JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 36, No. 1, January–February 1999

Quantifying and Reducing International Space Station Vulnerability Following Orbital Debris Penetration

Joel Williamsen*
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
and
Kevin Blacklock,† Hilary J. Evans,† and Thomas D. Guay†
Sverdrup Technology, Inc., Huntsville, Alabama 35806

The increase in the orbital debris environment in low Earth orbit has prompted NASA to develop new strategies to examine the effects of penetration on spacecraft and crew. In 1992, NASA's Marshall Space Flight Center developed the Manned Spacecraft and Crew Survivability computer program to quantify the likelihood of an orbital debris particle causing loss of the International Space Station or its crew following penetration, i.e., vulnerability. The personal computer-based model computes the likelihood of occurrence for six failure modes that may lead to crew or station loss: 1) critical cracking, 2) critical equipment loss, 3) thrust-induced loss of control or joint failure, 4) fatal and nonfatal injury to crew, 5) crew hypoxia during escape and injured crew member rescue, and 6) station late loss due to critical module depressurization. The ability of the crew to perform countermeasures, i.e., shut hatches, rescue the injured, or egress the station, has been implemented into the model to assess the effectiveness of different crew protocols in reducing the overall probability of loss. By varying these parameters and selecting alternate crew operations and internal equipment designs, one can identify the optimum configurations that, if implemented, may quantifiably increase overall station and crew member survivability.

Nomenclature

N_{pens}	= number of penetrations of any pressurized module of space station
P_{loss}	= probability of space station or crew loss
$P_{loss/pen}$	= probability that a penetration of pressurized module yields loss of station or crew
P_{pen}	= probability of penetration of one of space station's pressurized modules

Introduction

NASA has acknowledged the increasing number of orbital debris particles in low Earth orbit (LEO) as a serious threat to the survivability of Earth-orbiting spacecraft. Based on the limited internal volume, air supply, and other design features of early crewed spacecraft (Mercury, Gemini, Apollo, etc.), spacecraft developers considering the meteoroid environment conceded that nearly any penetration of the pressurized volume would cause loss of the spacecraft and its crew. This assumption drove spacecraft designers to develop protection systems focused on denying particles the ability to penetrate the spacecraft. However, crewed spacecraft such as the International Space Station, with larger internal volumes, multiple hatches, reserve air supplies, and escape vehicles, offer the crew members a far larger opportunity to survive a penetration, given proper internal spacecraft design and crew procedures. Furthermore, the longer orbital lives, larger exposed areas, and increased orbital debris population associated with today's steadily growing population of spacecraft in LEO, coupled with the limited weight and volume available for shielding, forces the designer to consider the penetration of valuable spacecraft systems as not just a contingency, but as an increasingly likely occurrence.

To improve the likelihood of spacecraft survival following orbital debris penetration, mission planners and spacecraft designers must employ military-style vulnerability analysis techniques.[1] These techniques allow the analyst to quantify the likelihood of spacecraft loss following penetration based on 1) establishing spacecraft failure modes, 2) associating each of them with a critical damage parameter triggering them, and 3) determining the probability of impact by orbital debris particles with characteristics that induce these levels of critical damage. This paper outlines the detailed vulnerability analysis that NASA has performed to determine the failure modes associated with space station or crew loss and describes the Manned Spacecraft and Crew Survivability (MSCSurv) computer program it developed to quantify the likelihood that these failure modes occur. Space station loss is defined here as the irreparable loss of one or more space station critical functions; crew loss is defined here as the loss of life for one or more crew members.

Probability of space station or crew loss P_{loss} due to a single impact can be thought of as the product of 1) the probability of a penetration and 2) the conditional probability that the penetration yields a loss of spacecraft or crew[2,3]:

$$P_{loss} = P_{pen} \times P_{loss/pen} \tag{1}$$

To account for multiple impacts over the life of the spacecraft (the actual case), the formula is

$$P_{loss} = 1.0 - \exp(-N_{pens} \times P_{loss/pen}) \tag{2}$$

The BUMPER computer model is the standard NASA tool used to determine probability of spacecraft penetration, the P_{pen} or N_{pen} terms used in Eqs. (1) and (2), respectively. The ability to quantify the $P_{loss/pen}$ term, the vulnerability of spacecraft to penetration, allows spacecraft designers to examine the entire probability of loss, thereby shifting some of the focus of increasing orbital debris safety from the external portion of the space station to the entire design, including the internal equipment design, crew procedures, and other factors that can lower overall probability of loss. However, the foremost utility for any quantitative risk assessment method is as a comparative tool for determining the relative merits of alternative designs and operations, not as an absolute measure of risk. Many uncertainties exist in the assumptions utilized within MSCSurv; additional work is being performed at Marshall Space Flight Center (MSFC) to quantify this uncertainty in $P_{loss/pen}$ and identify the assumptions/inputs that are its greatest contributors.

Received Nov. 21, 1997; revision received Sept. 14, 1998; accepted for publication Sept. 15, 1998.

*Aerospace Engineer; currently Senior Research Engineer, University of Denver Research Institute, 2050 E. Iliff Avenue, Denver, CO 80208. Senior Member, AIAA.

†Engineer, Structural Division.

MSCSurv Computer Model

MSCSurv is a Monte Carlo simulation tool that 1) randomly generates a large number of debris particles (size, velocity, and approach direction) based on one of two NASA orbital debris environment models, 2) selects a space station impact location for each particle based on exposure of the station from this approach direction, 3) assesses the resulting damage (hole size, crack length, internal damage) from each particle that penetrates the station, 4) compares the damage from the impact to critical levels required to induce loss of the station or crew members, and 5) quantifies the final probability of crew or station loss given a penetration (averaged over thousands of simulated penetrations). MSCSurv runs on a personal computer with a Pentium platform and 16-MB minimum RAM. MSCSurv was compiled using a Fortran 90 compiler. An average run of 100,000 simulated penetrations requires approximately 4 min to execute on a Pentium 200-MHz personal computer. Figure 1 shows a flowchart that outlines the general decision paths for MSCSurv.

In the first section of the program, MSCSurv reads in all input files (49 total) to fill the variable arrays that describe the space station geometry information, debris environments, debris shield parameters, essential equipment criticality factors, and module specific data (internal volume and crew travel lengths). The current MSCSurv geometry model contains over 23,000 individual external elements (Fig. 2) spread over 23 modules and was generated using a standard

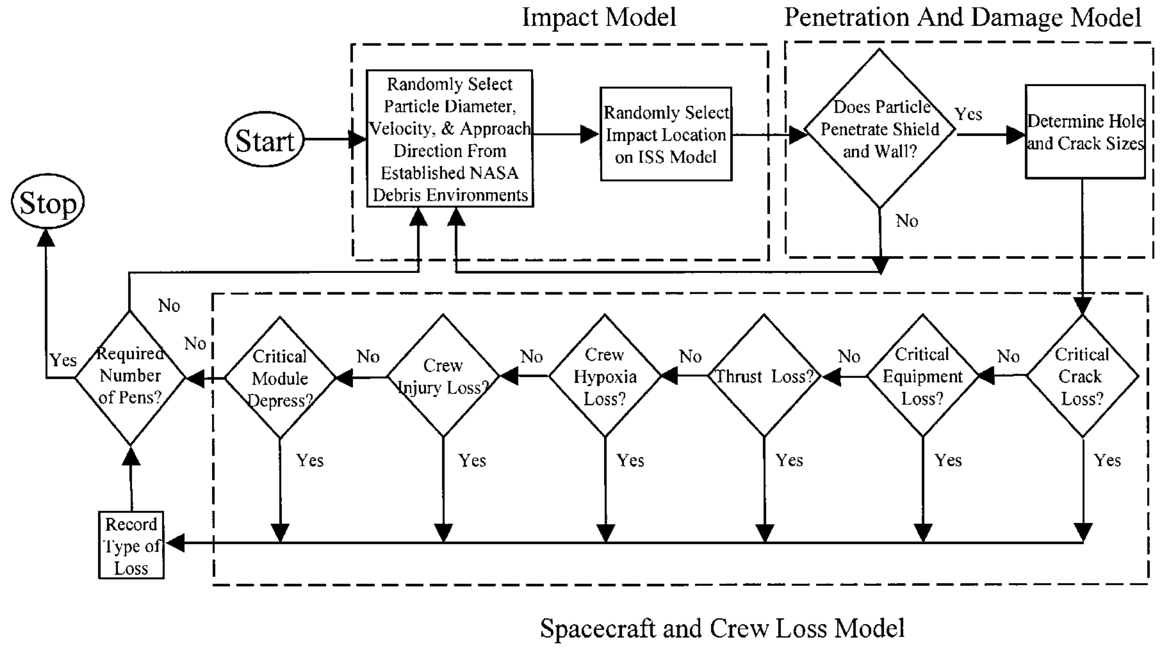

Fig. 1 MSCSurv computer code flowchart.

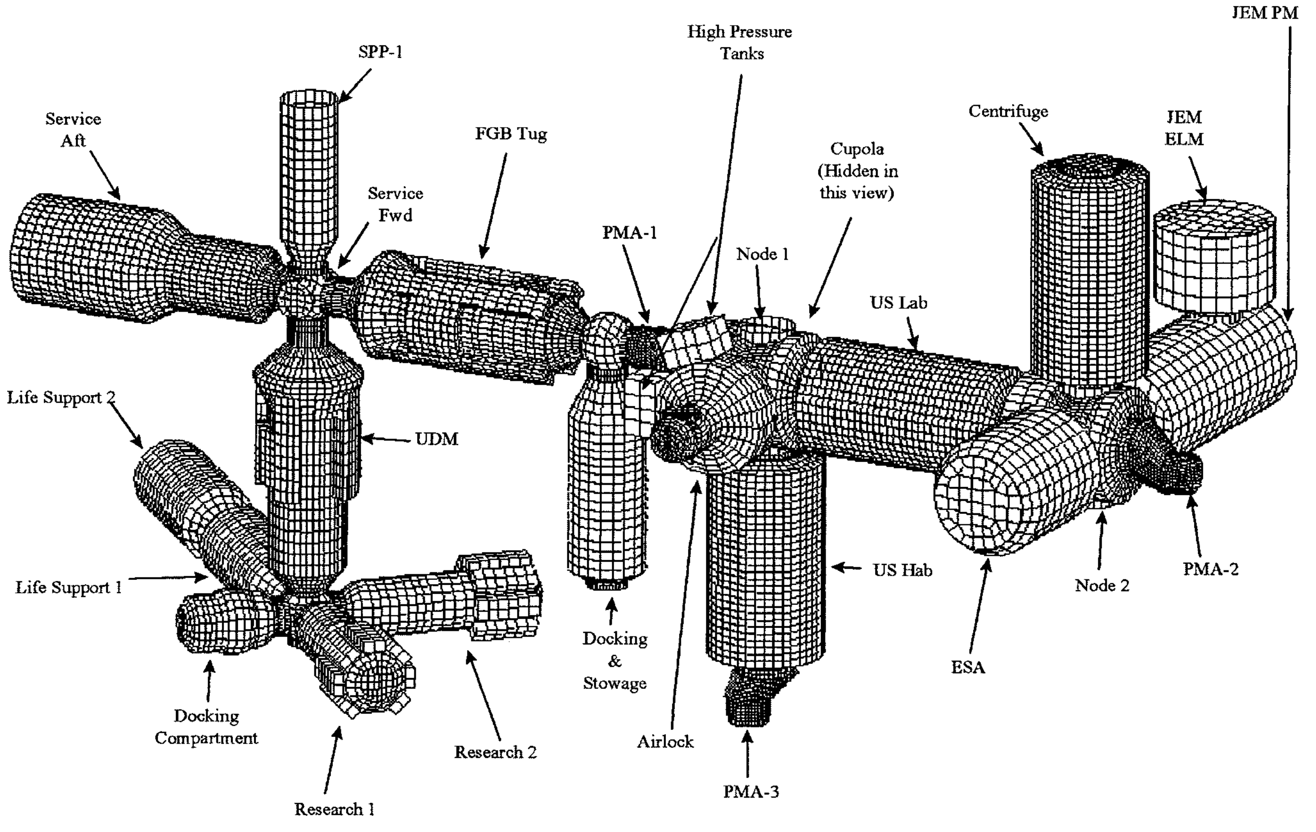

Fig. 2 MSCSurv geometry model for International Space Station.

Table 1 Sample MSCSurv output file[a]

Module	Total ratio	= CRAK	+ CRSY	+ Joint THST	+ EVs THST	+ RHYX	+ HYPK	+ INJY	Critical module depress	Nonfatal injury
	Probability of station or crew loss given an orbital debris penetration									
Node 2	0.45	0.25	0.02	0	0.08	0.01	0.09	0.01	0.05	0.06
ESA	0.63	0.17	0.04	0	0.26	0	0.16	0	0.03	0.02
JEM	0.52	0.15	0.03	0.01	0.20	0	0.13	0	0.05	0.02
ELM	0.61	0.20	0.02	0.04	0.20	0.01	0.14	0	0.03	0.06
U.S. LAB	0.50	0.11	0.04	0	0.02	0.02	0.30	0	0.06	0.04
Node 1	0.21	0.08	0.04	0	0.00	0.01	0.08	0.02	0.01	0.08
U.S. HAB	0.61	0.19	0.02	0	0.05	0.08	0.26	0.01	0.03	0.14
CUPOLA	0.74	0.04	0.07	0	0.00	0	0.63	0	0.05	0.02
Lifesup1	0.14	0.01	0.02	0	0.06	0	0.06	0	0.27	0.03
FGB TUG	0.68	0.04	0.11	0	0.00	0.02	0.50	0	0.18	0.02
SERVAFT	0.08	0.01	0.02	0	0.02	0	0.02	0	0.92	0
UDM	0.72	0.02	0.20	0	0.17	0.02	0.31	0	0.21	0.01
RESERCH1	0.36	0.01	0.02	0	0.11	0	0.21	0	0.28	0.02
RESERCH2	0.36	0.01	0.02	0	0.16	0	0.16	0	0.26	0.02
LIFESUP2	0.17	0.01	0.02	0	0.09	0	0.04	0	0.25	0.02
SPP 1	0.28	0.01	0.21	0	0.01	0	0.06	0	0.20	0
HP tanks	0.27	0.04	0.23	0	0.00	0	0.00	0	0	0
Airlock	0.46	0.19	0.02	0	0.01	0	0.23	0	0.06	0.04
Centfuge	0.60	0.20	0.02	0.02	0.20	0.01	0.14	0	0.04	0.03
DKSTOW	0.11	0.01	0.02	0	0.00	0	0.07	0	0.11	0.08
DKCOMP	0.15	0.02	0.03	0	0.03	0	0.07	0	0.29	0.04
1 PMA	0.51	0.06	0.03	0	0.00	0.05	0.36	0.01	0.14	0.04
2 PMA	0.72	0.05	0.04	0	0.31	0.03	0.29	0	0.06	0.02
3 PMA	0.76	0.04	0.05	0	0.15	0.05	0.46	0.01	0.04	0.02
SERVFWD	0.35	0.03	0.05	0	0.07	0.01	0.14	0.05	0.45	0.03
NASA	0.55	0.16	0.03	0.01	0.14	0.02	0.18	0	0.04	0.05
RSA	0.23	0.01	0.05	0	0.06	0	0.11	0	0.45	0.02
Station	0.28	0.03	0.05	0	0.07	0.01	0.12	0	0.39	0.03

[a]CRAK, critical crack; CRSY, critical system; Joint THST, joint thrust failure; EVs THST, escape vehicle thrust; RHYX, rescue hypoxia; HYPK, hypoxia; and INJY, injury.

BUMPER geometry model provided by NASA Johnson Space Center (JSC).[4]

Next, MSCSurv queries the user on a wide variety of input parameters, including damage assessment models, crew reaction procedures following penetration, each hatch's initial status (closed or open), crew movement rates, critical pressure limits (hypoxia onset), the time criteria for the crew to abandon all activities and egress to the escape vehicles, plus many more. The Appendix lists the baseline assumptions used to obtain some of the results reported later within this report.

For each particle it generates, MSCSurv initially determines if the particle possesses the correct characteristics to penetrate through the module wall. Ballistic limit curves are used to describe the combinations of impact parameters (particle diameter, obliquity, velocity) required to penetrate the module.[5,6] The MSCSurv model incorporates over 140 different shield types, requiring over 29 individual ballistic limit models to be employed. These shields and ballistic limit equations were carefully chosen to replicate exactly the ballistic limit equations used within the latest BUMPER program available from JSC[4] for each individual shield type. Generally, the shields that perform best in denying a particle the ability to penetrate will yield larger holes and larger $P_{\mathrm{loss/pen}}$ (as will be shown in later paragraphs).

Once a penetration occurs, MSCSurv initiates its process of quantifying how the possible hazards associated with the penetration contribute to the probability of crew or station loss. There are currently six general hazards or loss modes that MSCSurv analyzes as a result of debris particles penetrating crewed modules: 1) critical cracking, 2) critical equipment loss, 3) thrust-induced loss of control or joint failure, 4) fatal or nonfatal injury to crew, 5) crew hypoxia during escape or crew member rescue, and 6) station late loss due to critical module depressurization. As shown in Fig. 1, MSCSurv operates in a cascading fashion when calculating the overall $P_{\mathrm{loss/pen}}$ term. First, it determines whether the impact created a crack sufficient in length to propagate unstopped. If so, the penetration of the module is stored in MSCSurv memory as a station/crew loss, and a new debris impact simulation is initiated. If the critical crack is not exceeded, MSCSurv next determines if a critical subsystem is penetrated, which would induce a hydrazine detonation, loss of control, or other critical loss. Again, if this occurs, the penetration of the module will be stored as a loss of this type, and MSCSurv will return to the beginning to start another debris impact simulation. This cascading operation continues through all six hazards shown in Fig. 1, and the final results are sent to the output subroutine, where they are presented in tabular format, as shown in Table 1. Note that the precise order of the cascade shown in Table 1 is ordered such that the more immediate station hazards are examined first, and the crew level hazards generally are ordered last.

Because of the ordered, cascading nature of MSCSurv, the absolute value of the later hazards depends highly on the occurrence of the earlier hazards. MSCSurv prevents a penetration that yields a sufficiently large hole from inducing both a critical cracking failure and a hypoxia or crew injury failure; therefore, if critical cracking were not counted as a failure mode, the absolute magnitude of the value for hypoxia or crew injury would be higher. This is especially true in the case of nonfatal crew injuries, which are often hidden by MSCSurv due to their last place position in the cascade (shown in Table 1); large values for the critical module depressurization often hide the occurrence of nonfatal crew injuries. The next section of this paper details each of the six hazards and how MSCSurv determines whether that hazard contributes to a loss due to orbital debris penetration.

Critical Crack Hazard

Each exterior element of the Space Station cluster is independently assigned a critical crack length, based on the module's fracture toughness, rib spacing, wall thickness, and the station's internal pressure. These estimators are currently based in large part on a study performed by Lutz and Goodwin[7] for NASA, European Space Agency (ESA), Japanese Space Agency [National Space Development Agency (NASDA)], and Russian Space Agency (RSA) crewed module critical crack lengths. For each penetration, MSCSurv calculates the associated diameter of the hole and the tip-to-tip crack length. If the calculated tip-to-tip crack length exceeds the critical crack length, the crack will continue to propagate uncontrolled through the pressure wall at speeds near 60 m/s. The result is a module unzipping and the loss of the space station and crew by explosive decompression.

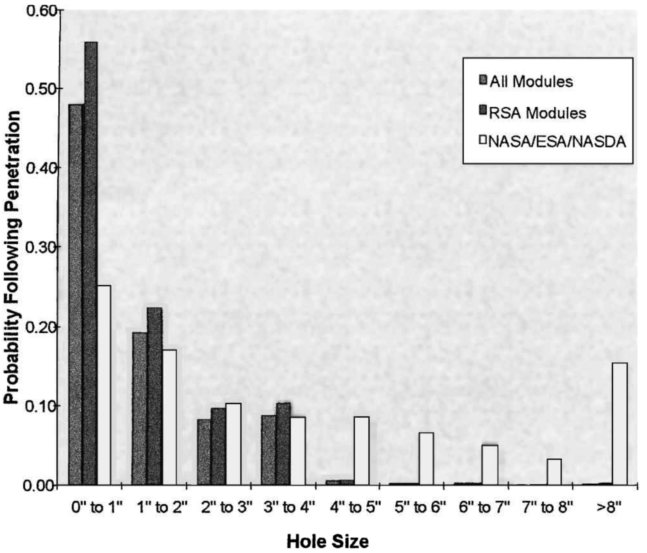

Fig. 3 Hole-size distribution for International Space Station modules.

MSCSurv provides the user with a choice of two model sets to calculate the hole diameter and crack size associated with a penetration. The Burch D90 hole size model was formulated in 1967 for simple aluminum sheets impacted at velocities from 4.5 to 7.3 km/s, and provides conservative hole size estimates for these ranges.[6] This model has been extended for use through the 15-km/s velocity region using an energy scaling technique.[2] Recently, Schonberg and Williamsen formulated a set of models for hole and crack size following a penetration for 14 common shields aboard the space station.[8] This model set is used as the primary estimator for hole/crack size in MSCSurv with the Burch D90 model used in shield types where the Schonberg/Williamsen models do not apply. Figure 3 shows a typical hole-size distribution computed by MSCSurv for the entire space station module cluster using the Burch D90 and Schonberg/Williamsen hole-size equations, as well as for RSA vs NASA/ESA/NASDA modules taken as a whole (hereafter clustered together and referred to simply as NASA modules, due to their inherent similarity to one another). When using the Burch D90 hole-size model, it is assumed that the tip-to-tip crack length is approximately twice the average hole diameter based on estimates by Grumman using hypervelocity impact data from MSFC, Boeing Aerospace, and others.[9]

Critical System Damage Hazard

Each of the space station modules contain critical equipment that, if impacted, will lose its functionality and, furthermore, will cause a loss of the station or crew. The critical equipment generally falls into two categories: either high-energy equipment or critical internal equipment. The propellant tanks, high-pressure nitrogen tanks, and the gyrodynes are examples of high-energy equipment; major electrical busses, power supplies, and guidance and navigation controls would be categorized as critical internal equipment. Each piece of internal equipment has a somewhat different protection level, denoted in a separate data file as its equivalent areal density, that is, the total mass of shielding divided by surface area between the module pressure wall and the critical equipment. The probability of damaging a particular piece of critical equipment following penetration of each element, $P_{cd/p}$, is also stored in a data file and is generally taken as the ratio of the critical equipment's exposed area (located behind the impacted external element) to the impacted element's exposed area.

For each penetration, MSCSurv computes the depth of penetration behind the pressure wall using a modified form of the Burch multiplate penetration equation.[6] If the particle's penetration capability exceeds the areal density of the critical equipment protection, MSCSurv determines whether or not the critical equipment is impacted by comparing a random number to the $P_{cd/p}$; if the critical equipment is impacted, it is considered to be lost. Portions of the space station where much of the protective areal density and locations of critical equipment are known include the service module, the energy block (FGB), the solar power platform-1 (SPP-1), and several other critical areas governing guidance, control, and power distribution. For example, the unsymmetrical dimethyl hydrazine (UDMH) propellant tanks located on the Russian FGB and service modules reflect a 53% $P_{cd/p}$; the gyrodynes located in the Russian SPP-1 module reflect a 70% $P_{cd/p}$. These values were obtained from a study performed by Lutz and Goodwin.[7] Unfortunately, much of the data that describes the critical equipment's exposed area and criticality aboard the station are incomplete. For these elements, it is assumed that there is a 0.861-g/cm^2 areal density behind the equipment racks (reflecting the standard thickness of the rear wall of an equipment rack) with a 10% $P_{cd/p}$ if the element's protective level is penetrated. This estimate reflects an average value for areas where the $P_{cd/p}$ is better known.

Thrust Hazard

The thrust hazard is generated as a result of the station's pressurized air venting through the damaged module, inducing a force that causes the station cluster to rotate about its center of gravity. Calculating the speed of the resulting angular rotations is integral to determining whether a loss occurs. Preliminary analyses indicate the space station's rotational motions due to thrust-induced forces will probably not exceed human thresholds. However, at some critical rotational velocity, one of two events can occur: 1) the station will rotate at such a high velocity that the crew escape module will be unable to pull away from the station and the station's reaction and control system will be unable to restabilize a station angular acceleration, or 2) the station will experience the failure of a major structural joint, causing rapid decompression of the module cluster or other critical damage.

To compute the likelihood of event 1, MSCSurv first utilizes the calculated hole size and distance of each individual hole from the station center of gravity to compute the resulting moment induced on the station. It then utilizes Euler's equations of motion to calculate the resulting angular velocity of the space station and compares this value to the critical values causing loss of control as input by the user. To simplify this calculation, MSCSurv assumes that the station is pinned at the center of gravity of the station and is only allowed to move in one of the three principle axes (roll, pitch, or yaw). MSCSurv considers the force from depressurization as hatches are closed by the crew based on the changing volume available to the hole. If hatches are safely closed on the module prior to reaching maximum allowable spin rates, the station's maximum spin rate is recalculated using the lower volume available to the hole.

There are currently three critical structural interfaces that MSCSurv inspects for structural integrity as they undergo thrust-induced stresses: the node 1 to FGB joint (a primary interface joining the RSA to NASA elements near the centroid of the station), the S0 array to U.S. laboratory interface (primary interface joining the crewed module cluster to the truss structure), and the array to S4 array interface (a weak joint holding the solar arrays to the truss). These three interfaces were chosen because they exhibit structural characteristics most vulnerable to holes induced in the crewed modules relative to the rest of the space station interfaces. At the instant the penetration occurs, the thrust force will be a maximum and, therefore, any bending moments applied at the critical interfaces will be a maximum. For every penetration, MSCSurv calculates the resulting bending moment for each of these structural interfaces. Thrust-induced structural failure is induced when the calculated bending moment exceeds the maximum allowable bending moment each interface can sustain.

Crew Injury and Loss

An internal penetration may cause crew loss due to direct injury by fragments if a crew member is near the penetrated area. A University of Alabama in Huntsville study[10] using a flash x-ray camera shows fragments will emanate within an approximate 60-deg cone from the penetration point. Projection of this cone correlates to a maximum debris fragment zone approximately 2 m wide within the crewed portion module if the cone of debris penetrates the internal equipment.

For every penetration, MSCSurv generates the individual positions of each of the crew members randomly throughout the station (or in fixed positions depending on user selection). Once the module is penetrated, MSCSurv compares the crew location points to the particle penetration point and then calculates the distance between the two. If a crew member is within the critical 2-m fragment zone, status is noted as possibly injured, subject to two additional criteria: 1) sufficient depth of penetration of the particle past internal equipment into the open crew cabin and 2) sufficient energy of the particle following penetration to induce injury. Penetration depth into the crew cabin is determined using the aforementioned Burch penetration model; this is compared to the equivalent areal density of the internal equipment, stored in a separate file. If penetration levels exceed protective levels, statistical military data on the effects of a hypervelocity penetration are used to determine the extent or level of injuries to a crew member. The Joint Technical Coordinating Group for Monitoring Effectiveness (JTCG/ME) released studies that define the criteria for the probability of incapacitation based on the speed and mass (kinetic energy) of fragments projected at prone and standing soldiers.[11] These data are used to determine if the crew member's injuries are to the extent that it causes incapability for self-rescue, i.e., an immediate loss of life, or loss of life eventually at a later time after the rescue. Users have the option of selecting to use these military relations for calculating the probability of immediate loss of life and the probability of a rescued crew member later losing a life, or inputting their own value for the Ref. 11 probabilities.

Any time a crew member is injured, MSCSurv will immediately initiate a rescue attempt. This is accomplished by simulating the crew searching for the injured, removing the injured from the damaged module, and finally, closing the hatch. If the other crew members are unable to accomplish a successful rescue, MSCSurv will count this particular penetration as fragment injury loss. If a successful rescue does take place, but the probability of immediate loss or the probability of later loss is high enough, a fragment injury will also be counted. If the rescue is successful and the probabilities of loss are low, then the fragment injury loss will be counted as a nonfatal injury.

An additional hazard that threatens the space station crew, immediately upon penetration, relates to the atmospheric effects of a hypervelocity impact. These secondary injury effects include light flash, pressure pulse (shock wave), and temperature spikes.

MSCSurv currently evaluates the prospects of atmospheric overpressure and light flash as possible causes for secondary effects leading to the loss of the space station or a crew member's life. Again, the crew position at the time of particle penetration plays an important role. MSCSurv uses military expressions that provide the user the probability of incapacitation due to atmospheric overpressure as a function of the overpressure level.[12] The overpressure level is computed using the distance from the penetration point, the energy from penetration, and the debris cloud mass.[2] If the crew member is close enough to the penetration that the shock wave causes incapacitation, MSCSurv counts the penetration as a secondary injury loss. The light flash at the instant of penetration is intense enough to cause temporary or permanent blindness to the crew member, but only if the crew member is facing in the direction of the penetration point.[13] To determine this, MSCSurv assigns a $\frac{1}{6}$ probability the crew member in the module was facing the direction of the penetration point (the $\frac{1}{6}$ assumption reflects one side of a six-sided cube toward which a crew member's vision could be directed). A random number is generated and compared to this probability; if the probability value is higher, MSCSurv counts the penetration as a secondary injury loss. As in the case with fragment injury, if the secondary injured crew member is later successfully rescued, the secondary injury loss is counted as nonfatal.

Hypoxia Hazard

An orbital debris penetration causes a crew loss due to hypoxia if the internal cabin air is reduced to a hazardous level prior to the crew's ability to escape to the crew return vehicles, close the hatch to the decompressing module, or repair the hole. Modules that employ shields that yield larger holes will experience relatively higher losses due to hypoxia. It should be noted that this loss mode can occur with crew members located in modules other than the penetrated module if the hatch to the penetrated module is not closed.

The pressure wall hole size, space station hatch status, and the crew movement rates play a major role in assessing whether hypoxia occurs as a crew loss mode. MSCSurv accomplishes this assessment by 1) generating individual positions (stations) for each crew member based on user inputs and 2) comparing the time required for crew members to reach safety from their stations, i.e., isolate penetrated module, repair hole, return to escape vehicles, to the time required for the internal available volume to decompress to the (user-defined) pressure level at which hypoxia occurs. Normal hypoxia is simply defined as the crew (no injuries reported) unable to reach safety due to a large hole allowing a very fast depressurization of the station. If the crew is in the midst of a rescue exercise when hypoxia occurs, the loss is stored in a separate bin called rescue hypoxia. As hatches are closed before or during emergency procedures, the overall volume of air available to the hole in the module is adjusted accordingly.

As a point of reference, the probability of loss term does not take into account the number of crew members lost. Defining the loss term in this way, disregarding the actual number of crew members lost, is consistent with the current NASA safety philosophy. The loss of one crew member is equal in severity to the loss of the entire crew. Fog is a visual hazard to the crew while escaping (it begins to form in the module when the pressure reaches approximately 11.3 psi) and is included at the user's option as a factor for slowing crew egress. MSCSurv also computes the intermodule wind force on a crew member caused by air escaping the station and compares it to the (user-defined) crew strength. If the crew member is not strong enough to overcome the wind force, the member is lost due to hypoxia.

Critical Module Depressurization

The final hazard that MSCSurv evaluates is the occurrence of complete depressurization in space station critical modules, that is, modules containing equipment providing such vital functions as guidance, propulsion, or environment control. This is considered to be a station loss only if 1) the internal equipment aboard the module fails to operate due to complete depressurization and 2) the failure, if not of immediate concern to station survival, cannot be repaired. Condensation on interior equipment following the onset of fog may also reduce the survivability of internal electrical components. Until recently, equipment aboard the Russian service module was feared to be susceptible to this failure mode, although steps have been taken recently by a special NASA/RSA depressurization working group to either strengthen the resistance of the components aboard this module to depressurization or off load vital functions of the module to NASA elements of the station. Nevertheless, it is still included as a possible failure mode within this study, even though it may or may not lead to actual station loss.

This critical module depressurization condition can be caused by penetration of the critical module or penetration of a module attached to a critical module with an open hatch. Similar to hypoxia, hatches closed on little-used modules prior to impact protect the critical modules. MSCSurv assumes there are two techniques the crew members use to stop the depressurization of a critical module: 1) repair the hole or 2) close the necessary hatches to isolate the penetrated module from the critical modules. MSCSurv gives the user the opportunity to select which of these actions the crew members will utilize. The user is also allowed to select which modules will be deemed critical before each simulation.

Once the simulation is over, MSCSurv will take the stored losses and move to the output subroutine. The output reveals, on a percentage basis, how each module was affected by all hazards and illustrates the overall probability of loss for the entire space station, as shown in Table 1 for the baseline assumptions and the systematic module isolation protocol (described in subsequent paragraphs). The Appendix is the output from an MSCSurv file summarizing user inputs for these conditions.

Results

Crew Reaction Protocols

One of MSCSurv's most powerful attributes is its capability to simulate the space station crew movements and repair activities immediately following a penetration to help define crew flight rules and associated reaction protocols following a penetration. Three crew reaction protocols have been incorporated to measure how effective crew operations can be made in reducing losses following a penetration by orbital debris.

The initial crew reaction protocol examined was called systematic module isolation (SMI). After the depressurization alarm sounds, the crew members check in with each other at a central assembly point (usually at the service module) to determine if injuries exist. If all of the crew members are not accounted for (injuries), healthy crew members search for the injured, remove the injured from the penetrated module, and seal off (close hatches) this module. At this point, the crew is assumed safe. However, if there are no injuries, everyone then moves to the escape vehicles. A system level check is performed to ensure the vehicles are functioning properly. If time permits (more than 5 min prior to reaching critical depressurization levels) two crew members will travel to the hatch between the PMA-1 and node-1 and determine which side of the station the leak is on by partially closing the hatch and checking the flow of air against it. If time permits, the crew begins systematically closing hatches on the side of the station that is depressurizing in an order defined by the user. As each module is isolated, a crew member monitors the overall station leakage to see if the leaking module has been isolated. When the alarm sounds noting only 5 min remaining until critical depressurization levels are reached, the crew must give up all activities, return to the escape vehicles, and egress the station.

The second crew protocol gives the crew more liberty to isolate the leaking module in a quicker fashion. As the crew members move within the modules during the SMI protocol, a crew member may possibly detect the hole as he passes through the penetrated module. Experiments performed by the European Space Research and Technology Center in 1991 indicated that crew members aboard the Spacelab crew trainer were able to detect the location of a simulated 2-cm hole or larger in seven of eight attempts to within one standard equipment track even with the noises associated with internal systems operating.[7] If the hole is detected, the crew member will close the hatches on that module to secure the rest of the station. Noted for the added flexibility, this protocol is called SMI + situational awareness (SMI+SA). If the hole is not detected, i.e., not passed or is too small to be recognized), this protocol is identical to the SMI protocol.

The third and final crew escape protocol assumes a hole detection system exists to indicate automatically which module is leaking. The immediate hole location capability (IHLC) protocol eliminates the procedure requiring the crew to first move to the escape vehicles. Crew members will operate the system after they check in at the central assembly point following activation of the depressurization alarms. The crew then moves to the leaking module and seals it from the remainder of the station.

Sensitivity Analyses

Five sets of MSCSurv simulations were generated to study how changes in several assumptions effected the probability of loss given penetration $P_{\mathrm{loss/pen}}$ term. The five simulation sets are titled as follows: 1) baseline, 2) selected hatches initially closed, 3) immediate hole repair, 4) oxygen masks available, and 5) best combinations. Each set of simulations includes the MSCSurv results of the three described protocols (SMI, SMI+SA, and IHLC). The results of these analyses are shown in Figs. 4–7. Each result shows both an immediate $P_{\mathrm{loss/pen}}$ and a total (possible) $P_{\mathrm{loss/pen}}$ value. The immediate $P_{\mathrm{loss/pen}}$ are represented by the sum of the first five hazards MSCSurv analyzes and are indicated on the right side of the bars on the graphs. The total (possible) $P_{\mathrm{loss/pen}}$, shown on top of the bar chart, is the sum of immediate $P_{\mathrm{loss/pen}}$ plus the occurrence of the RSA service module depressurization (the only module with critical equipment still sensitive to failure following complete depressurization). It is important to examine how variations in crew operations and internal designs affect both types of $P_{\mathrm{loss/pen}}$ values.

The Baseline set of simulation results appears as Fig. 4 and may be used as a reference with which to compare the remaining four sensitivity analyses; the baseline assumptions are shown in the Appendix. The SMI protocol shows that 70% of the time when a penetration occurred, one of the six penetration hazards was experienced; however, the immediate $P_{\mathrm{loss/pen}}$ value (for five hazards) is only 31%. The SMI+SA protocol showed improvements in reducing the total possible $P_{\mathrm{loss/pen}}$ to 63% and the immediate $P_{\mathrm{loss/pen}}$ to 29%. This is because the crew was more often able to hear a hole and isolate a penetrating module as they passed it. As such, the service module did not completely depressurize as often due to depressurization in adjacent modules. Note that this added flexibility also reduced overall hypoxia from 13 to 11%. The IHLC protocol illustrates the

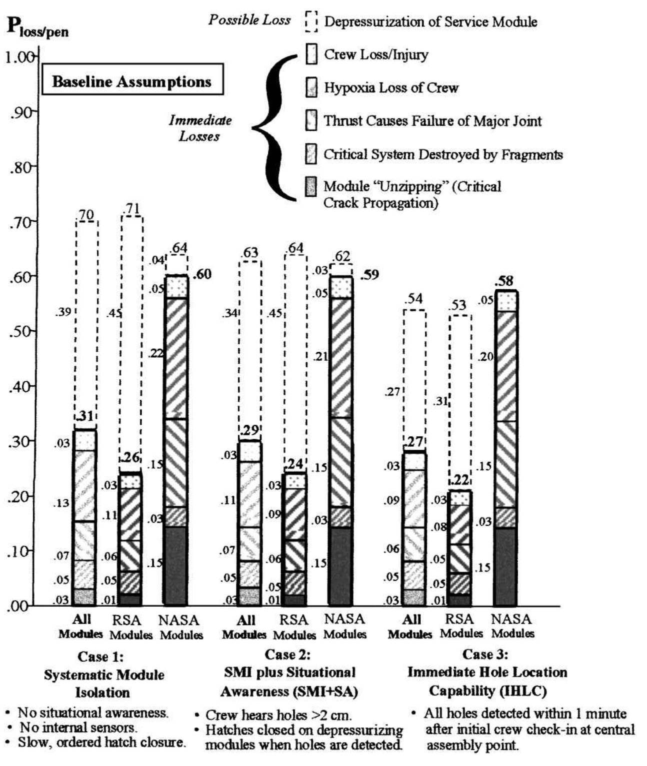

Fig. 4 Probability of station or crew loss given a penetration $P_{\mathrm{loss/pen}}$ for three cases using baseline assumptions.

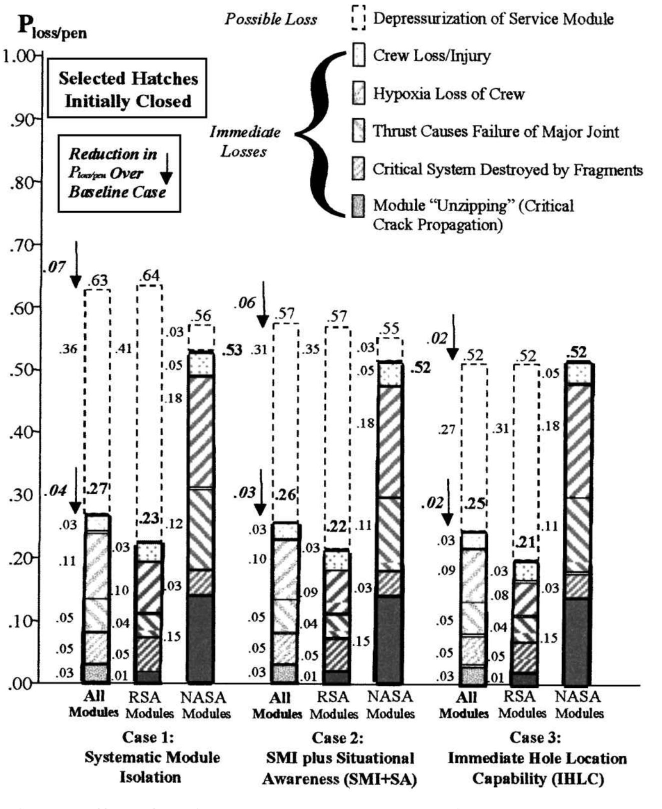

Fig. 5 Effect of closing selected hatches on reducing overall space station $P_{\mathrm{loss/pen}}$.

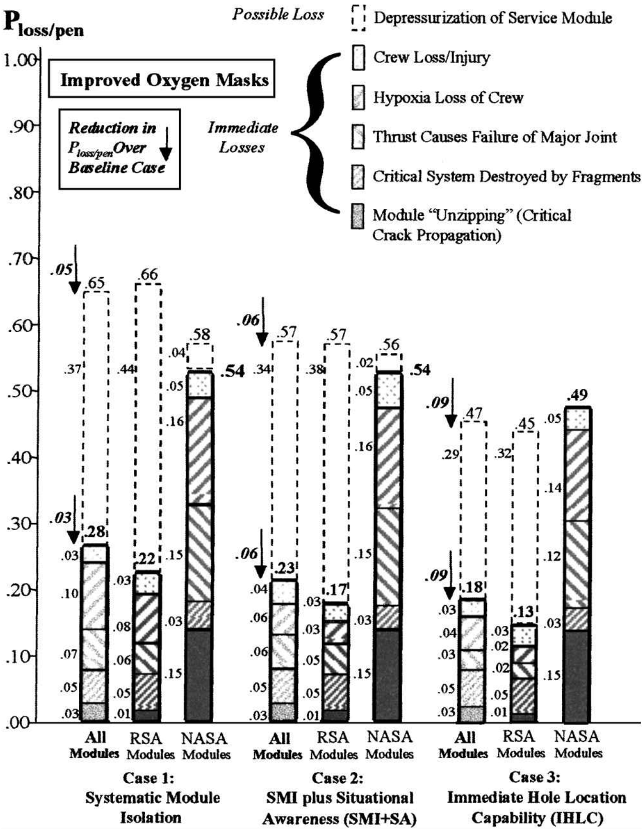

Fig. 6 Effect of improved oxygen masks (hypoxia limit to 7.0 psi) on reducing overall space station $P_{loss/pen}$.

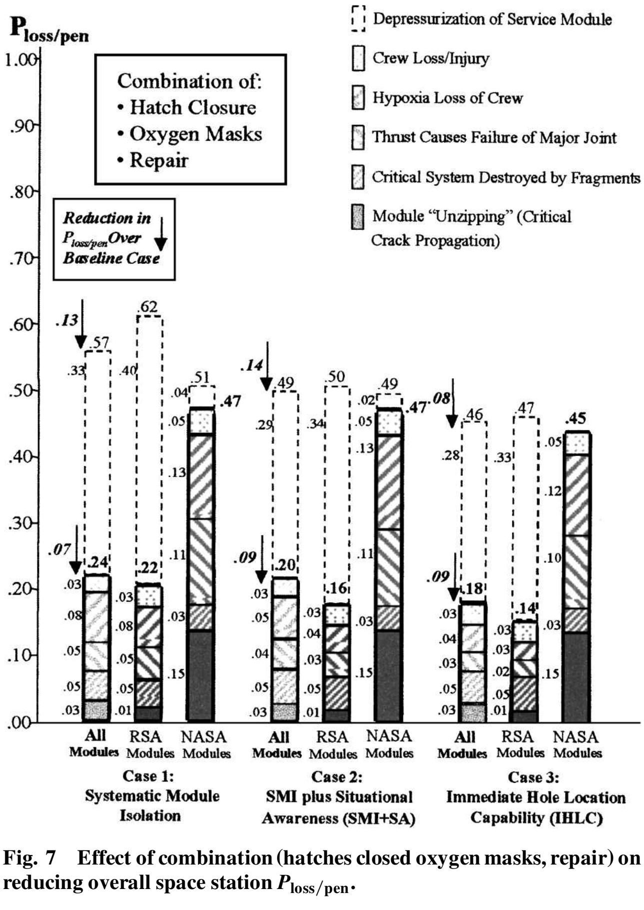

Fig. 7 Effect of combination (hatches closed oxygen masks, repair) on reducing overall space station $P_{loss/pen}$.

Table 2 Comparison of probability of no penetration for International Space Station modules from BUMPER vs MSCSurv computer models

	MSCSurv to BUMPERII PNP comparison for 1991 environment		
Module	MSCSurv PNP	BUMPERII PNP	% Difference[a]
Node 2	0.9994769	0.9994686	0.0008304
ESA	0.9989239	0.9989298	−0.0005917
JEM	0.9984148	0.9984173	−0.0002484
ELM	0.9993252	0.9993305	−0.0005285
U.S. LAB	0.9996793	0.9996697	0.0009621
Node 1	0.9995104	0.9995078	0.0002600
U.S. HAB	0.9988777	0.9988726	0.0005100
Cupola	0.9999275	0.9999298	−0.0002274
LIFESUP1	0.9950048	0.9950388	−0.0034124
FGB TUG	0.9980136	0.9980182	−0.0004618
SERVAFT	0.9822187	0.9823399	−0.0123365
UDM	0.9947044	0.9947247	−0.0020372
RESERCH1	0.9949544	0.9949760	−0.0021727
RESERCH2	0.9949148	0.9949847	−0.0070237
LIFESUP2	0.9939090	0.9939015	0.0007512
SPP 1	0.9964282	0.9964543	−0.0026167
HP tanks	0.9998361	0.9998364	−0.0000314
Airlock	0.9998191	0.9998138	0.0005314
Centfuge	0.9988056	0.9987970	0.0008573
DKSTOW	0.9912686	0.9913113	−0.0043040
DKCOMP	0.9992400	0.9992420	−0.0001958
1 PMA	0.9999216	0.9999207	0.0000902
2 PMA	0.9996872	0.9996887	−0.0001492
3 PMA	0.9996588	0.9996555	0.0003259
Totals	0.9344838	0.9347755	−0.0312224

[a][(MSCSurv PNP-BUMPERII PNP)/MSCSurv PNP] × 100%.

effectiveness of providing crew with hole location equipment. The total possible $P_{loss/pen}$ term was reduced to 54%, and the immediate $P_{loss/pen}$ term decreased to 27%.

It is important here to note difference in $P_{loss/pen}$ for RSA modules vs NASA/ESA/NASDA modules (included in Figs. 4–7 under NASA modules). The immediate $P_{loss/pen}$ figures are considerably higher in all cases for the NASA modules than for the RSA modules. This is because the more effective shields on the NASA modules screens out all but the most energetic particles from any penetration at all; when a penetration does occur, it is generally accompanied on NASA modules by a large hole and penetration depth into the module interiors. However, this increase in $P_{loss/pen}$ for NASA modules is more than offset by a far lower P_{pen} value, as will be shown in the next section.

In the second set of simulations (Fig. 5), the baseline assumptions remained the same with the exception of initially closing selected hatches. The little-used PMA2, PMA3, Japanese Experiment Logistics Module (JELM), SPP-1, and docking compartment modules were closed day and night. The three RSA research modules, cupola, Japanese experiment module (JEM), JELM, ESA, centrifuge, and life support modules were closed at night only, when no work is ongoing in these modules. It should be noted MSCSurv will not assign a crew member to a closed off module, thereby denying that crew member unrestricted access to the escape vehicles. The SMI protocol decreased the total possible $P_{loss/pen}$ from the baseline 70 to 63%, and the immediate $P_{loss/pen}$ decreased 4% from the baseline to 27%. The selected hatches initially closed protocol also decreased the total possible $P_{loss/pen}$ under SMI+SA from 63 to 57%, and the immediate $P_{loss/pen}$ measured a decrease from 29 to 26%. Smaller variations were experienced with the IHLC case: from 54 to 52% for the total possible $P_{loss/pen}$ and from 27 to 25% for immediate $P_{loss/pen}$. Overall, it is apparent that survivability of following orbital debris penetration increases by closing off selected little-used space station modules, even though the oxygen from these modules becomes unavailable to crew members should other modules be impacted. Additional sensitivity analyses using alternate hatch closure options may yield even further improvements in $P_{loss/pen}$.

The third simulation set examines the effectiveness of an alternate method for crew members to secure the space station from a leaking module. In this option, the crew is supplied with kits capable

Table 3 Comparison of P_{pen} and P_{loss} for five ISS manned modules

Module type	P_{pen}	N_{pen}	$P_{loss/pen}$	N_{loss}	P_{loss}
U.S. LAB	0.00032	0.00032	0.53	0.000169	0.000169
ESA	0.00107	0.00107	0.66	0.000706	0.000706
U.S. HAB	0.00112	0.00112	0.76	0.000851	0.000850
FGB TUG	0.00198	0.00199	0.55	0.001095	0.001094
RSA SERVAFT	0.01780	0.01794	0.09	0.001614	0.001612

Higher P_{pen} ↓ Higher P_{loss} ↓

of repairing the hole internally in areas accessible to the crew. In NASA modules, this amounts to approximately 60% of the module surface area, but only about 10% of the internal RSA module surface areas (due to the lack of direct access to the pressure wall in these modules). Larger holes also require longer times to repair under this option. The results from this sensitivity analysis were virtually identical in all cases with the baseline option (and as such are not presented in a separate figure). It is clear that the large holes in accessible NASA modules and inaccessible small holes in RSA modules work together to limit the effectiveness of this option.

In the fourth set of simulations (Fig. 6), crew members are provided oxygen masks, which allows them to be exposed to much lower cabin pressures. The hypoxia pressure is now assumed to be 7 psi rather than 9.5 psi as in the baseline set of simulations. The total possible $P_{loss/pen}$ value for the SMI protocol drops from 70 to 65% compared to the baseline run and from 31 to 28% for immediate $P_{loss/pen}$. The other two protocols also reduced the total possible $P_{loss/pen}$ by several percentage points from the baseline runs. Note that most of the improvements result from reductions in both thrust and hypoxia losses; the additional time provided by the oxygen masks allows further module isolation and spacecraft/crew survivability.

The final set of simulations (Fig. 7) simultaneously combines all of the earlier assumptions, which improves crew/station survivability. Selected hatches are initially closed, the crew is given capability to repair the hole, and improved oxygen masks are made available to all crew members. As expected, both the total possible $P_{loss/pen}$ and the immediate loss terms were significantly reduced for all three protocols.

Other Considerations

Verification of MSCSurv Impact and Penetration Model

As mentioned earlier, the impact model and the penetration model in MSCSurv (see Fig. 1) use the same geometric model and ballistic limit curves as the BUMPER computer program that NASA employs to calculate spacecraft probability of penetration. By tallying the fraction of module impacts resulting in a penetration within MSCSurv and combining this information with the expected overall orbital debris flux from NASA environment models,[14,13] MSCSurv can be used to estimate the total number of penetrations and overall probability of penetration (and probability of no penetration) through the use of

$$P_{pen} = 1 - \exp(N_{pen}) \tag{3}$$

Table 2 shows a comparison of probability of no penetration (PNP) from both BUMPER and MSCSurv for the International Space Station (ISS) modules. The calculation was made using the 1991 orbital debris environment[15] estimate for the year 2001, a solar flux of 70 L, and an orbital inclination of 51.6 deg (Refs. 2 and 4). The essentially identical results in PNP produced by both of the models verifies (to the extent that the BUMPER program is verified) the inherent accuracy of the MSCSurv geometry, impact, penetration, and damage subroutines.

Balancing P_{pen} vs $P_{loss/pen}$

MSCSurv provides only half of the information required to assess the probability of station or crew loss. The values of $P_{loss/pen}$ in Table 1 must be multiplied by appropriate P_{pen} (or N_{pen}) values to obtain the total value of P_{loss},

$$N_{loss} = N_{pen} \times P_{loss/pen} \tag{4}$$

Thus, Eq. (2) can also be written as

$$P_{loss} = 1 - \exp(N_{loss}) \tag{5}$$

Table 3 presents values for all three terms in Eq. (2) (P_{pen}, $P_{loss/pen}$, and P_{loss}) for the five different modules considered herein. Probabilities of penetration P_{pen} are provided from BUMPER results shown in Table 2 (Ref. 4). Note that even though the $P_{loss/pen}$ term is higher for modules with more effective shields (such as the U.S. laboratory and habitation modules), the decreased likelihood of penetration resulting from use of these shields in these modules lowers their overall P_{loss} values.

Thus, we see that the stronger shields will result in lower overall P_{loss} values despite their higher $P_{loss/pen}$ values. There are, of course, more than five modules in the ISS. However, the trends evident in the modules considered herein are expected to exist upon application of MSCSurv to the entire ISS module system. Furthermore, it is important to note that, although lowering the $P_{loss/pen}$ value can also lower the overall P_{loss} value, there is a larger uncertainty associated with $P_{loss/pen}$ calculations than with P_{pen} calculations. This larger uncertainty is due to the larger number of random variables and lower confidence in the internal damage equations used in $P_{loss/pen}$ calculations as compared to the equations used in the P_{pen} calculations. Therefore, qualification of spacecraft shields should be based largely (if not entirely) on probability of penetration calculations. By lowering the likelihood of penetration P_{pen}, enhanced shields also lower the expected cost of repair and downtime that are associated with penetrations. Although not directly related to immediate crew safety, the lowered cost expectation from the reduced penetration likelihood associated with using enhanced shields on habitable spacecraft modules should not be ignored in making spacecraft shielding design decisions.

Conclusions

The prominent benefit in calculating the $P_{loss/pen}$ term is its ability to provide quantitative data based on which internal equipment designs and crew operational procedures will result in the highest safety following orbital debris penetration. This study indicates that providing crew with a hole detection system and a portable breathing apparatus increases survivability following an orbital debris penetration. Furthermore, closing hatches on selected unoccupied modules before a penetration and isolating the depressurizing module as quickly as possible following a penetration can add additional benefits to survivability.

Spacecraft design should always balance penetration avoidance (minimizing P_{pen}) with limiting the effects of a penetration (minimizing $P_{loss/pen}$) to achieve lowest overall P_{loss}. Because of 1) the larger number of random variables and lower confidence in the internal damage equations used in $P_{loss/pen}$ calculations as compared to the P_{pen} calculations and 2) the avoidance of repair and downtime costs that are associated with avoiding penetration, stronger overall reliance should be placed on reducing P_{pen} through the use of enhanced shields or spacecraft design rather than on reducing $P_{loss/pen}$ when lowering the overall P_{loss} value. However, quantifying $P_{loss/pen}$ offers opportunities to lower P_{loss} through changes in spacecraft crew operations and in internal equipment layout/design, many of which may be made to spacecraft such as the ISS at little or no additional launch weight. NASA's MSCSurv computer code allows the user tremendous flexibility in evaluating these options for maximizing spacecraft and/or crew safety following an orbital debris penetration. Further studies in these areas are ongoing.

Appendix: MSCSurv Input File for Baseline Simulation

This file was written at 12:08 on 11/3/1997
These inputs were read from the Batch File case 1 cap.in
Number of penetration = 100000.
1994 0.1 cm to 20 cm Orbital Debris Environment

Particle Diameter That Causes Immediate Crack Loss = 5.00 cm
Schonberg/Williamsen Hole/Crack Size Model
Hole Size Crack Multiplier = 2.00
When The Alarm Sounds The Crew Goes to a Central Assembly Point in SERVAFT Module at Space Station 1.
Following Check-in Crew Goes Directly To EVS
The Time Required To Determine Which Side of The PMA/TUG Hatch The Leak is on = 120.00 seconds
After Completing The Half Station Isolation Exercise, The Crew Continues The Ordered Closure Protocol. The Time Required To Perform a Pressure Check After Each Hatch is Closed = 120.00 seconds
If The Hole is on The US/ESA/JEM Side of The Station
The Crew Shuts Hatches in This Order:
12 JEM-JELM
11 NODE2-JEM
10 NODE2-PMA2
9 NODE2-ESA
3 LAB-NODE2
2 NODE1-LAB
7 HAB-PMA3
6 NODE1-HAB
5 NODE1-AIR
4 NODE1-CUP
1 PMA1-NODE1
If The Hole is on The Russian Side of The Station The Crew Shuts Hatches in This Order:
13 PMA1-FTUG
14 FTUG-DSTW
15 FTUG-SFWD
17 SFWD-SPP1
24 SAFT-SFWD
16 SFWD-UDM
22 LIF1-LIF2
20 UDM-LIFE1
19 UDM-RSRC2
18 UDM-RSRC1
21 UDM-DKCMP
Escape Vehicle 1 Located at Module UDM
Escape Vehicle 2 Located at Module DKSTOW
The Modules Assigned as Critical are: SERVAFT
The Crew Movement Rate for Searching for Injured Crewmembers = 1.00 ft/sec
The Time Required for Stabilization of Injured Crewmembers = 300.00 sec
The Crew Movement Rate for Removal of Injured Crewmembers = 1.00 ft/sec
The Pressure at Which Fog Will Form = 11.80 Psi
Once Fog Forms, the Crew Movement Rates Will be Reduced by Multiplying by the Factor: .50
The Maximum Sustainable Armstrength for Crewmemebers = 50.00 Force Lbs.
The Delay Prior to Initiating Movement if Awake = 10.00 sec
The Delay Prior to Wake and Initiate Movement if Asleep = 30.00 sec
The Delay Put on the Crew Oxygen Masks = 30.00 sec
The Time Needed to Discuss Crew Injury Status at Intercoms = 60.00 sec
The Time Needed to Complete Checkout Procedures for EVS = 300.00 sec
The Minimum Interior Cabin Pressure Which Will Activate the Alarm = 13.90 Psi
The Minimum Time at which the Crew Will Give Up All Activities and Immediately Move to and Egress Via the Escape Vehicles = 300.00 seconds
The Minimum Interior Cabin Pressure at Which Hypoxia Will Set in = 9.50 Psi
The Time Required to Close a U.S. Hatch = 30.00 sec
The Time Required to Close Russian Hatch = 60.00 sec
All Hatches are Open for Daytime Operations
All Hatches are Open for Nighttime Operations
The Number of Crew = 6
Daytime Crew Locations are Randomly Assigned
Nighttime Location for Crewmember 1 is: SERVAFT Module at Station 1
Nighttime Location for Crewmember 2 is: SERVAFT Module at Station 3
Nighttime Location for Crewmember 3 is: SERVAFT Module at Station 5
Nighttime Location for Crewmember 4 is: US HAB Module at Station 1
Nighttime Location for Crewmember 5 is: US HAB Module at Station 3
Nighttime Location for Crewmember 6 is: US HAB Module at Station 5
Effect of Internal Shielding by the Equipment Racks is Included
Military Survivability Relationship Used for Probability That Person Injured by Fragment Is Immediately Lost Due to Fragmentation Injury.
Military Survivability Relationship Used for Probability That Person Injured by Fragmentation Is Lost (Due to Fragmentation Injury:EITHER Immediately or After Rescue.
The Discharge Coefficient = .90
The Roll Angular Velocity Limit (deg/sec) is 3.00
The Pitch Angular Velocity Limit (deg/sec) is 3.00
The Yaw Angular Velocity Limit (deg/sec) is 6.00
The Time required to prepare the Escape Vehicles for launch = 300.00 seconds
When Analyzing Thrust Forces, the S3/S4 Interface is not Included as a Catastrophic Failure.

References

[1]Ball, R. E., *Aircraft Combat Survivability*, AIAA, New York, 1985.

[2]Evans, H., Blacklock, K., and Williamsen, J., "Manned Spacecraft and Crew Survivability (MSCSurv) Version 4.0 User's Guide," Sverdrup Technology, Inc., Rept. 651-001-97-006, Huntsville, AL, Sept. 1997.

[3]Williamsen, J. E., "Vulnerability of Manned Spacecraft to Crew Loss from Orbital Debris Penetration," NASA TM-108452, April 1994.

[4]Hyde, J. L., "International Space Station Integrated Meteoroid and Debris Threat Assessment, Issue D," Lockheed Martin Missiles and Space Co., Inc., Mission Systems Rept. 32316, Houston, TX, Oct. 1996.

[5]Christensen, E., "Design and Performance Equations for Advanced Meteoroid and Debris Shields," *International Journal of Impact Engineering*, Vol. 14, No. 1–4, 1993, pp. 145–156.

[6]Burch, G. T., "Multiplate-Damage Study," Air Force Systems Command, Rept. AFATL-TR-67-116, Sept. 1967.

[7]Lutz, B., and Goodwin, J., "Catastrophic Failure Modes Assessment of the International Space Station Alpha," NASA CR-4720, Feb. 1996.

[8]Williamsen, J., Grosch, D., and Schonberg, W., "Empirical Prediction Models for Hole and Crack Size in Space Station Manned Modules at Impacts from 6 to 12 km/sec," *Proceedings of the Space Environment and Safety Symposium: Characteristics and Consequences of Orbital Debris and Natural Space Impactors*, edited by T. Maclay and F. Allahdadi, Vol. 2813, International Society for Optical Engineering (SPIE), 1996, pp. 28–38.

[9]Bloom, B., Goodwin, J., and Lutz, B., "Integrated Meteoroid and Orbital Debris Assessment," Grumman SSEIC Activity Rept. GSS-310-M093-084, Grumman Corp., May 1993.

[10]Serrano, J., Liquornik, D., and Schonberg, W. P., "Vulnerability of Space Station Freedom Modules: A Study of the Effects of Module Perforation on Crew and Equipment," NASA CR-4716, Feb. 1996.

[11]Sperrazza, J., and Kolkanis, W., "Criteria for Incapacitating Soldiers with Fragments and Flechettes," U.S. Army Ballistics Research Lab., Rept. 1269, Aberdeen Proving Ground, MD, Jan. 1965.

[12]Weibull, G., "A Proposal for Blast Incapacitation Criteria Concerning Soldiers Inside Armored Vehicles," *Proceedings of the 9th Ballistics Symposium*, American Defense Preparedness Association, 1986, pp. 141–152.

[13]Coronado, A. R., Gibbins, M. N., Wright, M. A., and Stern, P. H., "Space Station Integrated Wall Design and Penetration Damage Control," Final Rept., NASA Contract NAS8-36426, July 1986.

[14]Anderson, J., and Smith, R., "Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development," NASA TM-4527, June 1997.

[15]Kessler, D., "Update to the Orbital Debris Environment for Space Station," NASA Johnson Space Center, Memo SN4-94-164, Houston, TX, Nov. 1994.

A. C. Tribble
Associate Editor