptable, No Alternatives Exist
Schedule	Minimal or No Impact	Addt'l Activities Required. Able to Meet Need Dates	Key Team milestone slip $\leq$1 mo.	Key Team Milestone Slip>1 Mo, or Pgm Critical Path Impacted	Can't Achieve Key Team or Major Program Milestone
Cost	Minimal or No Impact	Team Budget Increase <5%	Team Budget Increase >5%, or Other Teams Impacted	Team Budget Increase >10%	Team Budget Increase >15%

Technical includes everything that is not cost and schedule: e.g., safety, operations, programmatic.

FIGURE 2-1 The ISS program risk matrix. Source: NASA.

BOX 2-1
Safety Office Top 10 Hazards (August 1996)

1. Extremely hazardous extravehicular activity (EVA) may be required to jettison a damaged or partially deployed but jammed solar array.
2. Software development for the ISS is behind schedule, resulting in an incomplete safety assessment for some systems.
3. The Russian functional cargo block (FGB) docking probe motor is not two-fault tolerant.
4. The structural interface between segments Z1 and P6 is not two-fault tolerant.
5. The ISS has no continuous carbon monoxide monitoring system.
6. The risk from meteoroids and debris is unacceptably high, primarily because of the inadequate shielding of the Russian modules.
7. The Russian segment may be unable to survive depressurization and repressurization without experiencing critical equipment failures.
8. Some features on the outside surface of the ISS would be hazardous to astronauts conducting EVAs.
9. During deberthing operations, the Soyuz could potentially collide with the ISS photovoltaic arrays.
10. The retraction mechanism for the KURs antenna on the FGB module is not two-fault tolerant, thereby creating a possible collision risk.

factors, ground tests, materials qualification, fracture control, and other design and process control measures to provide failure tolerance.

The ISS program created an AIT to be responsible for meteoroid and orbital debris risk management. The meteoroid and orbital debris AIT members are responsible for all aspects of the problem, including modeling the environment, calculating the likelihood that debris or meteoroids will penetrate modules, performing hypervelocity impact tests, and designing and evaluating shields. The meteoroid and orbital debris AIT reports to the mechanical subsystems AIT, which reports to the systems integration AIT, which, in turn, reports to the vehicle IPT. Figure 2-2 shows this chain of command.

The meteoroid and orbital debris AIT strategic plan for risk management is to shield against particles up to about 1 cm in diameter, to maneuver to avoid collisions with objects larger than about 10 cm in diameter that can be tracked by ground-based sensors, and to implement procedures to mitigate the damaging effects of impacts with objects between about 1 and 10 cm in diameter. These three methods are discussed in detail in Chapters 4, 5, and 6. Figure 2-3 illustrates this overall approach to managing the risk from meteoroids and debris.

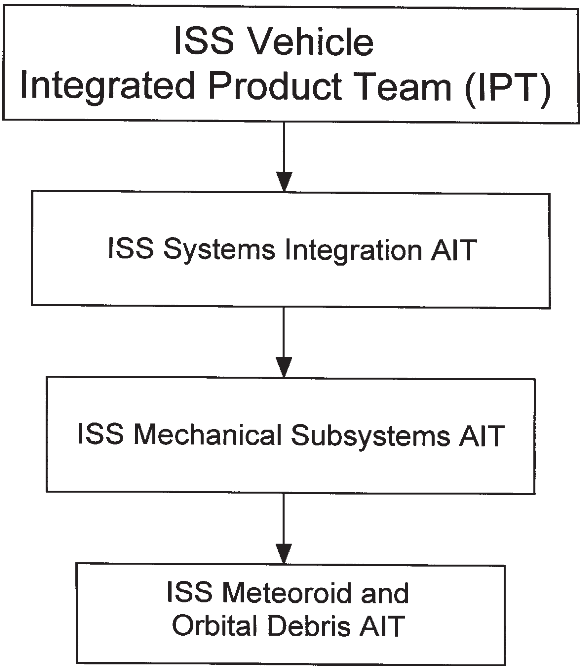


FIGURE 2-2 The ISS meteoroid and debris AIT chain of command. Source: NASA.

The main requirement the AIT uses to manage the risk from meteoroid and orbital debris is that the probability that no "critical" ISS component will be penetrated by debris over 10 years should be, at a minimum, 0.81. A 1991 model of the debris environment is used to calculate this probability of no penetration (PNP). As discussed in Chapter 3, the flux of orbital debris, collision velocity distribution, and impact angle distribution in recent models differ from those in the 1991 model.

The AIT has defined as critical those items whose penetration could cause the immediate loss of the ISS or a crew member. Items whose penetration could only cause failures that are not time critical or that could be overcome by system redundancy or operational procedures are considered noncritical. Some tests have been performed to verify whether items should be designated as critical. For example, hypervelocity impact tests of batteries and ammonia accumulators showed that gradual pressure decay, rather than an explosion, occurred after penetration; thus, these items are considered noncritical (Winfield, 1996).

Not all penetrations of critical items will necessarily cause the loss of life or of the station. In some cases, the ISS crew will be able to seal off the penetrated module from the rest of the station. The crew may also be able to repair some penetrations. As described in more detail in Chapter 5, the meteoroid and orbital debris AIT is studying the various sources of risk to the station and crew, including thrust from venting, critical equipment damage, injury to crew, hypoxia, and delayed effects. Risk and hazard reduction analysis is an ongoing activity for the AIT, and it will continue beyond the design phase in the ISS operational phase.

The PNP requirement of 0.81 was based on past precedent, combined with an understanding of the limitations of design and operations capabilities. The space shuttle orbiter cabin has a 0.95 PNP requirement over 500 missions (roughly equivalent to 10 years of continuous exposure) for the meteoroid environment alone. The precursor to the ISS, Space Station Freedom, adopted a 0.95 PNP for meteoroids and debris, but its design was never able to achieve this goal. The PNP requirement for the ISS was set at 0.90 because this was judged a reasonable goal that could be met with additional shielding. More than 1,400 kg of shielding was added to components derived from Space Station Freedom to achieve a PNP of 0.90. When the Russian modules were added to the ISS, the AIT proposed that the Russian segment of the ISS should also have a PNP of 0.90, thus reducing the overall combined PNP for the ISS to 0.81 (see Box 2-2).

The overall 0.81 PNP requirement was approved by NASA management, and it has been apportioned, by area, to the critical modules and equipment. Figure 2-4 shows how the PNP requirements for all critical items contribute to the overall PNP requirement. These requirements are documented in the top-level ISS system specification and in the specifications for the U.S. and other major segments of the ISS. The requirements are controlled by the specification control process, and modifications must be approved by the ISS program manager.

The BUMPER-II code is the primary tool used by the AIT to determine the

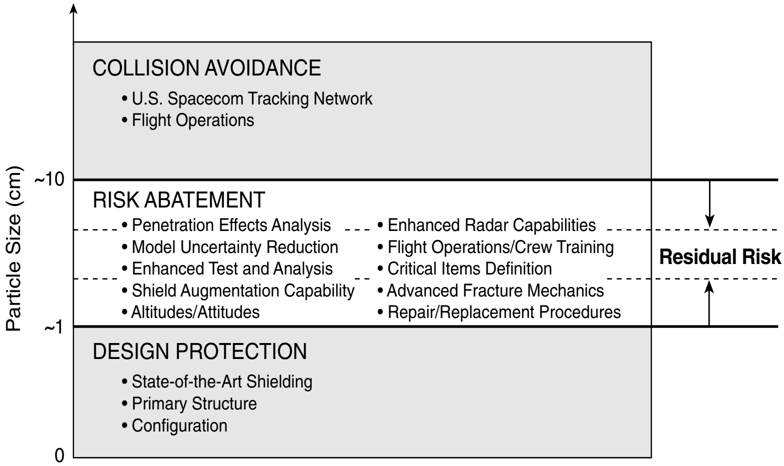


FIGURE 2-3 The ISS strategy for meteoroid/debris risk mitigation. Source: NASA.

BOX 2-2
What Does a 0.81 PNP Mean?

A PNP of 0.81 is equivalent to a 0.19 probability that one or more penetrations of a critical item will occur over a 10-year period. The expected number of penetrations (N_{pen}) of critical items on the ISS can be calculated from PNP using the equation:

$$N_{pen} = -\ln(\mathrm{PNP})$$

With a 10-year PNP of 0.81, the expected number of times an ISS critical item will be penetrated over 10 years will be about 0.21. If the 10-year PNP is 0.55, then the expected number of penetrations is 0.6.

The number of expected penetrations varies linearly with time, assuming no changes in the predicted environment. Thus, an expected rate of 0.21 penetrations over 10 years would increase to an expected value of 0.42 penetrations over 20 years, and an expected 10-year rate of 0.6 penetrations would increase to a predicted 1.2 penetrations over 20 years.

PNP values, however, are far from exact because they are based on many assumptions. First, they are based on assumptions about the future debris environment. If the rate of launches or breakups, for example, turns out to be higher or lower than expected, the predicted PNPs may prove to be incorrect. Second, PNPs are based on assumptions about the effectiveness of ISS shields in preventing the penetration of critical items. And finally, the PNP calculations do not include impacts on noncritical items, such as the truss or the radiators, even though such impacts could potentially cause severe damage to the ISS.

PNPs of ISS critical items. This computer program uses a finite element model and statistical analysis to combine spacecraft geometry and design, the meteoroid and orbital debris environments, and calculations of the particle size that would penetrate each component to calculate the PNP for each element of the ISS and to provide output for graphical representation of the results. Figure 2-5 depicts the BUMPER finite element model of the space station at the end of its assembly sequence. The BUMPER-II code can use both the 1991 and the 1996 NASA models of the meteoroid and debris environments. The environment model from 1991 is still used to assess whether critical items meet their PNP requirements, while the 1996 model is used for most other applications.

Although noncritical items are not included in the PNP calculations, contractors must meet requirements that ISS components have a low risk of failure; thus

Critical Item	S. Area m^2	Duration of Req.	PNP Req.		Roll-up
Node 1	81.20	10 yr	0.9925		
PMA 1	20.00	10 yr	0.9946		
PMA 2	13.60	10 yr	0.9946		
PMA 3	13.60	10 yr	0.9946		
CMGs *	20.00	10 yr	0.9955		
Lab	133.80	10 yr	0.9930		
Airlock / HP Gas Tanks	74.60	10 yr	0.9900		0.92
ma Contactor Xenon Tan	7.30	10 yr	0.9955		
TCS Comp.	15.30	10 yr	0.9955		
Node 2	94.70	10 yr	0.9925		
Cupola	94.70	10 yr	0.9980		
TCS Comp.	15.30	10 yr	0.9955		
Centrifuge *	133.80	10 yr	0.9856*		
Hab	133.80	10 yr	0.9820		0.90
CTV#1 *			TBD	**	
MPLM	94.85	800 days	0.9935		0.9935
ESA APM	113.29	10 yr	0.9861		0.9861
ESA ATV *			0.9973*	**	
JEM ELM PS	77.00	10 yr	0.9856		0.9737
JEM PM	174.20	10 yr	0.9822		
		15 Yr PNP Req	**quiv 10 Yr PNP Req.**		0.81
FGB	117.20	0.9790	0.9863		
Service Module	140.00	0.9760	0.9837		
niversal Docking Modul	117.20	0.9790	0.9863		
Docking Compartment	30.40	0.9953	0.9964	***	
SPP-1	58.00	0.9910	0.9932	***	
SPP-2	36.10	0.9944	0.9958	** & ***	
Research module (RM-1)	75.80	0.9883	0.9911		
Research module (RM-2)	75.80	0.9883	0.9911		0.90
LS Module	74.90	0.9884	0.9912		
Research module (RM-3)	75.80	0.9883	0.9911		
B LTV - Progress/M - /	117.20	0.9790	0.9863	** & ***	

* Added to configuration following baselining of 0.81 PNP. Requirements are at varying stages of resolution.
** The PNP for this item is not included in the PNP total.
*** No agreement has yet been reached to allocate a PNP requirement for this item.
Specified system PNP does not include Shuttle, Soyuz, or EVA.

FIGURE 2-4 The PNP requirement tree. Source: NASA.

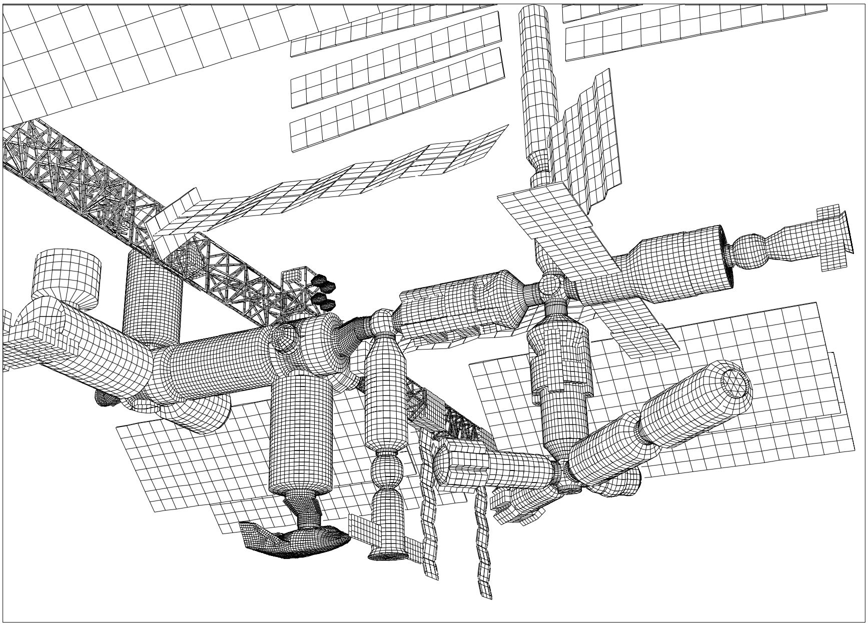


FIGURE 2-5 BUMPER finite element model of the ISS. Source: NASA.

some noncritical items that are particularly vulnerable to damage from meteoroids and debris are protected. The meteoroid and debris AIT provides the contractors with tools (including the environment model, hypervelocity impact equations, and hypervelocity impact tests) to help determine the risk of failure of particular components due to meteoroid or debris impact. For example, NASA has conducted for contractors numerous high-velocity impact tests on such items as wiring harnesses and pressure vessels. Contractors use the test results to determine whether actions need to be taken to reduce the risk of component failure.

ANALYSIS AND FINDINGS

The overall risk management approach employed by the ISS program is valid. It follows the risk management strategies that have been applied successfully to the space shuttle and to Department of Defense (DoD) programs. The approach provides a systematic framework that forces management to evaluate identified risks regularly and to take action to mitigate critical risk items. It encourages the continuous identification of new risks at the working level (AITs and IPTs), with a clear review and approval path to top ISS program management. It is a qualitative system that emphasizes the relative magnitude of risks but does not try to quantify that which cannot be quantified.

There are two concerns with this overall approach. First, the meteoroid and debris hazard does not fit well into the risk assessment approach of either the program office or the safety office. The risk matrix of the program office focuses on items that may affect the cost and schedule of the program, rather than on hazards to the ISS and crew once the ISS is operational. Due to the unique nature of the meteoroid and debris hazard—it is a hazard for which the ISS is forced to accept a risk of single-point failure—it does not fit well into the scheme of the safety office either. The second concern is that because the meteoroid and orbital debris AIT is so far down in the chain of command, the team may have difficulty bringing issues to the attention of top management.

Finding 1. The ISS approach to risk management appears to be valid, but the unique nature of the meteoroid and orbital debris hazard makes it difficult for the top-level ISS risk management schemes to properly weigh this hazard against other risks to determine whether urgent action is needed.

The plan to use shielding to protect the ISS against smaller particles and collision warning to avoid larger objects makes sense. However, the ISS program may be optimistic about the size range of objects against which these methods will protect the ISS. Program hazard reports suggest that objects larger than 10 cm in diameter will be tracked and avoided, and objects smaller than approximately 1 cm in diameter will be stopped by shielding. As discussed in Chapter 6, however, the U.S. Space Surveillance Network (SSN) is unable to catalog many objects in the 10 to 20 cm diameter size range, and the capability of the SSN to catalog small objects is more likely to decline than to improve over the next few years. In addition, as discussed in Chapter 4, the ISS program may be optimistic in assuming that current shielding can stop all objects smaller than 1 cm in diameter.

The BUMPER code appears to be an effective tool for determining the level of shielding necessary for particular modules. However, the capability to use two different environment models in the code raises some potential problems. Users need to be made aware that there are significant differences between the two models. Although using the 1991 model to determine whether modules meet PNP requirements is acceptable, using it for any other purpose (such as to determine mean-time-between-failure values for external ISS components) may produce misleading results.

The PNP-based system has been largely successful in reducing the hazard to the ISS from meteoroids and debris. ISS components derived from the previous Space Station Freedom design have been enhanced for meteoroid and orbital debris resistance and survival. The U.S. segment has thicker pressure walls and improved and added shielding that result in calculated PNPs that exceed the requirement (and also reduce the probability of loss due to catastrophic "unzipping"—a significant effect). In addition, the European and Japanese partners have agreed to adopt the U.S. approach to shield design and to accept their respective PNP requirement allocations.

The design of the Russian segment for meteoroid and orbital debris resistance is a major problem, however. A 1994 design review indicated that the Russian segment had a total PNP of 0.122, which is equivalent to more than two predicted penetrations over 15 years, even assuming an "on-orbit fix" to provide additional protection for the service module. Considerable improvement has occurred since then, but the current Russian segment design still falls far short of its apportioned requirement. The current estimated PNP for the Russian segment is 0.60, compared to the 0.90 requirement. This shortfall brings the overall PNP of the ISS down to 0.55—well short of the 0.81 requirement.

The ISS team believes this problem can be solved. If the 1996 (instead of the 1991) debris environment model is used to calculate PNP, the meteoroid and debris AIT estimates that with additional proposed Russian module shielding, the ISS can be brought up to a PNP of 0.85, which exceeds the requirement. However, the tight launch schedule and launch vehicle volume constraints make it impossible to augment the shielding on the Russian-built service module—a key element of the early ISS configuration—before launch. The current proposal is to augment the shielding of the service module in space at a later date. However, the tight schedule of ISS assembly flights will not allow such an augmentation until years after the module has been launched.

The Russian international partners appear to be responding to NASA's concerns about meteoroids and orbital debris. They are using the BUMPER code (and thus the NASA model of the debris environment) to determine whether their modules meet PNP requirements. They are also actively investigating shield designs and sending shield samples to NASA for testing. However, the Russian partners have not officially reached agreement with the ISS program on individual module PNP apportionments. Sustained NASA pressure is required to negotiate Russian compliance with meteoroid and orbital debris requirements. Having a Russian engineering representative on site at the Johnson Space Center might be helpful, and continued technical exchanges and video conferences will be necessary.

Finding 2. As currently planned, some segments of the ISS will be much less well protected from meteoroid and debris impact than others. The service module poses a particular problem because shielding cannot be added before launch if the ISS program is to stay on schedule.

RECOMMENDATIONS

Recommendation 1. The International Space Station program should take action to ensure that the findings of the meteoroid and debris analysis integration team are communicated clearly to senior program managers. The International Space

Station hazard reports, for example, should be modified to reflect the fact that some debris larger than 10 cm in diameter are not tracked and cataloged. Particular concern should be taken to address issues that may not fall within the purview of either the overall International Space Station program risk management approach or that of the safety office.

Recommendation 2. The International Space Station program should strive to improve the shielding for areas of the International Space Station that do not meet required probabilities of no penetration. In particular, improving the protection of the service module must receive a very high priority.

Recommendation 3. Further efforts—such as exchanging on-site engineering representatives and augmenting the schedule of technical interchange meetings and video conferences—to improve coordination with the Russian Space Agency and hasten agreement on meteoroid and orbital debris issues should be explored.

REFERENCE

Winfield, D. 1996. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

3

Meteoroid and Debris Environment Models

CURRENT PROGRAM

NASA has created models of the meteoroid and debris environment to aid in designing the ISS and in evaluating the effectiveness of techniques to mitigate the hazard from meteoroids and debris. The meteoroid environment used in the design of the ISS consists of a flux model (Grün et al., 1985) and a velocity model (Erickson, 1968; Kessler, 1969). The primary model of the debris environment used in the ISS design was created in 1991 (Kessler et al., 1994). Since then, NASA has updated the debris model twice, once in 1994 (Kessler, 1994) and again in 1996 (Zhang, 1996). The 1991 model is now primarily used to assess whether elements of the ISS meet their PNP requirements. The later models are primarily used to assess the effectiveness of shielding and other hazard mitigation approaches.

The 1991 debris model describes the flux of debris on a spacecraft orbiting at any inclination and altitude below 1,000 km. This model consists of a set of equations that describe the existing flux of debris and projected changes in the environment. The part of the model describing the 1991 environment was created by "curve fitting," or developing equations that produce results that correspond well with observed data. These data came from a variety of sources, including the analysis of panels returned from the Solar Max satellite (Barrett et al., 1988), the Arecibo (Thompson et al., 1992) and the Goldstone (Goldstein and Randolph, 1990) radars, the U.S. Space Command satellite catalog, the Massachusetts Institute of Technology experimental test site telescope (Taff et al., 1985), and the ground-based electro-optical space surveillance (GEODSS) telescope system (Henize and Stanley, 1990). The 1991 model assumes that objects are in circular orbits and bases the distribution of orbital inclinations on the inclinations of objects tracked and cataloged by the U.S. Space Command. Terms of the equations predicting future changes in the debris flux were based on assumptions about future spacecraft launches and the number and nature of future spacecraft and rocket body breakups.

The 1994 debris model updated the 1991 model for altitudes between 350 km and 600 km and inclinations of approximately 51.6 degrees. The updated model incorporates new data primarily from the Haystack radar (Stansbery et al., 1994), but also from an analysis of data from the Goldstone radar, the analysis of the Long Duration Exposure Facility (LDEF) surfaces (Levine, 1991), and a recalibration of U.S. Space Command radars. The 1994 model uses many of the same assumptions as the 1991 model, including estimates for object density and shape and the assumption that objects travel in circular orbits.

The ISS program replaced the 1994 debris model with the 1996 model for ISS safety evaluations conducted after May 1996. The new debris model, which was peer-reviewed by NASA and outside reviewers, incorporates additional data from the Haystack radar (Stansbery et al., 1996), LDEF, space shuttle impacts, and from an analysis of the perturbing force of solar radiation. The 1996 model provides debris flux information for spacecraft in all orbital inclinations for altitudes up to 2,000 km. Unlike earlier models, this model begins by defining a population of debris divided into six inclination bands, two eccentricity families, and six size ranges. These populations are based on the existing data, but, where data are lacking, estimates derived from the complex NASA EVOLVE model (Reynolds, 1993) and other support models are used. The debris model then calculates the flux of this population on a spacecraft in a given orbit. The 1996 model is thus better than previous models at accurately representing changes in the size distribution of debris with altitude and inclination. This is also the first debris model that incorporates the large amounts of debris that travel in elliptical orbits.

In the meteoroid model, the impact velocity of meteoroids with orbiting spacecraft velocities can range up to about 70 km/s, with an average velocity of about 19 km/s. The mean density of meteoroids is modeled as 2 g/cm^3 for meteoroids smaller than 10^{-6} g, as 1 g/cm^3 for meteoroids between 10^{-6} and 0.01 g, and as 0.5 g/cm^3 for masses above 0.01 g. The meteoroid model includes the effects of the normal annual meteor showers, but it does not account for rare meteor storms that occur when the Earth passes through a particularly dense portion of a comet dust trail. The ISS program, however, is aware of the potential hazard from such storms and is evaluating potential actions (e.g., restricting extravehicular activity during meteor storms) to reduce the hazard. Figure 3-1 compares the modeled flux of meteoroids and debris in the ISS orbit.

The debris environment predicted by the 1996 model differs in a number of ways from the environment predicted by the 1991 model. For example, the predicted flux of objects larger than 1.0 cm in diameter in the 1996 model is half the

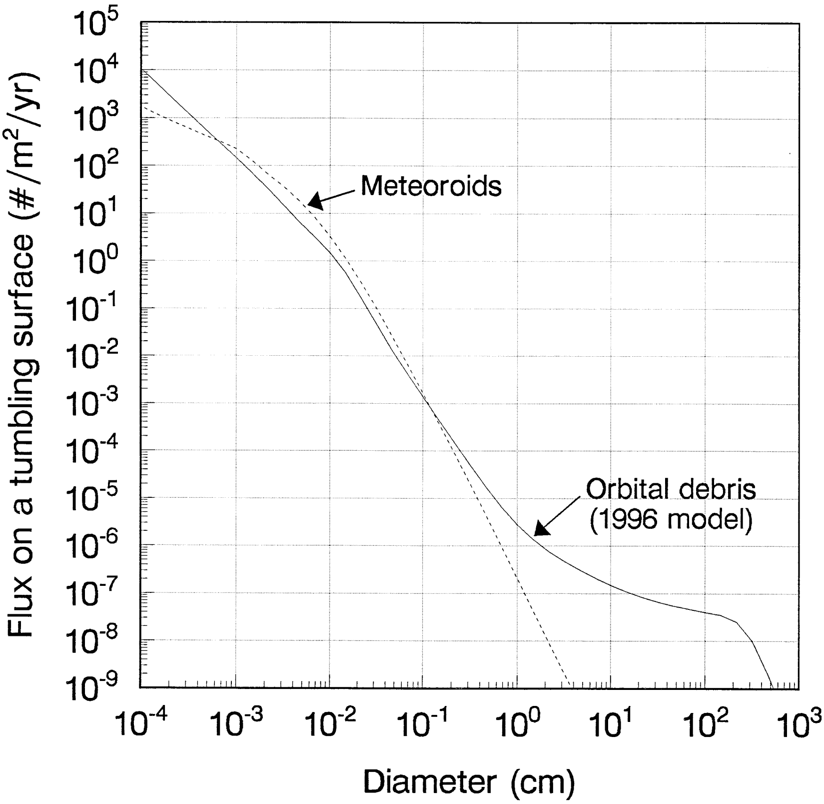


FIGURE 3-1 Comparison of meteoroid and debris flux in ISS orbit. Source: NASA.

flux predicted in the 1991 model. Figure 3-2 compares the flux of debris in the ISS orbit predicted by the 1991, 1994, and 1996 models. Another difference is that the latest model includes objects in elliptical orbits, while the 1991 and 1994 models assume that all objects travel in circular orbits. A third change is that the predicted average impact velocity has been reduced. (The small increase in average collision velocity due to collisions with objects in elliptical orbits is overshadowed by the reduction in average collision velocities for the much larger population of objects in nearly circular orbits.) Figure 3-3 compares the orbital debris impact velocity distribution predicted by the three models. Table 3-1 compares the 1991, 1994, and 1996 models.

ANALYSIS AND FINDINGS

NASA has developed a series of increasingly reliable orbital debris environment models using the limited data available. The 1996 model, which incorporates new data from a number of sources and divides debris into size, inclination, and eccentricity ranges, will be a useful tool for assessing both the risk posed to the station by debris and the steps that can be taken to manage that risk. The committee believes the model is generally sound, but there is still room for improvement.

The ISS program is most concerned about debris ranging from about 0.5 cm to 20 cm in diameter. Debris with diameters in this range may be too large to shield against and too small to track and avoid. Further efforts to more accurately determine the current population of these objects in the ISS orbit, however, may not be the most effective way to help improve the models. At the altitude of the ISS, atmospheric drag steadily removes debris from orbit, and new debris may enter the altitude band as satellites and rocket bodies break up, solid rocket motors eject slag, and the orbits of higher-altitude objects decay. The population of debris at the altitude of the ISS can thus change dramatically in just a few years,

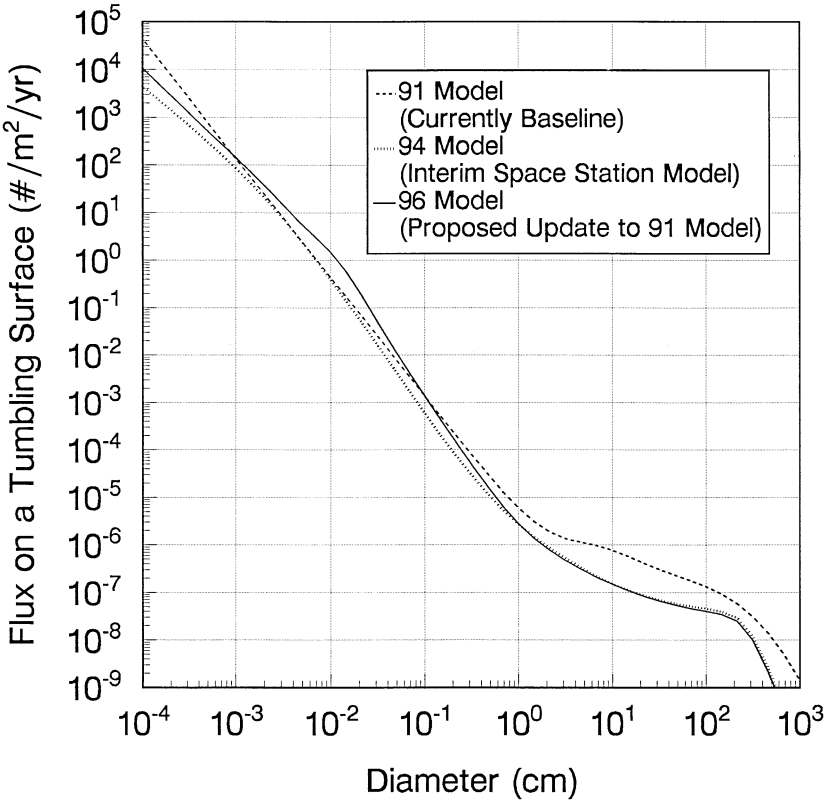


FIGURE 3-2 Comparison of model flux predictions. Source: NASA.

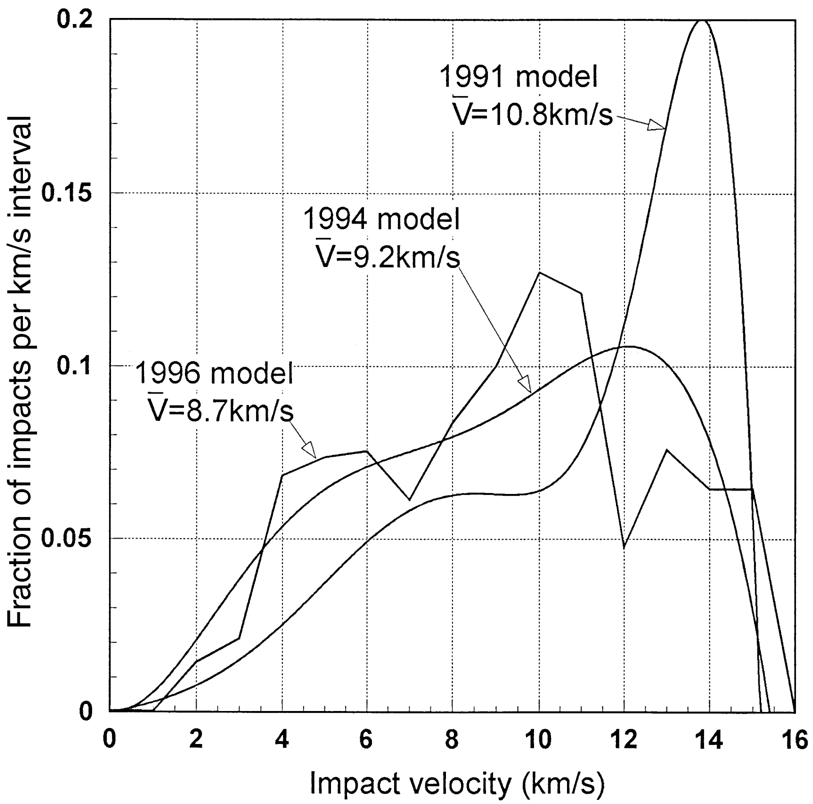


FIGURE 3-3 Comparison of model impact velocity predictions. Source: NASA.

depending on the solar cycle (which causes the atmosphere to expand and contract over an 11-year period) and the rate at which new debris is created in LEO. Understanding the sources of objects in this size range and the processes that add and remove these objects from the ISS altitude regime should thus be a priority of further efforts to improve debris models.

A major gap exists in the available data about another key size range of meteoroids and debris. Figure 3-4 shows the various data sources used in developing the NASA meteoroid and debris environment models. This figure, which groups together data acquired at a variety of altitude regimes over a multiyear period, shows the extreme paucity of data on meteoroids and debris in the 0.1 mm to 0.5 cm size range. The models deal with this gap by essentially drawing a line connecting the measured flux of objects smaller than 0.1 mm with the measured flux of objects larger than 0.5 cm. A better understanding of the population of objects in this range would be valuable for ISS risk management because most of the potentially damaging impacts with the ISS will come from objects in this size

TABLE 3-1 Comparison of Orbital Debris Models

Characteristics (in ISS orbit)	1991 Model	1994 Model	1996 Model
Approximate number of impacts of objects larger than 1 cm in diameter with ISS over 10 years	0.7	0.35	0.35
Average impact velocity	10.8 km/s	9.2 km/s	8.7 km/s
Growth in future environment	5% of 1988 population per year (300 new objects per year) for d ≥10 cm	5% of 1991 population per year for altitudes with little atmospheric drag	8% of 1995 population per year for 7 degree incl. band; 4% per year for other bands for altitudes with little atmospheric drag
	Growth of 2% per year through 2010; 4% per year after 2010 for d <10 cm	Reduced population growth at lower altitudes, decreasing to no growth at around 200 km	Reduced population growth at lower altitudes, decreasing to no growth at about 200 km
Inclination distribution	Based on satellite catalog	Based on Haystack data	Based on Haystack, catalog, and other sources
Object shape	Sphere	Unchanged	Unchanged
Density of individual objects	$2.8d^{-0.74}$ g/cm^3 (d in cm) for d ≥0.62 cm; 4 g/cm^3 for d <0.62 cm	Unchanged	Unchanged
Predominant source of objects larger than 1 cm	Breakups	Breakups	Breakups and solid rocket motor ejecta
Includes debris in elliptical orbits	No	No	Yes
Approximate number of impacts of objects larger than 0.5 cm in diameter with ISS trailing surfaces over 10 years	0	0	2×10^{-5} per square meter

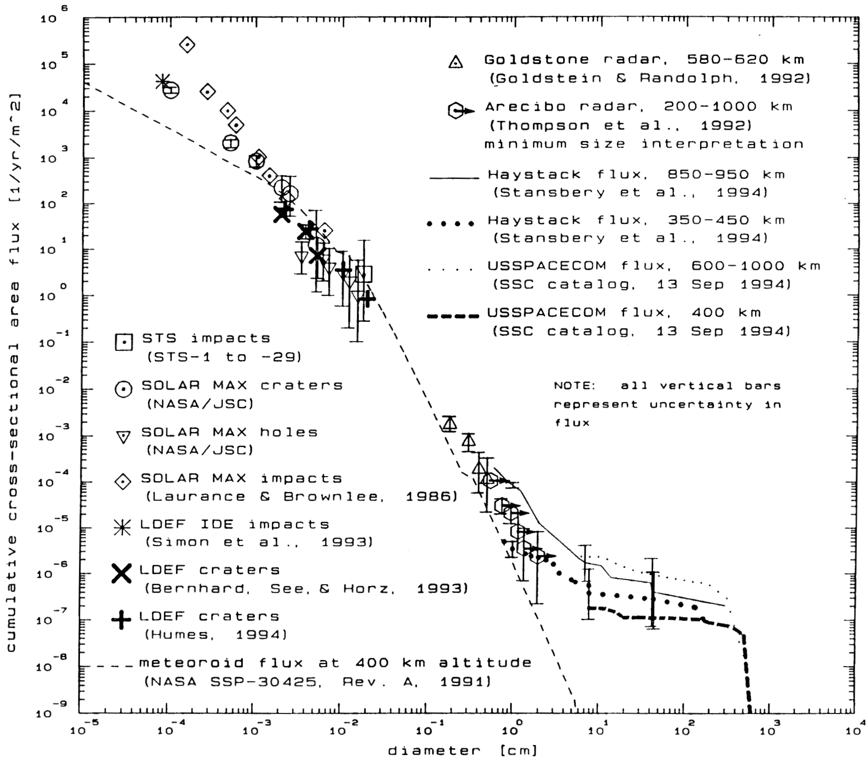


FIGURE 3-4 Data used to create environment models. Source: NASA.

range. The population of these small objects is far more volatile than the population of larger objects; therefore, investigations should focus on the sources and characteristics of the debris.

Another issue of concern is the assumptions in the models about debris shape and composition. The models represent debris as spheres with a density of 4 g/cm^3 for objects smaller than 0.62 cm in diameter. For objects larger than 0.62 cm, the modeled density decreases as the size of the object increases and equals about 2.8 g/cm^3 for objects around 1 cm in diameter. The actual composition and shape of debris is not well known. Recent NASA analysis of data from the Haystack radar suggests that aluminum oxide ejected from solid rocket motors may be the most common debris detectable from Earth in the ISS orbit (Reynolds and Zhang, 1996). Fragments from the breakup of spacecraft and rocket bodies may be the second most common debris. Because the density of aluminum oxide is 3.9 g/cm^3, the density estimates in the models may be close to the actual values for smaller debris, but may underestimate the density of debris 1 cm in diameter and larger. In addition, solid rocket motor ejecta and breakup fragments are unlikely to be spherical. Improved knowledge about the actual shapes and composition of debris would be useful for predicting the damage caused by impact and for developing appropriate shields and damage control strategies.

Finally, in any model providing a statistical representation, it is essential to have some accompanying estimate of model uncertainties. Although defining the level of uncertainty in a debris environment model is difficult because of sparse data and the large variability in the environment over time, an assessment of the uncertainty in the debris environment model would be very useful for groups involved in shielding the ISS and in developing damage control hardware and procedures.

Finding 3. NASA has done a good job of improving its models of the debris environment in LEO by incorporating new data and making reasonable assumptions about areas where data are sparse. The 1996 model appears to be a good tool for ISS meteoroid and debris risk management.

RECOMMENDATIONS

Recommendation 4. Wherever possible, the meteoroid and debris analysis integration team should use the 1996 model to assess and mitigate the meteoroid and debris hazard to the International Space Station. Contractors should also be encouraged to use the 1996 model to assess the vulnerability of their International Space Station components.

Recommendation 5. NASA should continue to update the 1996 debris environment model by using new data and analyses. Efforts should focus on improving understanding of the processes that add and remove objects in the 0.5 to 20 cm size range from the International Space Station altitude regime, the sources and characteristics of smaller debris down to 1 mm in diameter, and debris composition and shape. NASA should also strive to describe the uncertainty in any new models. Changes to the model should undergo a thorough peer review. To support this improvement, NASA should continue to gather more data to better understand the orbital debris environment.

REFERENCES

Barrett, R.A., R.P. Bernhard, and D.S. McKay. 1988. Impact Holes and Impact Flux on Returned Solar Max Louver Material. Presented at Lunar and Planetary Science XIX, Houston, Texas, March 14–18, 1988.

Erickson, J.E. 1968. Velocity distribution of sporadic photographic meteors. Journal of Geophysical Research 73:3721–3726.

Goldstein, R., and L. Randolph. 1990. Rings of Earth Detected by Orbital Debris Radar. JPL Progress Report 42-101. Pasadena, California: NASA Jet Propulsion Laboratory.

Grün, E., H.A. Zook, H. Fechtig, and R.H. Giese. 1985. Collisional balance of the meteoritic complex. Icarus 62:244–272.

Henize, K., and J. Stanley. 1990. Optical Observations of Space Debris. AIAA Paper 90-1230. Presented at AIAA/NASA/DoD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, Maryland, April 16–19, 1990.

Kessler, D.J. 1969. Average relative velocity of sporadic meteoroids in interplanetary space. AIAA Journal 7: 2337–2338.

Kessler, D.J. 1994. Update on the Orbital Debris Environment for Space Station. NASA Memorandum SN3-94-164. Houston, Texas: National Aeronautics and Space Administration. November 16, 1994.

Kessler, D.J., R.C. Reynolds, and P.D. Anz-Meador. 1994. Space Station Program Natural Environment Definition for Design. NASA SSP 30425, Revision B. Houston, Texas: National Aeronautics and Space Administration Space Station Program Office.

Levine, A., ed. 1991. LDEF—69 Months in Space: First Post-Retrieval Symposium. NASA Conference Publication 3134, Part 1. Hampton, Virginia: NASA Langley Research Center.

Reynolds, R.C. 1993. Orbital debris environment predictions for space station. In Proceedings of the First European Conference on Space Debris, April 5–7, 1993, Darmstadt, Germany. Darmstadt: European Space Operations Center, pp. 337–339.

Reynolds, R.C., and J.C. Zhang. 1996. Orbital Debris Environment Modeling at NASA Johnson Space Center. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 1, 1996.

Stansbery, E.G., T.E. Tracy, D.J. Kessler, M. Matney, and J.F. Stanley. 1994. Haystack Radar Measurements of the Orbital Debris Environment; 1990–1994. JSC-26655. Houston: NASA Johnson Space Center.

Stansbery, E.G., T.J. Settecerri, M.J. Matney, J. Zhang, and R. Reynolds. 1996. Haystack Radar Measurements of the Orbital Debris Environment; 1990–1994. JSC-27436. Houston: NASA Johnson Space Center Space and Life Sciences Directorate, Solar System Exploration Division, Space Science Branch.

Taff, L.G., D.E. Beatty, A.J. Yakutis, and P.S. Randall. 1985. Low altitude one centimeter space debris search at Lincoln Laboratories (M.I.T.) experimental test system. Advances in Space Research 5(2):35–45.

Thompson, T.W., R.M. Goldstein, D.B. Campbell, E.G. Stansbery, and A.E. Potter. 1992. Radar detection of centimeter-sized orbital debris: Preliminary Arecibo observations at 12.5 cm wavelength. Geophysical Research Letters 19(3):257.

Zhang, J.C. 1996. The 1996 Orbital Debris Engineering Model. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 1, 1996.

4

Shielding the International Space Station

CURRENT PROGRAM

The ISS program plans to shield many ISS elements to protect the station from meteoroids and orbital debris. The meteoroid and debris AIT has developed numerous potential shield designs and tested their performance against hypervelocity impacts. Such shielding will be necessary because meteoroids and debris will impact the ISS at velocities sufficient to cause a wide range of damaging effects.

The pressurized modules, for example, have multiple vulnerabilities to impact. Large enough meteoroids or debris striking a pressurized module at typical velocities will cause the module wall to spall or break off chips, sending pieces of the wall into the module, even if no air pressure is lost. If the wall is perforated, then particles of the impactor will also enter the module. While spallation particles are much slower than the originating impactor, they can be much larger. Both types of particles can cause injury or loss of life to the crew, as well as damage to internal components in the path of the projectile. Aluminum spallation particles (the ISS is primarily constructed of aluminum) can also burn quite actively, creating a fire hazard inside the module.

In addition, the perforation of a module will be accompanied by a strong acoustic shock wave and an intense light flash that could temporarily incapacitate crew members in the module. Such perforations typically are accompanied by rapid temperature changes and a decrease in air pressure, which can cause an internal fog. In a module wall, perforations can lead to crack growth and, for very large perforations, rapid crack growth that can cause the module to “unzip” or break apart.

Pressurized storage tanks can be subject to the same spallation, perforation, shocks, temperature and pressure changes, and crack growth phenomena when they are struck by high-velocity debris. If a tank containing liquid is hit, then the perforation can also result in a hydrodynamic ram effect (depending on the size of the storage tank and the density of the liquid) that can lead to increased crack growth and catastrophic tank failure. Impacts may also result in the release of stored energy in the tanks, perhaps in the form of chemical reactions or explosions. In addition, the venting of pressurized gases from modules or tanks could result in strong torques to the ISS structure.

The ISS attitude stabilization gyrodynes are another source of stored energy that could damage the ISS if they are penetrated. Stored rotational energy in the gyrodynes could be released in the event of an impact-induced fragmentation of the rotating components of a gyrodyne. In addition to causing the loss of ISS stabilization, fragments created in the breakup could damage other ISS components or adjacent gyrodynes.

Impact damage or perforations of noncritical ISS components can also lead to performance degradation and the failure of ISS systems. Impacts into thermal control radiators, for example, could result in loss of the working fluids, and impacts into solar arrays could result in arcing and short circuits. Secondary ejecta expelled from impact sites can damage other components or even penetrate a critical module. Depending on the angle and the velocity of impact, these ejecta can range from low-speed (a few km/s) particles to highly energetic jets, either of which can be more lethal than the original impactor.

Shielding Approach

As discussed in Chapter 2, the ISS program requires that both the Russian and the non-Russian (U.S./European/Japanese) segments have an overall PNP of 0.90 or better (a maximum 10 percent probability of penetration) over 10 years. To achieve this goal, the ISS will employ different shield designs to protect various critical components. In general, the approach aims to prevent internal damage from the nominal threat of an aluminum sphere approximately 1 cm in diameter, over the predicted velocity range. Other more effective shields are placed in forward-facing areas where most impacts are expected. Less capable shields are located in aft and nadir-facing areas that are expected to be hit less frequently.

In addition to being capable of preventing penetration by the nominal threat, shields for the ISS must be lightweight, low in volume (to fit in the space shuttle payload bay), and durable in the space environment. These constraints have led the ISS program to use passive conformal (i.e., conforming to the shape of the module being protected) armor for the initial ISS configuration. The ISS, however, is designed to allow for future shield augmentations if the threat increases or if the life of the station is extended. NASA is currently evaluating various augmentation concepts and shield design modifications for future use, including both conformal and nonconformal passive shield designs. Active armor, which uses an internal energy source to deflect incoming objects, is not being considered for use on the ISS.

More than 100 different shields have been designed to protect the various critical components of the ISS, although all of the designs are modifications of three ISS primary shielding configurations: the Whipple bumper, the multishock (or stuffed Whipple) shield, and the mesh double-bumper shield.

The Whipple bumper, the simplest shield configuration, consists of a single plate of material (typically aluminum), called the bumper, spaced some distance from the underlying module wall (often called a catcher). The role of the bumper is to break up, melt, or vaporize a high-velocity object on impact. The smaller, slower remnants of the object then travel between the bumper and the catcher and spread the remaining energy of the impact over a larger area on the catcher. This configuration has been studied experimentally for over half a century (Cour-Palais and Crews, 1990; Christiansen et al., 1995b; Hortz et al., 1995). Figure 4-1 shows how a Whipple bumper shield works.

The Whipple bumper is most effective at high impact velocities, where the disruption and dispersion of the impacting projectile can be maximized (Christiansen et al., 1996). At lower velocities, the collision with the bumper may not break up or liquefy the impactor; thus it may still be intact when it strikes the catcher (Christiansen et al., 1995a). Whipple bumpers and their derivative designs are vulnerable to low-velocity (a few km/s) impacts, oblique impacts, and the impacts of objects whose sizes, densities, and shapes differ from the threat the shield was designed to counter. Figure 4-2 shows how the maximum object size that various Whipple bumper derivatives can stop changes with impact velocity.

Whipple bumper shields and their derivatives can be optimized against a specific threat by modifying the bumper materials, bumper thickness, bumper spacing, catcher material, and catcher thickness. Derivatives of the Whipple bumper concept (such as the stuffed Whipple bumper) have been developed by NASA since the mid-1980s (Cour-Palais and Crews, 1990).

The stuffed Whipple bumper consists of an outer bumper, a catcher, and one or more underlying layers of materials spaced between the bumper and the catcher to further disrupt and disperse the impactor. The advantages of this design are its improved performance over the standard Whipple design and, with some bumper materials (e.g., Nextel), its reduced production of secondary ejecta. In current ISS stuffed Whipple designs, the outer bumper is made of aluminum, and the shield is normally stuffed with a single intermediate blanket consisting of six layers of Nextel and six layers of Kevlar. The module wall serves as the catcher. This design performs significantly better than the Whipple bumper, but it does not significantly reduce the production of secondary ejecta.

The mesh double bumper is the newest NASA derivative of the Whipple bumper concept. Developed in the early 1990s, this shield has a metallic mesh disrupter in front of each of two bumpers (Hortz et al., 1995). This design

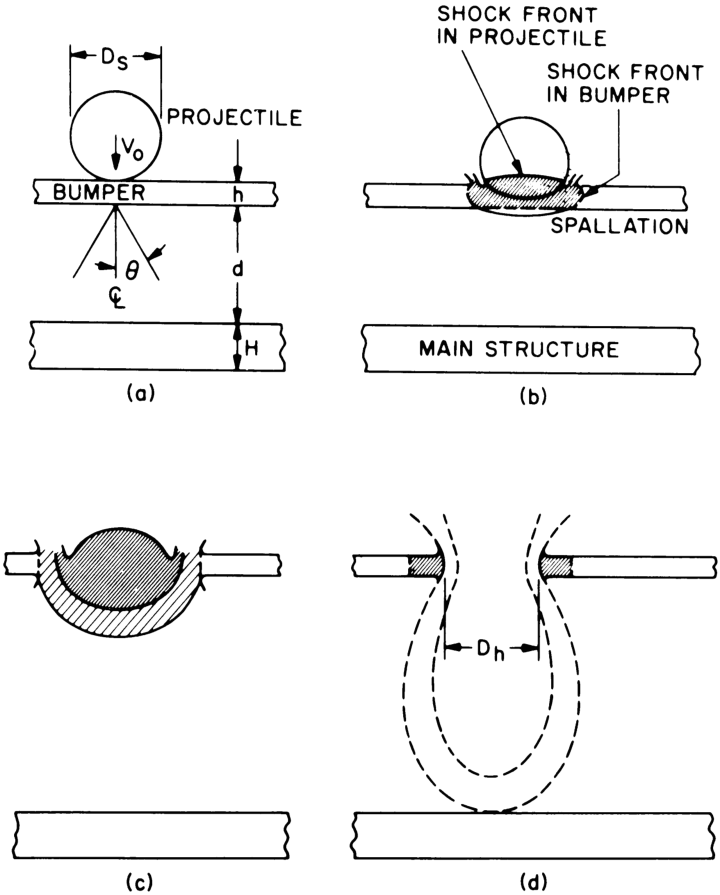


FIGURE 4-1 Projectile interacting with a spaced shield. Source: Riney.

also provides significantly improved performance over the Whipple bumper. Figure 4-3 shows some of the many shielding concepts planned for use on the ISS.

The ISS shield designs have been extensively tested against the design threat (a 1-cm aluminum sphere), and some tests have been performed with different-sized impactors. As a result, substantial experimental data exist to support the performance claims for these designs against the design threat. Experimental results have been compared with, and extended by, hypervelocity impact simulations using hydrodynamic codes (hydrocodes), such as CTH (developed at Sandia National Laboratories) and SPHINX (developed at Los Alamos National Laboratories) (Kerr et al., 1996; Hertel et al., 1994; Wingate and Stellingwerf,

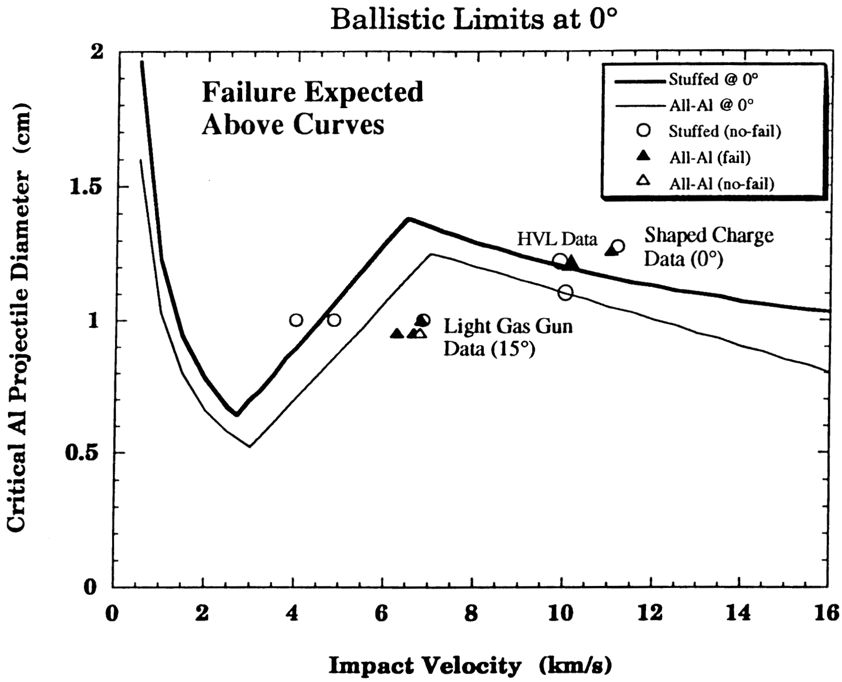


FIGURE 4-2 Effectiveness of Whipple bumper derivatives at various impactor velocities. Source: NASA.

1994). Data from the impact tests also have been used to develop semi-empirical shield scaling laws. These scaling laws can be used both for designing and optimizing shields, as well as for determining which sizes of aluminum spheres are capable of penetrating specific shield configurations. These scaling laws, along with the meteoroid and debris environment models, have been built into the BUMPER code to allow the rapid evaluation of PNPs resulting from various shield configurations.

Extravehicular Activities

For the foreseeable future, the non-Russian ISS crew will use the extravehicular activity mobility unit (EMU) currently used by space shuttle astronauts. This space suit is protected by multiple layers of material and a single bladder that, together, provide a pressure vessel and a degree of protection from the thermal extremes of space and from meteoroids and debris (Cour-Palais, 1996). A secondary oxygen pack will provide at least 30 minutes of supplementary oxygen, should a hole up to 4 mm in diameter develop in the suit. There are multiple

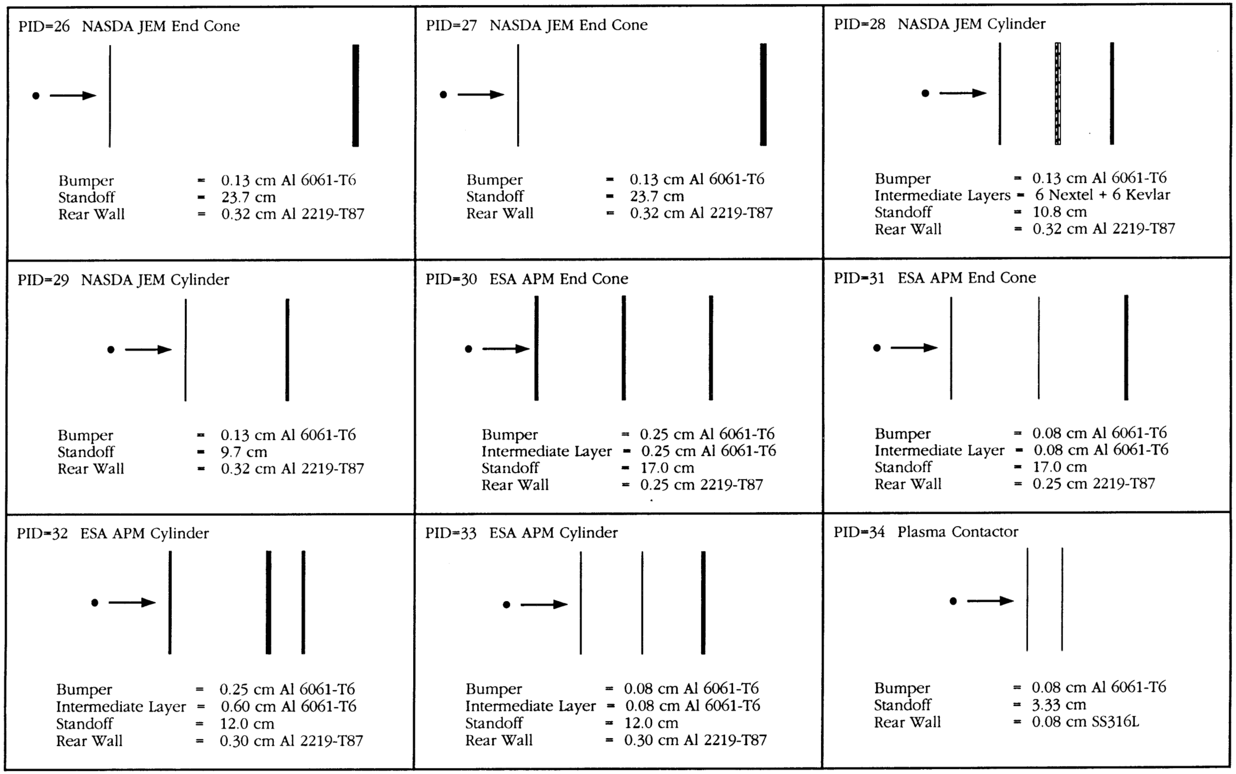


FIGURE 4-3 ISS shield configurations. Source: NASA.

failure recovery modes from other impact-induced failures. Analysis shows that more than 75 percent of the hazard will result from penetrations of soft parts of the space suit (i.e., arms, gloves, and legs). The ISS program is considering augmenting the arms and legs with removable gauntlets and "chaps" (McCann, 1996) to reduce this hazard.

ANALYSIS AND FINDINGS

The effort to shield the ISS from meteoroid and debris impacts appears to be extensive and thorough. No major aspects of the problem appear to have been overlooked. Critical research is under way to investigate areas where the physics and mechanics are not fully understood. Good engineering is addressing problems where a need has been recognized. The findings and recommendations below identify issues where additional effort or a shift in focus would enhance existing activities to the overall benefit of the ISS.

Shielding for the Actual Environment

As described in Chapter 3, significant strides in defining the orbital debris environment have been made in recent years. As a result of new debris orbit characteristics, the 1996 environment model identifies mean velocity and velocity distribution properties markedly different from those in the 1991 model. Hypotheses about the type of debris most likely to impact the ISS have also changed recently. As described above, limited experimental data or modeling capabilities are available to evaluate how well the ISS will survive these threat excursions.

The 1991 model is still used for ISS design issues, and the ISS meteoroid and debris AIT seems to believe that the newer models indicate a reduced threat (because of the significantly lower flux of objects larger than 1 cm in diameter). This assessment has not yet been evaluated, and it may not be accurate for several reasons. First, the 1991 model did not include debris in elliptical orbits; thus, no debris impacts were predicted to occur on ISS trailing surfaces. Because only high-velocity meteoroids were predicted to strike trailing surfaces, many of these surfaces use a simple Whipple bumper design. The 1996 model, however, includes debris in elliptical orbits, which can strike the ISS trailing surfaces at lower velocities (averaging about 4.5 km/s). Fortunately, most debris known to be in elliptical orbits are small and in lower-inclination orbits. Therefore, the threat of serious damage to ISS trailing surfaces is currently believed to be very small. ISS designers, however, should be aware that debris can strike ISS components from a wider variety of directions than was predicted by the 1991 model.

The altered orbit characteristics in the recent models have also resulted in a reduction of mean relative impact velocity, from about 10.5 km/s in the 1991 model to less than 9 km/s in the 1996 model. This significant statistical reduction in impact velocities does not, however, necessarily represent a reduction in the threat to the ISS. The newer models predict approximately double the object flux within the 2 to 6 km/s impact velocity range—a regime in which the Whipple effect, the basis for ISS shielding, is less effective (Christiansen et al., 1995a).

Shield Testing

Debris resulting from explosions, breakups, degradation, or rocket firings probably will not be spherical, and the densities of meteoroids and debris may vary greatly. However, minimal data have been gathered on the performance of the proposed ISS shields against threats other than the nominal 1-cm aluminum sphere. The performance of shields against impactors with different characteristics (density, impact angle, velocity, etc.) typically have been extrapolated using scaling laws or hypervelocity impact simulations calculated by hydrocodes.

The interaction between threat and shielding in a high-velocity impact event, however, is a complex, nonlinear set of processes involving a host of poorly understood mechanical and physical effects. Dynamic strength, multiphase equations of state, and the fragmentation of both threat and shield materials play interrelated roles in determining the outcome of an impact and potential penetration. For these reasons, scaling laws for projectile shape, projectile density, or impact obliquity should not be applied to impact threats for which data were not collected or included in the development of the scaling law.

Therefore, extensive impact testing is critical to the development of improved ISS shielding and to the characterization and validation of the engineering codes (such as BUMPER) used to assess ISS vulnerability to meteoroid and orbital debris impacts. Testing over a wide range of threat materials, densities, and shapes is needed to acquire a fuller understanding of shield performance in more typical environments and to gain confidence in assessing the vulnerability of ISS components. In particular, it is necessary to emphasize testing in the velocity regimes of 2 to 5 km/s and greater than 10 km/s. In these regimes, current ballistic limit curves indicate the highest susceptibility to shield failure and pressure wall penetration. The lower-velocity regime is particularly complex because material strength effects inhibit the full development of the Whipple effect on which the spaced-armor concept relies. The upper velocity range is critical because of the extreme on-target energy produced by the impact.

Finding 4. ISS shields have been designed to resist a particular threat. However, the actual threat may be quite different from the threat the shields were designed to counter. Extensive testing against a variety of different impactor sizes, shapes, velocities, and compositions is needed to ensure that the shields provide adequate protection.

Secondary Ejecta

The ISS has a substantial exposed area of trusses and other noncritical components. The effects of impacts on these components have not yet been evaluated in detail. Of particular concern is the threat to critical components from secondary ejecta created by impacts into other critical or noncritical components. Ejecta that does not immediately strike the ISS may remain in orbit, posing a potential long-term collision hazard. However, evaluations of ISS vulnerability to date have not included assessments of the threat of secondary ejecta; nor are secondary ejecta included in current orbital debris environment models. Ejecta production is not well understood, and ejecta characteristics (e.g., mass, shape, and velocity) are not well characterized. Tests over a wide range of conditions would be needed to acquire the fuller understanding of ejecta production and characteristics needed to assess the vulnerability of the ISS to this threat.

Hydrodynamic Codes

Computational simulations of shield performance during orbital debris impact, using state-of-the-art continuum and structural codes, offer a unique capability for improving ISS shield performance (Kerr et al., 1996). Recent strides in large-scale parallel computing have brought computational simulation of large-scale, three-dimensional impact events into the realm of practical engineering applications. Concerted efforts toward this end are currently a priority at some Department of Energy and DoD facilities. The effective application of computational tools to ISS shielding problems could provide methods for optimizing shield design and expanding the investigation of threat/shield interactions outside of the range of practical testing limits. NASA has recently begun using hydrodynamic codes to evaluate shield performance in the velocity regimes where testing is not currently feasible. However, NASA has limited capabilities and facilities for these simulations.

Advanced Shield Materials

The properties of materials used in shield construction are crucial to armor performance. The bumper plate should be made of the highest shock-impedance material possible, consistent with other design requirements. High shock impedance will lead to shattering and the lateral momentum dispersion of the impacting object at the lowest possible velocity. Secondary plates should lead to the further diffusion of the threat momentum, while the catcher plate material should have a high transverse acoustic velocity to distribute the impulse of the threat debris. In recent years, a wide range of metal-ceramic and ceramic-ceramic composites, with densities comparable to aluminum but with significantly higher shock impedance, have been developed outside NASA. Also, a number of glass-reinforced polymeric composites have been developed that have served well in other armor applications. In the future, these advanced shielding materials could be used in lighter and more effective shields for the ISS.

In-Orbit Shield Augmentation

Extensive testing and analysis shows that the U.S. segment meets or exceeds its required PNP levels for the design threat. However overall PNP compliance will not be achieved in the early stages of ISS assembly because of the inability of the Russian participants to achieve all of their PNP requirements within the time frame of the launch schedule. NASA and the Russian Space Agency (RSA) have agreed that PNP compliance will be achieved by augmenting the shielding of some Russian modules in orbit.

Augmenting ISS shielding in orbit could be very effective in protecting against meteoroid and debris threats. Both conformal and nonconformal methods provide a range of shielding options. Conformal shielding techniques offer high shielding potential if the shields can be installed without an unacceptable level of extravehicular activity (EVA). The ISS team is also considering nonconformal shield designs, which are easier to attach in orbit and offer the attraction of an extended dispersion path for secondary ejecta. Nonconformal shields, however, are very directional and would leave the shielded item exposed if the station were to operate in a different attitude (as it is projected to do for a period of time during assembly) or if more debris were found in elliptical orbits.

Extravehicular Activities

Because of the relatively small surface area of a space suit, the limited exposure times involved, and the light shielding offered by the suits, the primary threat to astronauts performing EVAs comes from particles in the 1-mm size range. NASA has evaluated the EVA suits experimentally, and the meteoroid and debris AIT has a good understanding of the sizes of particles able to perforate the suits for the design threat (Cour-Palais, 1996). These evaluations showed that the EVA suits exceeded their required PNPs and that no component of the EMU will catastrophically release energy upon penetration. The expected probability of ever experiencing a penetration resulting in the consumption of the oxygen reserve in less than 30 minutes was calculated to be less than one percent through the year 2012. This assessment showed that the risk from meteoroids and debris to astronauts performing EVAs was significantly less than the risk posed by other hazards to spacewalking astronauts. However, the assessment was made with a 1989 environment model. Newer environment models indicate an increase by a factor of 2 to 3 in particle flux in the size range of concern for EVA suits.

RECOMMENDATIONS

Recommendation 6. All groups developing shielding for the International Space Station should incorporate new environment models into their design considerations, as soon as official model acceptance is achieved. Shield designers should recognize that the environment is likely to continue to change and that future shields will have to be designed to resist a broader spectrum of threats. For example, designers should be very wary of nonconformal shield concepts that only block objects coming from one direction.

Recommendation 7. The International Space Station program should initiate an accelerated shield-testing program aimed at acquiring a fuller understanding of shielding performance against a wider range of impactor characteristics. A series of tests, with emphasis on the lower velocity regimes, should be performed to determine how the various shields on the International Space Station perform against the expected threat and to develop a scaling technique for converting nominal test performance to performance when shields are exposed to the actual threat.

Recommendation 8. In conjunction with any impact testing, the International Space Station program should initiate a laboratory-based data collection and test instrumentation program with emphasis on acquiring a fuller understanding of secondary ejecta phenomena and threat characteristics.

Recommendation 9. NASA should evaluate current hydrocode support for International Space Station meteoroid and debris shield development and consider upgrading current capabilities through greater NASA emphasis or through cooperation with other national facilities.

Recommendation 10. The meteoroid and debris analysis integration team should contemplate using advanced shielding materials in upgrades to existing International Space Station shielding and future shield augmentations. The analysis integration team should consider holding a workshop to bring in shielding experts from outside NASA to discuss advanced shielding concepts.

Recommendation 11. The International Space Station program should reassess extravehicular activity suit survivability with respect to the 1996 meteoroid and debris environment model.

REFERENCES

Christiansen, E.L., J.L. Crews, J.H. Kerr, B.G. Cour-Palais, and E. Cykowski. 1995a. Testing the validity of cadmium scaling. International Journal of Impact Engineering 17:205–215.

Christiansen, E.L., J.L. Crews, J.E. Williamsen, J.H. Robinson, and A.M. Nolan. 1995b. Enhanced meteoroid and orbital debris shielding. International Journal of Impact Engineering 17:217–228.

Christiansen, E.L., J.L. Crews, J.H. Kerr, and L.C. Chhabildas. 1996. Hypervelocity Impact Testing Above 10 km/s of Advanced Orbital Debris Shields. In S.C. Schmidt and W.C. Tao, eds. Shock Compression of Condensed Matter '95, pp. 1183–1186. New York: American Institute of Physics Press.

Cour-Palais, B.G. 1996. Spacecraft Thermal Blanket as Hypervelocity Impact Bumper. 1995. In S.C. Schmidt and W.C. Tao, eds. Shock Compression of Condensed Matter '95, pp. 1175–1178. New York: American Institute of Physics Press.

Cour-Palais, B.G., and J.L. Crews. 1990. A multi-shock concept for spacecraft shielding. International Journal of Impact Engineering 10:135–146.

Hertel, E.S. Jr., R.L. Bell, M.G. Elrick, A.V. Farnsworth, G.I. Kerley, J.M. McGlaun, S.V. Petney, S.A. Silling, P.A. Taylor, and P. Yarrington. 1994. CTF: A Software Family for Multi-Dimensional Shock Physics Analysis. Proceedings of the 19th International Symposium on Shock Waves, July 26–30, 1993, Marseilles, France. Heidelberg, Germany: Springer-Verlag.

Hortz, F., M.J. Cintala, R.P. Bernhard, and T.H. See. 1995. Multi-mesh bumpers: A feasibility study. International Journal of Impact Engineering (17):431–442.

Kerr, J.H., E.L. Christiansen, and J.L. Crews. 1996. Hydrocode Modeling of Advanced Debris Shield Designs. In S.C. Schmidt and W.C. Tao, eds. Shock Compression of Condensed Matter '95, pp. 1167–1170. New York: American Institute of Physics Press.

McCann, J. 1996. Vulnerability of EVA Activities and Mitigation Measures. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

Wingate, C.A., and R.F. Stellingwerf. 1994. Los Alamos SPHINX Manual, Version 5.7. Los Alamos National Laboratory Report LAUR 93-2476.

5

Reducing the Effects of Damaging Impacts

CURRENT PROGRAM

The ISS program has begun to develop systems and procedures to reduce the risk to the ISS and its crew in the event of a damaging meteoroid or debris impact. A current focus is on developing a software tool to aid in determining the effectiveness of various risk reduction systems and procedures. The ISS partners are also working to establish baseline damage control procedures (such as keeping some hatches closed) and to determine which equipment (such as oxygen masks) will be necessary to cope with and mitigate the operational and crew safety hazards resulting from a damaging penetration of the station. The program has also begun to develop repair tools and strategies.

MSCSurv Computer Code

NASA has developed an analysis tool, the Manned Spacecraft Crew Survivability (MSCSurv) computer code, to attempt to quantify the probability of space station or crew loss in the event of a meteoroid or orbital debris penetration of the space station (Williamsen and Guay, 1996). The code randomly generates the parameters—debris diameter, velocity, approach angle, and strike location on the space station geometric model—of an individual orbital debris particle impact, based on the relative probability distribution of each parameter. It then determines whether this particular impact would penetrate a pressurized module by comparing the impact parameters to the ballistic limit of the space station shielding at the impact location. Currently, this code addresses only crewed modules and does not include secondary effects caused by the failure of other items, such as the thermal control system compartment, the high-pressure oxygen/nitrogen tanks, the gyrodynes, or the plasma contactors.

If the code determines that a penetration will occur, it checks for seven possible failure modes that could result in crew or station loss. These are:

- immediate critical crack propagation (unzipping)
- loss of control or structural failure due to venting
- penetration of critical equipment
- crew injury from fragments
- crew injury from light flash and overpressure
- individual crew hypoxia and multiple crew hypoxia from rescue attempts
- delayed loss of the station resulting from irreparable failures of critical systems

The code determines the overall likelihood of loss by dividing the number of penetration combinations resulting in a loss by the total number of penetrations.

This tool also has been used to perform preliminary evaluations of the effectiveness of various escape protocols and of the efficacy of having personal oxygen bottles readily available. Figure 5-1 depicts current MSCSurv predictions for the probability of loss in the event of a penetration under baseline assumptions for three cases: where hatch closure is used to isolate the half of the station in which the leak has occurred, where the individual leaking module can be isolated as the crew proceeds to the safe haven, and where the leak can be immediately located. Figure 5-2 shows MSCSurv predictions for the same cases if oxygen masks are readily available to the crew.

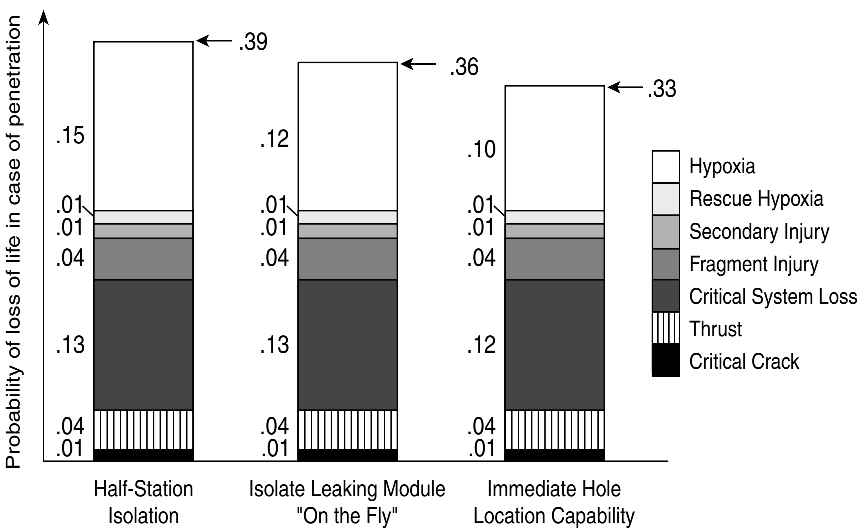


FIGURE 5-1 MSCSurv baseline predictions of probability of loss. Source: NASA.

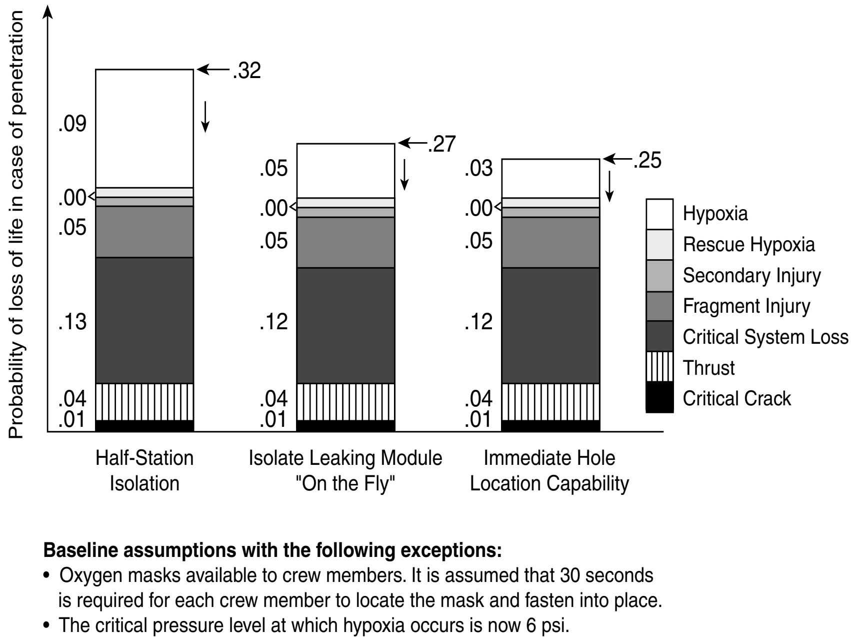


FIGURE 5-2 MSCSurv predictions of probability of loss if oxygen masks are available. Source: NASA.

Damage Control Procedures and Supplementary Equipment

The ISS team is developing a set of procedures for the crew to follow when a pressurized module is penetrated by meteoroids and debris. The Russian approach currently differs from the U.S. approach in terms of operational responses to a penetration. For example, once a warning is given, the Russian approach calls for the crew to assess the situation and then to proceed directly to the Soyuz vehicle. Under the planned U.S. procedure, the crew will first establish communications with each other to verify the health and safety of each crew member. The ISS team is working to standardize the operating procedures (Remaklus, 1996).

The current ISS design does not include dedicated hardware to alert the crew to a penetration and to help them locate it. However, sensors that can monitor pressure and changes in pressure are distributed throughout the station as part of the ISS life support system. Sonic impact warning systems for detecting and locating leaks are also not currently planned for the ISS (although test results indicate that astronauts may be able to detect penetrations by the sound of the air hissing through the hole). The Russian ISS team has performed a trade study of possible leak detection and location system concepts. According to NASA, the most technically feasible option is based on using 30 to 40 piezoelectric sensors per module to record acoustic signals from the penetration and the resulting air outflow. Negotiations to determine the cost and schedule impacts of implementing such a system are ongoing (Meteoroid/Debris FGB Design Team, 1996).

A major concern in the event of a penetration is the health and location of each crew member. The station partners have agreed that portable oxygen masks should be available in each ISS module. Risk assessment studies have indicated that their immediate availability in the event of a penetration could significantly improve crew survivability. Various crew locator systems are also being considered. One approach is a routine call-in using the existing ISS communication system. However, there is some concern that this system may not provide the quick response needed in an emergency. Another approach being evaluated is the use of more automated bar code or badge swipe systems.

Another important concern in the event of a penetration is the ability of astronauts to isolate a penetrated module by closing its hatches. All ISS hatch designs permit closure under some pressure difference, a necessary feature to isolate a penetrated module. The Russian hatches between modules, however, often contain drag-through ventilation and electrical umbilicals, and closing them can take minutes.

The ability to repair penetrations of ISS modules will be useful for ensuring that minor penetrations do not cause massive disruptions in operations. The ISS design currently includes a kit to repair penetrations from the inside of a module. Design concepts for hole repair kits from outside the station have been developed, and a prototype may be tested in space around the year 2000.

ANALYSIS AND FINDINGS

Because of the statistical size distribution of meteoroids and orbital debris, effective damage control should be able to prevent the catastrophic loss of ISS equipment and lives in most cases where existing shielding is insufficient to stop incoming objects. The ISS team, however, has been very slow to devote serious attention to damage control issues. Despite the late start, the ISS damage control protocol is now evolving, aided by the MSCSurv analysis tool.

To date, the ISS damage control approach has focused on catastrophic events that can rapidly result in the loss of life or of the station through fairly straightforward effects. Impacts that are not immediately catastrophic, however, could cause complex failures that could result in the loss of the ISS or in a major disruption of its operations. Indeed, it is likely that a penetration will result in failures in more than one system. A failure modes and effects analysis that accommodates multiple system failures will be useful both in ensuring that multiple key components are not unnecessarily exposed to simultaneous failures and in conducting post-impact damage control and analysis. One area on which this analysis should focus is determining whether an independent emergency attitude control and reboost capability is needed to minimize the likelihood of a catastrophic spin-up or drag-induced reentry if the primary systems are disabled by meteoroid or debris impact or by some other means.

MSCSurv Computer Code

Although the committee is not in a position to validate the assumptions and implementation of the MSCSurv code, the committee does believe that it could be quite useful in assessing the relative merits of a variety of options that could be implemented to minimize the hazards to the crew and to the station. The cautions of the MSCSurv code author regarding the use of the code are worth repeating:

- The probability of loss (P_{loss}) calculations require significantly more information to compute accurately than PNP calculations. Therefore, there is considerable uncertainty in absolute P_{loss} values.
- The benefit lies in relative comparisons of one set of operating/design assumptions to another, instead of to an absolute P_{loss} value.
- The probability of penetration, not P_{loss}, should form the basis for any design requirement.

Damage Control Procedures and Supplementary Equipment

The ISS team has been slow to begin work on damage control hardware, such as differential pressure sensors and oxygen masks. However, it is important that such hardware be developed as soon as possible because modifications to the ISS in orbit, when feasible, could be difficult and costly. Unlike the shuttles, the space station cannot be modified during regularly scheduled visits to a repair facility. If needed damage control hardware cannot be developed before the launch date, modifying the ISS to facilitate the subsequent addition of the hardware could help reduce future costs. However, some damage control approaches may be infeasible unless they are executed before launch. For example, major modifications to the hatches between ISS modules probably would not be feasible once the station is in orbit.

Developing procedures for the crew to follow in the event of a penetration can be a cost-effective method of reducing the hazard to the crew and to the station itself. Ground and on-orbit damage control training for the entire crew is needed to ensure standardization and crew coordination during an emergency. Significant differences, however, still exist between the planned Russian and U.S. operational approaches, and the ISS program needs to work to standardize these procedures. In these negotiations, NASA would be wise not to discount the many years of experience the Russians have had operating space stations.

Returning the ISS to full operational status after a penetrating impact will require the development of permanent repair procedures. For repair to be possible, the ISS needs to be designed in such a way that damaged components, systems, and modules can be isolated and essential electrical power, control signals, and services can be rerouted around the affected area until permanent repairs can be made. Current plans to repair the ISS from the inside appear marginal because 80 percent of the Russian modules and 30 percent of the non-Russian modules cannot be accessed from the inside (under depressurized conditions pressurized space suits will not fit through the connecting hatches). Permanent repair from the outside will probably require the use of specialized processes, such as EVA welding.

Improved knowledge of failure modes, such as petalling, wall weakening, and the frequency of single and multiple punctures, are also crucial for repair efforts. When the shielding is overmatched by the orbital debris threat, a number of failure modes can occur. These include erosion and pressure wall weakening, spallation, single and multiple puncture, and enhanced perforation with petalling. A full understanding of the character and extent of damage that will have to be dealt with will be critical to effective damage control and recovery.

Finding 5. Damage control and repair hardware and procedures are at an early stage of development. If work in these areas is not accelerated immediately, some damage control approaches will become infeasible, and more difficult and costly on-orbit modifications of the ISS will eventually be required.

RECOMMENDATIONS

Recommendation 12. NASA should continue to refine the Manned Spacecraft Crew Survivability (MSCSurv) program. It should be updated to reflect failure modes associated with critical and high-energy systems, toxic gas releases, nonpenetrating impacts, and equipment and system failures caused by impact.

Recommendation 13. NASA should intensify its cooperation with the Russian Space Agency in identifying and resolving areas of difference in design features, operational procedures, and repair techniques to mitigate the hazardous effects of meteoroid and orbital debris penetrations. Issues to be discussed should include emergency procedures, crew location aids, warning systems, oxygen masks, and hatch positioning.

Recommendation 14. The capability of the International Space Station to continue safe operations with damaged wiring, piping, and other systems needs to be assessed. An analysis of failure modes and effects that addresses multiple failures resulting from single penetrations should be performed.

Recommendation 15. The International Space Station program should accelerate efforts to plan for mitigating the effects of penetration. Recent efforts to evaluate relative hazards and to assess response strategies should be expanded and accelerated. The involvement of the astronaut corps in this effort is vital. More work is needed to develop escape protocols, evaluate the use of sensors to detect and localize penetrations, and develop procedures for making permanent repairs. If enhancements are to be made in orbit when the station is operational, then program managers must prepare for the enhancement now.

Recommendation 16. A study of the failure modes of shielded pressure walls should be performed over the critical range of the threat size, shape, and velocity to fully characterize damage control and repair requirements for potential International Space Station orbital debris penetration.

REFERENCES

Meteoroid/Debris FGB Design Team. 1996. NASA/Russia TIM #17 Protocol, Houston Texas, February 19–March 1, 1996. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

Remaklus, D. 1996. Crew Response to Depressurization. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

Williamsen, J., and T. Guay. 1996. Quantifying and Enhancing Space Station Safety Following Orbital Debris Penetration. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

6

Collision Warning and Avoidance

CURRENT PROGRAM

The ISS program plans to maneuver the space station to avoid collision with objects tracked and cataloged by the U.S. space surveillance network (SSN). A modified version of the scheme currently used in the space shuttle program will be employed. In support of that program, the SSN routinely screens the catalog for objects predicted to approach the orbiter within a defined "warning box" approximately 25 km along the track of the orbit (either leading or trailing), 5 km across the track of the orbit, and 5 km out of the plane of the orbit. The estimated 10 to 30 objects per day that come within the warning box are reassessed using a more accurate algorithm to determine whether any come within a "maneuver box" of 5 km along track × 2 km across track × 2 km in the radial direction. If an object does, the ISS may initiate a maneuver to avoid impact (Schultz, 1996). The maneuver box is many times larger than the ISS to provide a safety margin because the locations of tracked objects are not precisely known.

To reduce disturbance to microgravity experiments, the ISS program requires that the avoidance scheme require less than six maneuvers per year. The SSN, however, projects that 200 trackable objects will enter a 5 km × 2 km × 2 km box around the ISS each year by 2005. To decrease the number of required maneuvers, the ISS program plans to use the global positioning system (GPS) to increase the accuracy with which the position of the ISS is known. This information will be fed into an algorithm to determine the probability that an object entering the maneuver box will collide with the station. If the probability exceeds a certain threshold, the station will maneuver to avoid collision. The ISS program has not yet set this threshold probability, but it predicts that fewer than 10 maneuvers will be conducted each year.

The ISS will maneuver itself to avoid debris by firing thrusters to raise the orbital altitude with a velocity increment of less than 1 m/s. The ISS is expected to execute similar maneuvers about once a month to maintain orbital altitude. Thus, it is expected that avoidance maneuvers will simply change the scheduling of reboost maneuvers, and no extra propellant will be required. Because the thrusters are in the Russian part of the ISS, the maneuvers will be controlled by the Russian crew or by Russian ground stations. The ISS program estimates that, once a warning is received, it will take two hours to coordinate the maneuver through the RSA, communicate instructions to the crew, prepare the ISS to perform the boost maneuver, fire the thrusters, and have the ISS actually move the required distance.

ANALYSIS AND FINDINGS

Reducing False Warnings

To minimize disturbances to microgravity experiments, the ISS program needs to reduce the number of unnecessary collision avoidance maneuvers. One approach to reducing the number of false warnings would be to accept a higher level of risk. A better approach would be to determine with greater accuracy the location of the object threatening the ISS. For normal LEO objects, the SSN has demonstrated its ability to reduce tracking errors to less than 500 m for periods of up to 24 hours. New technologies under evaluation by the U.S. Space Command and NASA may further improve this capability. If the SSN can reliably sustain such an effort, the need to maneuver the ISS will be markedly curtailed.

However, there are difficulties in achieving this goal. Some approaches to increase the accuracy with which the positions of incoming debris are known will require the development and deployment of new sensor systems, as well as the retasking of current and future sensor systems. Although this may be technically feasible, the U.S. Space Command is not currently funded or responsible for providing this type of support or for retasking or upgrading SSN sensors. In addition, because of uncertainties in atmospheric density, ballistic coefficients, and gravity models, the validity of these procedures for objects with large area-to-mass ratios and for periods of high solar activity has yet to be verified. Reliably tracking objects in eccentric orbits will also require further demonstration.

The ISS itself might produce debris that could force the station to perform maneuvers. An unpublished Air Force Space Command analysis of close conjunctions of debris with the Russian Mir space station showed that 5 of the 16 objects that entered a 5 km × 2 km × 2 km box around Mir in 1995 were originally associated with Mir operations. Although the collision velocities between the ISS and debris from ISS operations would be low, the station would still need to maneuver itself to avoid trackable items. Minimizing the production of debris during ISS assembly and operations could help reduce the number of debris avoidance maneuvers the ISS would need to perform.

Avoiding More Objects

If the gap could be reduced between the population of objects that can be tracked and the population of objects that can be shielded against, then the risk to the ISS could be cut drastically. (Shrinking the maneuver box is a prerequisite, however, because the number of false warnings will increase greatly as the size of the debris the tracking system is able to catalog decreases.) The SSN has difficulty tracking smaller objects, however, because it was designed to detect and track space objects that reflect a large radar cross section.

The current catalog at ISS altitudes is essentially complete for objects larger than 100 cm in diameter and about 95 percent complete for objects larger than 30 cm in diameter. Although some objects as small as 10 cm are cataloged, somewhere between 15 and 50 percent of the objects between 10 cm and 20 cm may be missing from the catalog (Kessler, 1996; Lord, 1996). Improving the system to allow it to catalog debris smaller than 10 cm would require adding new sensors, retasking current and future sensors, developing new procedures and algorithms, and improving computational capability.

Although NASA would like to see the SSN sensitivity threshold improved, the DoD does not have a mission to achieve tracking accuracies for objects smaller than 10 cm in diameter. The DoD, therefore, cannot be expected to exert great effort to improve its capabilities in this direction. Indications are that network sensitivity is more likely to decline than improve in the near future as a result of sensor closures or other actions.

In the early 1990s, NASA assessed the feasibility of developing a system to detect and track a greater number of debris objects in the 1 cm to 30 cm range (Loftus and Stansbery, 1993). The scheme, which involved building a number of short-wavelength radars, was estimated to cost approximately one billion dollars, plus a hundred million dollars a year to operate. Assuming its only function were to support the ISS, building such a system would probably not be a cost-effective method of reducing the risk to the ISS from meteoroids and debris.

Finding 6. Although it would be technically feasible to track a larger population of objects and warn the ISS about more potential collisions, doing so would require a significant effort. If this effort were made, additional steps would need to be taken to reduce the number of false alarms generated by this larger population.

Maneuvering the International Space Station

The SSN is believed to be capable of delivering warnings of the potential hazards it is able to track at least six hours (three to four orbits) in advance. This should provide sufficient time for maneuvers to be executed. A number of issues, however, need to be resolved before the effectiveness of the avoidance maneuver scheme can be fully evaluated. Currently, for example, the ISS often will be unable to maneuver because a radio link to the Russian ground stations (which will coordinate the maneuvers) will be unavailable for at least part of every orbit. In addition, the ISS program currently has no plans to maneuver the ISS during the estimated one week out of every ten that the shuttle orbiter is docked with the station because of the effect the shuttle would have on the behavior of the ISS under acceleration. For similar reasons, the ISS currently has no plans to maneuver to avoid debris during some periods of the assembly sequence.

Use of On-Board Sensors

ISS collision warning systems that rely solely on on-board sensors are currently infeasible. There are two underlying problems. First, it is difficult to track debris from an orbiting spacecraft. On-board sensors would be unable to identify and track most objects for multiple orbits. Thus, the sensors would have to detect and obtain accurate knowledge of the orbital characteristics of an incoming object only from data obtained as the object approaches the station at average closing speeds of about 9 km/s. (Such a sensor capable of reliably detecting oncoming debris from a wide variety of angles, without consuming the majority of the electric power generated by the station, is well beyond current capabilities.)

Second, even if such sensors were available, the space station would still be unable to maneuver fast enough to avoid a collision. At typical speeds, a hypothetical advanced sensor capable of detecting and tracking an incoming object on its final impacting orbit at a range of 500 km (or about half the distance to the horizon) would provide less than a minute of warning at the expected approach velocities. Even if the ISS program could cut the time to prepare for a maneuver from two hours to two seconds, it would still take the ISS about 30 seconds to achieve a velocity of 1 m/s and 100 seconds at that velocity to move a distance equal to its own length.

Finding 7. Barring major leaps in technology, on-board sensors will not be effective in providing the ISS with a collision avoidance capability.

RECOMMENDATIONS

Recommendation 17. The efforts of the International Space Station program to reduce the disturbances to microgravity experiments from collision avoidance schemes should concentrate on reducing the number of false warnings, rather than on accepting a higher level of risk.

Recommendation 18. The International Space Station program should take particular care to avoid producing debris during the operation and assembly of the space station.

Recommendation 19. The International Space Station program should continue to work on ensuring that the International Space Station is able to maneuver when threatened by debris. Efforts should be made to reduce the time between receiving a warning and executing an effective maneuver.

Recommendation 20. NASA should work closely with the Space Surveillance Network to determine what Space Surveillance Network support will be available to the International Space Station over its lifetime and to determine whether improvements in that support are possible.

REFERENCES

Kessler, D.J. 1996. Private communication to Robert Culp, April 17, 1996.

Loftus, J.P. Jr., and E.G. Stansbery. 1993. Protection of Space Assets by Collision Avoidance. Presented at the 44th Congress of the International Astronautical Federation, Graz, Austria, October 16–22, 1993.

Lord, Maj. Gen. L.W. 1996. Memorandum to the NRC Committee on International Space Station Meteoroid/Debris Risk Management. April 3, 1996.

Schultz, E.D. 1996. Planned Operations for Orbital Debris Collision Warning/Avoidance. Briefing presented to the NRC Committee on International Space Station Meteoroid/Debris Risk Management, Houston, Texas, April 3, 1996.

List of Acronyms

AIT	analysis integration team
DoD	U.S. Department of Defense
EMU	extravehicular activity mobility unit
EVA	extravehicular activity
FGB	functional cargo block
GEODSS	ground-based electro-optical space surveillance
GPS	global positioning system
IPT	integrated product team
ISS	International Space Station
LDEF	Long Duration Exposure Facility
LEO	low Earth orbit
MSCSurv	Manned Spacecraft Crew Survivability
NASA	National Aeronautics and Space Administration
PNP	probability of no penetration
RSA	Russian Space Agency
SSN	U.S. Space Surveillance Network

APPENDIX A

Statement of Task

Drawing upon available data and analyses, including information presented by NASA and other space agencies, the committee will:

I. Assess the International Space Station strategy for reducing the probability that the space station or its crew will be damaged or lost as a result of meteoroid or orbital debris impact and recommend alternate strategies where appropriate.

   - Review the meteoroid/debris environment model used for space station design and assess its validity.
   - Review the current approach to space station shielding and assess the ability of this approach to protect the space station.
   - Assess current plans to minimize the hazard to the space station and crew in the case of damaging meteoroid or debris impacts.

II. Assess the potential benefits and costs of schemes to reduce the hazard to the space station from meteoroids and debris through the use of improved radar tracking and onboard debris collision sensors.

The committee will conduct approximately four meetings. The committee's findings and recommendations will be presented in a report for the NASA Administrator, Congress, the White House, and other interested parties. The report will be subject to National Research Council report review procedures prior to release.