CR-97-
NASA/TM-112981

ASSESSMENT AND MANAGEMENT OF THE RISKS OF DEBRIS HITS DURING SPACE STATION EVAs

Elisabeth Paté-Cornell
Professor of Industrial Engineering and Engineering Management
Stanford University, Stanford, California
and

Marc Sachon
Doctoral Student
Department of Industrial Engineering and Engineering Management
Stanford University, Stanford, California

August 1997

Research Report # 97-1
Stanford University
Department of Industrial Engineering and Engineering Management
Stanford, California 94305-4023

FINAL REPORT
NAG2-980

C.A.S.I.
202A-3

TABLE OF CONTENTS

FIGURES

TABLES

SECTION 1

INTRODUCTION

1.1 EVA RISK: THE ROLE OF SPACE DEBRIS

The risk of EVAs is critical to the decision of whether or not to automate a large part of the construction of the International Space Station (ISS). Furthermore, the choice of the technologies of the space suit and the life support system will determine (1) the immediate safety of these operations, and (2) the long-run costs and risks of human presence in space, not only in lower orbit (as is the case of the ISS) but also perhaps, outside these orbits, or on the surface of other planets. The problem is therefore both an immediate one and a long-term one. The fundamental question is how and when to shift from the existing EMU system (suit, helmet, gloves and life support system) to another type (e.g. a hard suit), given the potential trade-offs among life-cycle costs, risks to the astronauts, performance of tasks, and uncertainties about new systems' safety inherent to such a shift in technology. A more immediate issue is how to manage the risks of EVAs during the construction and operation of the ISS in order to make the astronauts (in the words of the NASA Administrator) "as safe outside as inside".

For the moment (June 1997), the plan is to construct the Space Station using the low-pressure space suits that have been developed for the space shuttle. In the following, we will refer to this suit assembly as EMU (External Maneuvering Unit). It is the product of a long evolution, starting from the U.S. Air Force pilot suits through the various versions and changes that occurred for the purpose of NASA space exploration, in particular during the Gemini and the Apollo programs. The Shuttle EMU is composed of both soft fabrics and hard plates. As an alternative to the shuttle suit, at least two hard suits were developed by NASA: the AX5 and the MRKIII. The problem of producing hard suits for space exploration is very similar to that of producing deep-sea diving suits. There was thus an opportunity to develop a suit that could be manufactured for both purposes with the economies of scale that could be gained from a two-branch manufacturing line (space and deep sea). Of course, the space suit would need to be space qualified. Some of the problems in adopting one of the hard suits were first that the testing had to be completed, and second that it required additional storage space. The decision was made not to develop a hard suit in time for the construction and operation of the ISS. Instead, to improve the safety of the current suit, it was decided to reinforce the soft parts of the shuttle EMU with KEVLAR linings to strengthen it against debris impacts. Test results, however, show that this advanced suit design has little effect on the penetration characteristics (Cour-Palais, 1996).

The advantage of the existing EMU design is that it is a mature technology. It has the familiar flexibility of fabric and a relatively small mass, it can be stowed in a smaller space and it does not require major further development costs. The downsides of the current suit are that the soft parts are more vulnerable to space debris than the hard plates or the hard suits, that the current (improved) shuttle EMU is very costly to manufacture and maintain, and that its low pressure may affect the performance of the astronauts. Both the AX5 and MRK III are more robust but are bulky and have more mass than the current space suit. In the long run, an alternative solution will probably have to be developed anyway for the work that will be done in Earth's orbits and for planetary exploration. NASA, however, may face political as well as economic and technical constraints in that decision.

The problem of EVA safety has changed slightly in recent years because the density of space debris in low-earth orbit (up to 1,000 km above the Earth's surface) has increased markedly and is likely to continue to increase. The hard plates of any suit are not invulnerable to these debris hits if the debris particles are large enough, but the soft fabrics, which at this time constitute about 2/3 of the total exposed surface of the EMU, are definitely more vulnerable. Debris 0.4mm in diameter and above can result in fatal accidents, especially (depending on their shape) if they hit the fabric perpendicularly to the surface.

Debris hits, of course, are not the only source of failure risk in EVAs. In a risk analysis model developed for EVAs out of the space shuttle (Paté-Cornell, 1994) and adapted in this report for the construction of the ISS, eight *accident types* were identified:

- Suit failures
- Separation
- Airlock failures
- Life support system failures
- Radiation accidents
- Industrial accidents
- De Novo events (medical emergency that is independent of the system's performance)
- Fire in the suit

For each accident type, accident scenarios were analyzed, starting from the initiating events and ending with outcomes that were characterized along two dimensions: the state of the astronaut at the end of the incident/accident, and whether or not the mission for which the

EVA was done was accomplished. In the 1994 study, we used statistics when available. There were, however, very few such data. Therefore, we relied heavily on expert opinions (including those of astronauts and of the NASA technicians involved in each of the subsystems) to come up with a risk estimate and the risk contribution of the different failure modes. The overall result suggested that the risk of a typical shuttle EVA is comparable to the risk run by the astronauts for each Shuttle mission (in other terms that an EVA doubles the individual risk of a Shuttle flight). This result is consistent with the result cited by the General Accounting Office in a memo to the Administrator dated April 1992 (Gebicke, 1992). Based in large part on expert opinions, we also found that the probability of an astronaut's death due to debris hits was in the order of 2.5x 10-4 per EVA.

Space debris and micro-meteorites, therefore, contribute only part of the risks of EVAs. They are, in fact, only a part of the failure mode "suit failure" which includes other initiating events such as a seam failure or a joint restraint failure. Based on the very soft data that we used in this previous study for illustrative purposes, we estimated that suit failure accounted for about 20% of the overall probability of an incident (initiating event, followed or not by an accident). In turn, space debris represented only 5% of the probability of incidents affecting the space suit. Clearly, the construction and maintenance of ISS requires EVAs in which the astronauts will often be more exposed to particle flux than in the cargo bay of the Space Shuttle. Also, current estimates show that the flux of orbital debris present in the ISS's orbit will be increasing in the future.

In the present study, we computed the risk of an EVA accident due to debris and micro-meteorites for the construction and maintenance of the ISS for a total of about 3,000 man hours of EVA. It is therefore clear that the results that we obtained and that we present further in this report represent only a fraction of the overall EVA risks.

1.2 THE CHALLENGE OF MANAGING NEW EVA TECHNOLOGY DEVELOPMENTS

The goal of a complete risk analysis in the EVA context is presumably (1) to support management decisions regarding the use of EVAs and the design of EVA missions, and (2) to help decide whether or not to develop a new, less vulnerable space suit for activities in LEO or planetary exploration.

The problem of whether and when to develop a new EVA technology is a general one. A technology may become obsolete and need improvements. Gradually improving the old system presents the advantage of avoiding the new development costs and the risks inherent to infancy problem in radically new systems. The problem, however, is that the costs of the old technology over the lifetime of the project may be much higher than what a new solution might permit and also, that some aspects of the risks might be better handled by a new system. In the case of space suits, NASA contemplated for a long time the possibility of a shift to a hard suit. The decision was finally made to use the existing EMU because it was then too late and too costly to finish the development of a new suit design in time for the beginning of the construction of the space station. Now the question is whether the existing system is safe enough for the duration of the anticipated EVA needs related to the ISS.

At the same time as these decisions were made, the number of EVA hours considered necessary for the construction of the space station grew in the planning stage from about 300 initially, to about 600 a few years ago, and to 905 in May 1997. In addition to these, further hours of EVA will have to be spent for maintenance and perhaps unforeseen events during the planned 10 year life-time of the ISS. Currently, NASA expects a total of 2,000+ EVA man-hours during the life-span of ISS. The question is whether the actual length of the EVA work will increase substantially, and whether the resulting risks are acceptable with the currently available (and somehow upgraded) shuttle EMU. In general, the optimal timing of a technological shift depends (1) on the initial cost of the shift, (2) on the costs of operation and maintenance of the old technology, (3) on the risks associated with the operation of the old system, (4) on the infancy risks associated with the introduction of the new system, and (5) on the expected performance and safety level of the new system in the long term.

The decisions that remain to be taken by NASA concerning the construction of the ISS are thus no longer whether or not a new system will be used (the old, improved one will), or whether the buddy system will remain in effect (all EVAs will involve at least two astronauts). There may, however, be some further decisions to add EVA hours to the construction operations, some decision involving the relative position of the astronaut and the station, and opportunities to provide some shielding against directed orbital debris (as opposed to ambient micro-meteorites). In the long run, the question of whether to continue with the current space suit is likely to resurface and to have to be addressed again in terms of costs, risks, and performance.

The objective of this study is to present a risk analysis methodology, focusing on orbital debris and micro-meteorites, illustrated with the current data available from the different space centers and from the main suit contractor in order to support further decisions concerning the use of EVAs during the construction of the station. In Section 2, we present a general risk analysis model for EVAs during the space station construction and operations. This model which involves all anticipated failure modes is adapted from the probabilistic model that was developed a few years ago for the shuttle EVAs (Paté-Cornell, 1994), accounting for a different environment, the number of planned EVA hours, the current information about debris and micro-meteorites and the modifications that have been made to the current suit. This model allows placing the debris problem in the larger context of the different possible accident sequences. In Section 3, focusing on particle flux, we present the data available to us regarding the flux of debris in lower orbit ("loads"), and the resistance ("capacities") of the different parts of the shuttle EMU to debris of different masses, velocity, shape and impact angle. We describe the results of studies performed at Johnson Space Center (JSC). In Section 4, we present our model and the data that we use. The main difference between our model and the current ones is that we also consider the possibility of penetration/resistance of hard plates, and the effect of passive shielding by the shuttle or by the ISS. In conclusion, we discuss the limitations and uncertainties of our model. We identify the areas where further data gathering will be necessary and we examine some of the potential implications of our results for the analysis of EVA management options in the ISS context.

SECTION 2

AN OVERALL RISK ANALYSIS MODEL FOR EVAs DURING THE CONSTRUCTION OF THE SPACE STATION

Although the focus of this report is on the effect of debris and micro-meteorites on the risk of EVAs during the construction of the Space Station, this portion of the total EVA risk needs to be put in perspective. In this section, we present an overall risk analysis model that allows computation of the total EVA risk, to which particle penetration may contribute only a small portion.

2.1 ACCIDENT TYPES

The structure of this overall model relies on the identification of a set of accident types similar to those that were used in the shuttle EVA risk study. These accident types are assumed to be mutually exclusive and collectively exhaustive (see Table 2.1-1).

AT_1: ***Suit, glove or helmet failure leading to decompression*** of different severity levels (from minor leak to sudden, catastrophic and total) Includes impact of space debris and micro meteorites as initiating events.

AT_2: *Separation* (astronaut drifting away from planned site, due either to mechanical failure or to human error)

AT_3: *Airlock failure* (e.g., failure of the hatch, the structure, or the pressure valves)

AT_4: ***Life Support System failure*** excluding the pressure maintenance systems (included in AT1): breathing problems, thermal system and communication failures, includes impact of space debris and micro meteorites as initiating events

AT_5: *Radiation accidents.*

AT_6: *Industrial accidents* (e.g., glove stuck in equipment, astronaut hit by a tool)

AT_7: *"De novo"* events (new medical events that could occur elsewhere as well; e.g., cardiac failure or nausea)

AT_8: *Fire inside the suit* caused by oxygen ignition (initiated by short circuit or frictions)

AT_I in bold: Accident types involving particle penetration

Table 2.1-1: Classification of accident types (AT_i) for the PRA model (Paté-Cornell, 1994)

Two of the accident types involve impact by debris and micro-meteorites as possible initiating events: AT1 (failure of the suit, glove or helmet), and AT4 (failure of the life support system). The overall risk analysis model can be represented by the influence diagram of Figure 2.1-1.

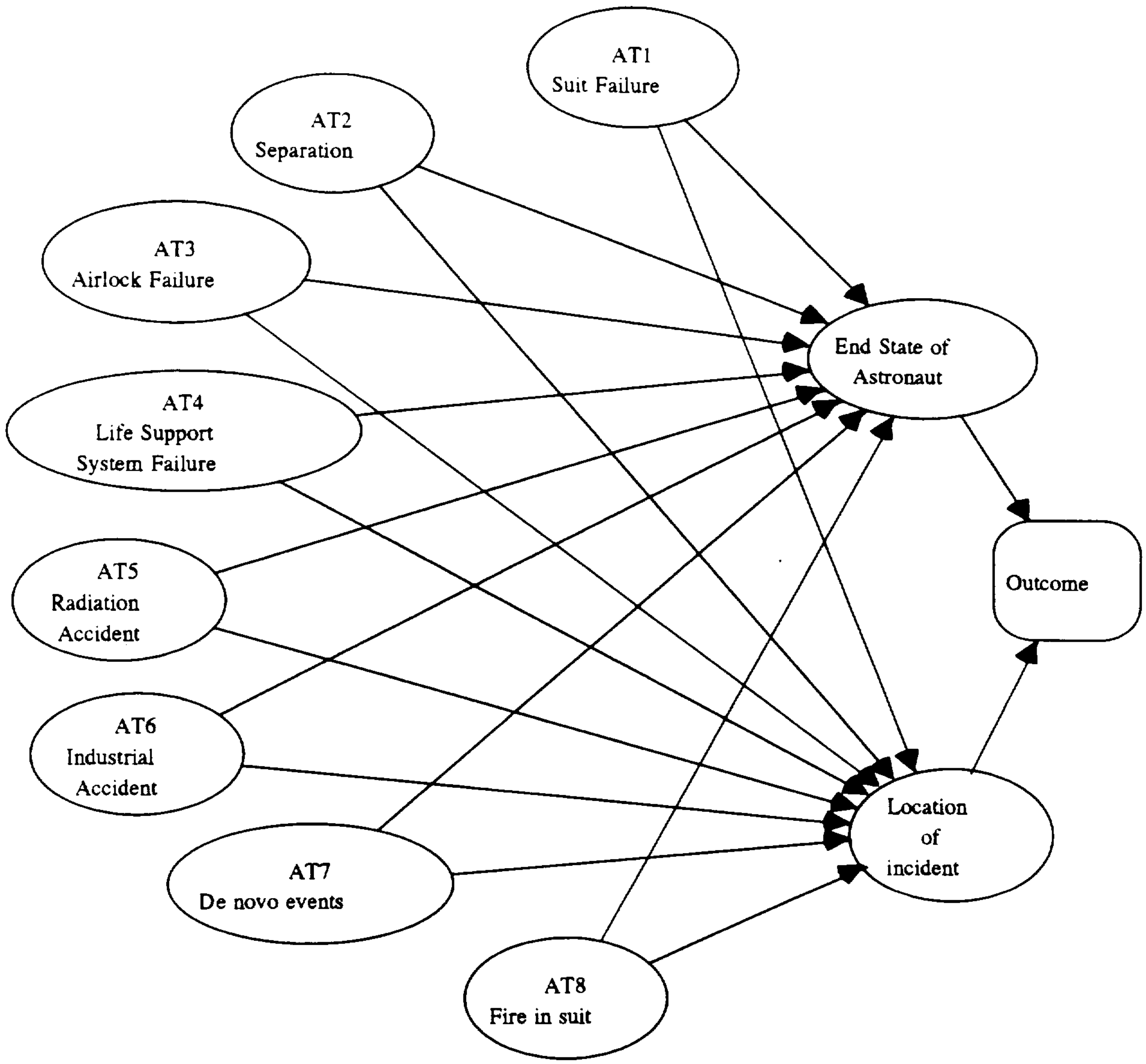


Figure 2.1-1: Influence diagram of overall model of accident types and outcomes (state of the astronaut and status of the mission, i.e., EVA job).

2.2 OUTCOMES

The model of Figure 2.1-1 indicates that the state of the astronaut and the status of the EVA job given an initiating event depends on the accident type (characterized by its level of severity), and on the location of the incident (described by the distance between the astronaut and the closest airlock). The outcomes of the possible accident scenarios are described in Table 2.1-2 They are defined by the state of the astronaut (death or severe brain damage, alive or light injury), and the status of the EVA work (accomplished or canceled).

We do not explicitly consider here property or equipment damage, or less severe astronaut injury. The models, however, can be easily extended to several intermediate states if justified.

OC1:	Recovery (with or without minor astronaut injury). EVA work accomplished (Code notation: AOK, WA)
OC2:	Loss of EVA work without astronaut casualty (no death or serious injury) (AOK, WO)
OC3:	Astronaut casualty without loss of EVA work (AD, WA)
OC4:	Loss of EVA work with astronaut casualty (AD WO).

Table 2.1-2: Outcomes of the possible accident scenarios

2.3 ACCIDENT SCENARIOS

For each accident type (e.g., decompression), failure scenarios are analyzed. This analysis starts with each possible *initiating event* (i.e., the first incident that starts the accident process in orbit), then the *sequences of events* that can follow this initiator, ranging from the detection and fixing of a minor problem to a catastrophic event from which recovery is impossible. This second phase can involve a dynamic analysis based on stochastic processes since the time factor is often critical to human survival. For each sequence of events, one computes the probability that it ends in several possible consequence categories, conditional on the initiating event. The probability of each scenario is obtained by multiplying the marginal probability of the initiating event and the probabilities of different outcomes conditional on the initiating event. This is done by multiplying the probabilities of a sequence of intermediate events and variables, all conditioned on those that precede them in the scenario.

2.4 PROBABILITY COMPUTATION

The probability of each outcome is then computed by summing the probabilities of the accident sequences leading to that outcome. One may want to proceed to further treatment of uncertainty by defining, instead of the probability of various outcomes per EVA, the future frequencies of the different outcomes and treating these future frequencies as random variables. This approach may be desirable to provide a measure of the uncertainties involved given that there is little information on EVA risk. For simplicity, however, this preliminary study is limited to first-order probabilities per flight.

The success or failure of a mission conditional on the occurrence of an incident is linked to the location of the astronaut at the time of the initiating event. The different phases of the EVA are defined as shown on the time axis of Figure 2. "δt" represents the very short time following the exit of the airlock when a decompression accident can occur if there is a defect in the space suit itself, or if it has not been properly assembled. For each of the EVA phases, an important factor in the assessment of the probability of particle hits is the level of shielding given the position of the astronaut with respect to the space station or to the cargo bay of the space shuttle (at the beginning of the construction program).

Notations:

AT_i: Accident types

IE_{ij}: Initiating events (indexed in ij) within each accident type

OC_k: Outcomes (Four classes and indexed in k)

p(.): Probability of an event

p(.|.): Conditional probability of second event given the first

p(.,.): Joint probability of two events.

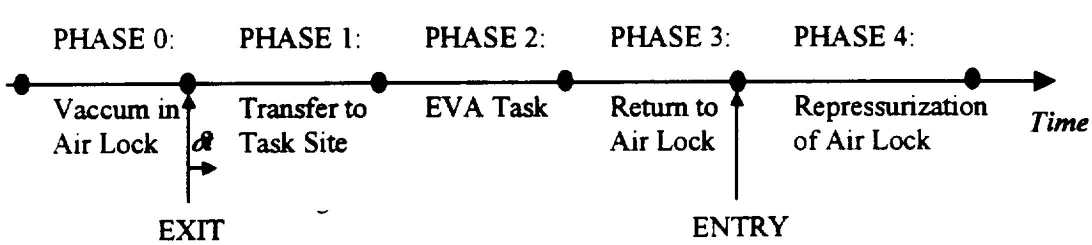


Figure 2.4-1: Different phases of the EVA (Phase 0 to Phase 4)

Assuming that the initiating events within each accident type are mutually exclusive and collectively exhaustive, the probability of each accident type is the sum of the probabilities of the initiating events that trigger the accident type:

$$p(AT_i) = \sum_j p\,(IE_{ij}) \qquad (2.1\text{-}1)$$

The risk is characterized by the overall probability distribution of the outcomes described by the four possibilities of Table 2. The overall probability of each outcome is the sum for all accident types of the probabilities of outcome *and* accident type:

$$p(OC_k) = \sum_i p(AT_i) \times p(OC_k |\, AT_i) \qquad (2.1\text{-}2)$$

Therefore, characterizing each accident type by its set of initiating events:

$$p(OC_k) = \sum_i \sum_j p(IE_{ij}) \times p(OC_k | IE_{ij}) \qquad (2.1\text{-}3)$$

The initiating events (IE_{ij}) for each accident type AT_i are subdivided into several categories (severity level, incident characteristics, etc.). Each of accident initiators is then described by its possible realizations. For instance, one of the initiating events of AT_1 (failure of the suit, glove or helmet) is the impact of debris or micro-meteorites. It could be subdivided into different event categories describing both the size of the particle and the angle of impact.

At the time of the space shuttle EVA study (1994), no angles of impact were considered for particle penetrations of the EMU. Yet, when focusing on the effect of particle hits on the space suit, the impact angle is likely to play a role: a shallow angle may permit the particle to be reflected by the surface. The probability of a hit of different categories depends on the time spent by the astronaut at different levels of shielding, which itself may depend on the phase of the EVA as shown in Figure 2.1-2. The effect of shielding on the EVA outcome depends both on the part of the suit that is hit (soft goods vs hard plates) and, for a severe but survivable hit, on the distance to the airlock, as the time available to bring the astronaut back to Station pressure might be critical.

Each of the accident types and each of the initiating events within an accident type may require a different risk analysis model. Some of these models are described in the 1994 report by their respective influence diagram and apply to the ISS as well (e.g., separation).

SECTION 3

PENETRATION RISKS OF EMU: CURRENT STATE OF RESEARCH

A great deal of research has taken place in the different space centers to gather the information necessary for the analysis of the contribution of orbital particles to the EVA risk. In this section, we summarize the state of these data.

During some EVA operations, the astronauts will operate outside the protection of the space shuttle or the ISS, exposing themselves to the particle flux of orbital debris and micro-meteorites present in LEO. For safety purposes, two astronauts will be active at the same time in the vicinity of the space shuttle or the space station (the buddy system). Current estimates for the total amount of EVA man-hours are in the range of 2,600h (i.e. 2 astronauts at 1,300h each). As mentioned earlier, this number has changed in the past and we expect it to be modified again in the future. There is a direct relation between probability of particle penetration for the EMU and total EVA time, albeit not necessarily a linear one as particle flux is expected to vary in the future. It is therefore important to assess the probability of particle hits and penetrations during EVA operations for the management of both the shuttle EVAs and the construction of the space station.

Models of both orbital debris and micro-meteorite flux have been developed by NASA. Employing these models, we can calculate the probability of particle hits for objects orbiting in LEO. Given the probability of a particle hit, its energy, and the penetration characteristics of the EMU, we can calculate the probability of penetration. Unfortunately, there are still large areas of insufficient knowledge concerning the materials and physical processes involved (e.g. penetration of different suit materials at different velocities and impact angles). This gap calls for extensive research in the area of particle flux and space suit impact characteristics. The particle flux present in LEO varies with altitude and, to a lesser extent, with inclination. While the flux stemming from meteorites and large debris is well documented, the same is not true for small and medium orbital debris (less than 10cm in diameter) which can be critical to EVA safety. More research into the sources of small and medium debris is needed.

In this section we analyze the loads and the capacities of the system under consideration. The loads considered here are the particles impacting the EMU, i.e. the micro-meteorite and orbital debris particle flux. The capacity of the system is the suit's ability to withstand the impacts of these particles without losing its ability to provide life support for the astronaut. Once the load exceeds the capacity, the system fails. Generally, the probability of system failure can be expressed as follows:

p(Failure) = p(Loads > Capacities, over total exposure time)

It is therefore important to have reliable data for the system's capacity and the loads to which it might be exposed over time. Uncertainties about the loads (or capacity) automatically result in uncertainties about the probability of failure[1].

3.1 LOADS: THE FLUX MEASUREMENTS

The particle flux to which astronauts are exposed in LEO consists of micro-meteorites and orbital debris. Meteorites are natural objects orbiting the sun and passing through the earth's orbit. Orbital debris are man-made objects in Earth orbit that are non-functional. They include spent rocket bodies, nonfunctional spacecrafts, fragmentation debris and mission-related debris (e.g. exhaust products from solid rockets). Generally, micro-meteorite particles are of lower density than orbital debris (roughly by a factor of 2), but travel at higher velocity.

Micro-meteorite flux is dependent on the altitude and inclination of EVA operations as well as calendar time (solar activity). Orbital debris flux depends on altitude and inclination of EVA activities and on recent orbital incidents. As a result of these parameters, the flux of particles will vary over the life time of the space station (mainly due to the meteorite flux related to solar activity and additional orbital debris). Current estimates predict that during the scheduled life of the ISS, the particle flux will be at its peak in 2009. The models developed by NASA for particle flux in LEO take these variations and other particle characteristics into consideration. The US Space Command monitors and catalogues all known objects in LEO that are of diameter 10cm or larger. For smaller sizes, however, no exhaustive monitoring is possible and only samples of the population can be taken (allowing to estimate the population size).

[1] By this we mean uncertainty about the probabilities – having an estimate of p(Failure) = 25% to 30% clearly is superior to having an estimate of p(Failure) = 20% to 60%

Size	Number of Objects	Percent Number	Percent Mass
10- cm	*8,000*	*0.02%*	*99.93%*
1 - 10 cm	*110,000**	*0.31%*	*0.035%*
0.1 - 1 cm	*35,000,000**	*99.67%*	*0.035%*
Total	35,118,000	100.00%	2,000,000 kg

Source: G.M. Levin, Office of Space Flight, 1996

*Statistically estimated value

Table 3.1-1: Estimated Debris Population

Due to increasing space activity, the amount of orbital debris will increase at a rate greater than the natural decrease due to atmospheric re-entry. With an increasing number of spacecraft orbiting Earth, the probability of collisions of spacecraft also increases (e.g. collision of satellites 18208 and 23606 on July 24th, 1996). Debris clouds resulting from these collisions are considerable and pose a threat to other orbiting objects.

In its 1995 Interagency Report, the National Science and Technology Council published estimates of orbital debris and meteorites orbiting Earth at altitudes of up to 2,000km. It is estimated that 1,000 kg of mass is orbiting Earth in the form of debris of diameter sizes of less than 1.0 cm, 300 kg of which are attributable to orbital debris smaller than 0.1 cm in diameter. The total mass of meteorites in these orbits is estimated at 200kg. This makes the orbital debris environment more hazardous than the micro-meteorite environment.

Data retrieved from space-shuttle flights show that during a total of 592 mission days, 313 relevant impacts took place in the windows area of the shuttle (i.e. producing pits or even window replacements). The total window area of the shuttle is 3 m^2, which is comparable to the surface area of the EMU and therefore a first estimate for the number of expected impacts. Two of these shuttle window impacts would have had sufficient energy to penetrate the soft parts of the EMU. The effect of shielding, however, may be different for the shuttle windows and astronauts during planned shuttle EVAs.

3.2 CAPACITIES: EMU VULNERABILITY TO PARTICLE HITS

During EVAs, the EMU has to provide astronauts with life support while protecting them against the environment. One of the environmental threats is that of being hit by a high-velocity particle. The space suit currently used by NASA consists of various types of materials. Its penetration characteristics can be broadly categorized into soft parts and hard parts. Soft parts are parts that are only protected by the Thermal Meteorite Garment (TMG) and that are not covered by metal or plastic plates. With the current design, roughly 2/3 of the suit's surface area consist of soft parts. Soft parts are used to cover the feet, legs, arms and hands of the astronaut. These areas are more easily penetrated by high-velocity particles than hard parts. The soft parts of the EMU can support a hole of not more than 4mm in diameter for 30 minutes (i.e. the astronaut will have sufficient oxygen pressure during that time). Any hole larger than this would be critical.

The following table shows the surface areas for the parts that constitute the space shuttle suit (Cour-Palais, 1996). The element's failure criteria are listed. For the elements consisting of TMA and bladder (soft parts), there are two failure criteria: a penetration hole of at least 4mm diameter, resulting in a critical incident – or a leak of less than 4mm in diameter, which would be non-critical. The 4mm threshold appears to be a step function, but in reality, it is not. For all other elements any spall or leak would be critical.

Suit Elements	**Material Layup**	**Failure Criteria**	**S. Area [m^2]**
Boots	*TMG+Bladder*	*NL & 4mm*	*0.46*
Gloves	*TMG+Bladder*	*NL & 4mm*	*0.10*
Lower Legs	*TMG+Bladder*	*NL & 4mm*	*0.60*
Upper Legs	*TMG+Bladder*	*NL & 4mm*	*0.26*
Lower Arms	*TMG+Bladder*	*NL & 4mm*	*0.38*
Upper Arms	*TMG+Bladder*	*NL & 4mm*	*0.28*
Waist Brief	*TMG+Bladder*	*NL*	*0.23*
Helmet&Visors	*Lexan+Polysulfone*	*NPS*	*0.21*
HUT	*TMG+Fiberglas*	*NPS*	*0.12*
D&CM	*TMG+1.6mm Alumin.*	*NPS*	*0.05*
PLSS: Valves etc.	*TMG+1.6mm Alumin.*	*NPS*	*0.31*
PLSS: CCC	*TMG+2.3mm Alumin.*	*NL & 4mm*	*0.07*
PLSS: Battery Cover	*TMG+0.46mm Alumin.*	*NPS*	*0.03*
PLSS: Primary Gox	*TMG+3.6mm Alumin.*	*NPS*	*0.24*
PLSS: Secondary Gox	*TMG+1.8mm Alumin.*	*NPS*	*0.24*
Sizing Rings	*TMG+3.2mm Alumin.*	*NPS*	*variable*

(NPS: No Perforation or Spall; NL: No Leak; HUT: Hard Upper Torso; D&CM: Display & Control Module; PLSS: Portable Life Support System; CCC: Containment Control Cartridge; GOX: Gaseous Oxygen)

Source: Cour-Palais, 1996

Table 3.2-1: The Space Shuttle Suit Elements

Hard parts consist of some form of metal sheet or plastic (in the case of the helmet), covered by the same TMG as the soft parts of the suit. Hard parts protect the LSS on the back of the astronaut, the display and control module on the chest of the astronaut as well as the astronaut's helmet.

To estimate the effect of high-velocity impacts (HVI) on soft parts, high-velocity impact tests have been performed at AMES. The tests subjected the suit material to impacts of nylon spheres (1.14 g/cc, representing micro-meteorite particles) and aluminum particles (2.78g/cc, representing debris particles). The test data were then analyzed and a functional relationship between the kinetic energy of the penetrating particle and the resulting hole diameter was developed (Cour-Palais 1996). These formulae are only applicable for the soft parts of the suits.

Shot Nr.	*Mat.*	*Diam.* [mm]	*Mass* [g]	*Speed* [km/s]	*Energy* [J]	*Angle* [deg]	*V.Energy* [J]	*Result* [Bladder]
A2905	Al	0.299	0.000311	6.85	5.25	0	5.25	No Hole
A2894	Al	0.300	0.000314	7.00	5.54	0	5.54	No Hole
A2896	Al	0.392	0.000701	6.90	12.01	0	12.01	No Hole
A2897	Al	0.404	0.000768	6.68	12.32	0	12.32	No Hole
A2900	Al	0.500	0.001456	7.03	25.88	0	25.88	No Hole
A2907	Al	0.600	0.002515	6.95	43.70	0	43.70	Pinhole
A2910	Al	0.599	0.002503	5.79	30.18	0	30.18	Hole (1.3mm)
A2911	Al	0.520	0.001637	4.35	11.14	0	11.14	No Hole
A2912	Al	0.794	0.005829	5.23	57.35	0	57.35	Hole (2.5x2.1mm)
A2929	Al	0.407	0.000785	6.95	13.64	30	11.81	No Hole
A2930	Al	0.495	0.001412	6.84	23.77	30	20.58	Pinhole
A2931	Al	0.608	0.002617	7.18	48.53	30	42.03	Hole (0.5mm)
A2932	Al	0.517	0.001609	5.66	18.54	30	16.06	Hole (0.8mm)
A2933	Al	0.404	0.000768	7.11	13.96	45	9.87	No Hole

(Specific mass of Aluminum: 2.7g/cm^3; Kinetic Energy: _ m v^2 with m measured in [kg] and v measured in [m/s])

Source: Kosmo, Joseph

Table 3.2-2: Results of HVI tests

For the hard parts of the suit (aluminum sheets, covered by TMG), no closed functional relationships have been developed so far. Instead, a combination of formulae is used: a formula derived by Fish and Summers in 1967 for the penetration of metal sheets and a formula for the penetration of the TMG (the same formula is used for the soft part of the suit). We use these formulae in section 4. Based on these formulae, Cour-Palais calculated the ballistic limits for the hard parts of the suit. These ballistic limits are estimates. At this point, there are no penetration tests available for the TMG covered hard parts of the suit.

3.3 CURRENT RESULTS

Calculations of probabilities of penetration rely on four sources: Hodgeson (1993), Cour-Palais (1996), ORDEM96 (1996) and SSP30425A (1991).

Hodgeson, an employee of Hamilton-Standard, the company that produces the current space suit, found that the probability of penetration of the hard parts of the EMU is negligible compared to the probability of penetration of the soft parts. Cour-Palais developed the formulae for penetration of the soft parts and the estimated the ballistic limits (i.e. the kinetic energy necessary for suit penetration) for the hard parts of the suit. Finally, ORDEM96 and SSP30425 are used for the calculation of the flux of orbital debris and meteorites in LEO, respectively.

Orbital Debris Impact at 10km/s:		
Diameter [cm]	**Mass[g]**	**Energy [J]**
0.03	0.0000	1.9156
0.04	0.0001	4.5406
0.05	0.0002	8.8685
0.06	0.0003	15.3247
0.07	0.0005	24.3350
0.08	0.0007	36.3252
0.09	0.0010	51.7208
0.10	0.0014	70.9476
0.11	0.0019	94.4313
0.12	0.0025	122.5975
0.13	0.0031	155.8720
0.14	0.0039	194.6803
0.15	0.0048	239.4483

Table 3.3-1: Impact energies of orbital debris particles

Cour-Palais (1996) provides formulae to calculate the kinetic energies necessary to penetrate the various parts of the EMU. For orbital debris, a level of 75 J would be sufficient to penetrate any part of the suit (including hard parts). From table 3.3-1 we conclude that any debris particle of diameter 0.11 cm and larger would have sufficient kinetic energy[2] for penetration. This means that a particle of little more than 1mm in diameter would penetrate any part of the EMU and most likely result in a fatal accident.

To obtain the ballistic limits for penetration of the hard parts, Cour-Palais used results obtained from HVI tests on aluminum sheets and the results obtained for the soft parts of the suit (penetration of the TMG). He then combined these data to calculate the results for hard parts, shown in table 3.3-2.

ORDEM96 is a FORTRAN-based computer code that can be run on DOS PC's. It was developed by Kessler et al. at JSC. The code requires various inputs concerning the object in orbit and takes into consideration a growth rate of orbital debris. The code's output is the flux data for a given range of particle diameters.

Suit Element	Failure Mode	Meteorite BL [J]	Debris BL [J]
Arms&Legs	No Leak	3.4	3.2
Arms&Legs	4 mm Hole	68.0	56.0
Boots&Gloves	No Leak	3.4	3.2
Boots&Gloves	4 mm Hole	68.0	56.0
Sizing Rings	No Spall/Leak	47.6	39.3
HUT	No Spall/Leak	70.0	44.0
Waist(Brief)	No Leak	3.4	3.2
Helmet&Visor	No Spall/Leak	167.0	71.0
D&CM	Not Critical	NA	NA
D&CM	No Spall/Leak	11.5	10.0
PLSS: Primary GOX	No Spall/Leak	75.0	60.4
PLSS: Secondary GOX	No Spall/Leak	15.4	13.4
PLSS: CCC	No Spall/Leak	25.5	21.4
PLSS: CCC	4 mm Hole	172.0	71.0
PLSS: Battery Cover	No Spall/Leak	3.5	3.5
PLSS: Valves etc.	Not Critical	NA	NA
PLSS: Valves etc.	No Spall/Leak	11.5	10.0

Source: Cour-Palais, 1996

Table 3.3-2: Ballistic Limits of Suit Elements

[2] We follow standard procedure and assume a relative velocity of 10km/s for orbital debris particles

SSP30425A (1991) was released by the Space Station Freedom Program Office in Reston, Virginia. It defines the natural environment for the space station's design. Paragraph 8 deals with meteorites and orbital debris. The formulae stated therein allow to calculate the flux of meteorites in LEO (the debris model of SSP30425 has been updated in ORDEM96 and therefore, we use ORDEM96 data to model the debris flux).

Based on SSP30425, Simonds (1996) developed a Monte-Carlo simulator that calculates the probability of no penetration for the soft parts of the space suit. Simonds computes the *probability of no penetration* (**PNP**) over a time period of 2,172 hours (estimate for total EVA during life-time of ISS) of EVA to be in the range 0.69 - 0.90. This result includes penetrations that are non-critical, due to their small size. Simonds' estimate for the *probability of no critical penetration*[3] (**PNCP**) over that time period is 0.984 - 0.994 (with a best estimate of 0.992).

At the Micro-Meteorite and Orbital Debris Summit organized by the EVA project office in June 1996, a limit of acceptable risk was defined. The probability of no penetration (PNP) was set to **PNP** = 0.92 over 10 years of operation of the US segment of the space station. Simonds' results indicate that this level cannot be obtained by the current design of the space suit. However, he also indicates that the AX-5 Ames space suit is superior to the current space suit in some of the critical aspects. He refers in particular to the AX-5 Ames suit component that was used in tests of the advanced space suit in penetration tests. This part was superior to the corresponding part in the space shuttle suit.

The data available for the penetration of the space suit fabric are not conclusive: the number of tests is small, no penetration tests of TMG with metal plate are available, the possibility of suit ignition was not fully investigated, and the physical and psychological effects of suit penetration on astronauts is poorly known. Yet, the main factor of uncertainty is the flux of orbital debris in LEO: a high level of uncertainty about the loads (i.e. debris flux) necessarily implies a high level of uncertainty in the risk analysis results (i.e., the probability of suit penetration over time).

[3] "Non-Critical" refers to a situation where the astronaut is not severely injured or killed

SECTION 4

PROBABILISTIC RISK ANALYSIS OF EMU PENETRATION

4.1 EVAS

EVAs will be conducted during the construction and operation of the ISS. Each EVA involves different phases that are relevant to the probability of particle penetration. We have identified these phases as: "leaving the hatch", "transition to the operation area", "activities in the operation area" and "transition back to the hatch". During some of these phases, the astronaut will be shielded to some degree by the space shuttle or the ISS. During other times, he/she will not be shielded and will operate in open space.

Orbital debris will be approaching the astronaut from the direction of the ISS's velocity vector, while the micro-meteorite flux is omni-directional. This implies that passive protection measures will have significant impact on the probability of debris hits, but less so regarding meteorite hits. Therefore, the meteorite flux will only decrease slightly if the astronaut operates "behind" the shuttle while the debris flux will be noticeably smaller.

In the case of a particle hit during an EVA, there are four different possible outcomes:

a) the particle does not penetrate the EMU, no damage is done
b) the particle penetrates the EMU but is non-critical (i.e. hole of less than 4mm in the a soft part of the suit) and the astronaut reaches the hatch
c) the particle penetrates the EMU and creates a hole of more than 4mm in diameter (soft part) – but the astronaut can still reach the hatch in time
d) the particle penetrates the EMU and immediately kills the astronaut or the astronaut is not able to reach the hatch before his LSS fails to function

The outcomes depend on the kinetic energy of the particle, its impact angle, the part of the suit being hit and the astronaut's distance to the hatch of the shuttle or the ISS. Given that the particle penetrates the suit, the performance of the LSS is also relevant (i.e. will the secondary GOX provide enough oxygen to get the astronaut back to the hatch?).

4.2 PROBABILISTIC RISK ANALYSIS MODEL

Our model is represented by the influence diagram[4], shown in figure 4.2-1. The model simulates the LEO environment for the ISS. We use the data obtained from the space shuttle window impacts (313 hits in 592 mission days) to assess the hourly probability of impact during EVAs. The impact data for the shuttle mission were gathered in orbits that are different from the planned orbit of ISS, but presumably, the shuttle orbits have a lower particle flux than the planned ISS orbit (therefore, we are conservative).

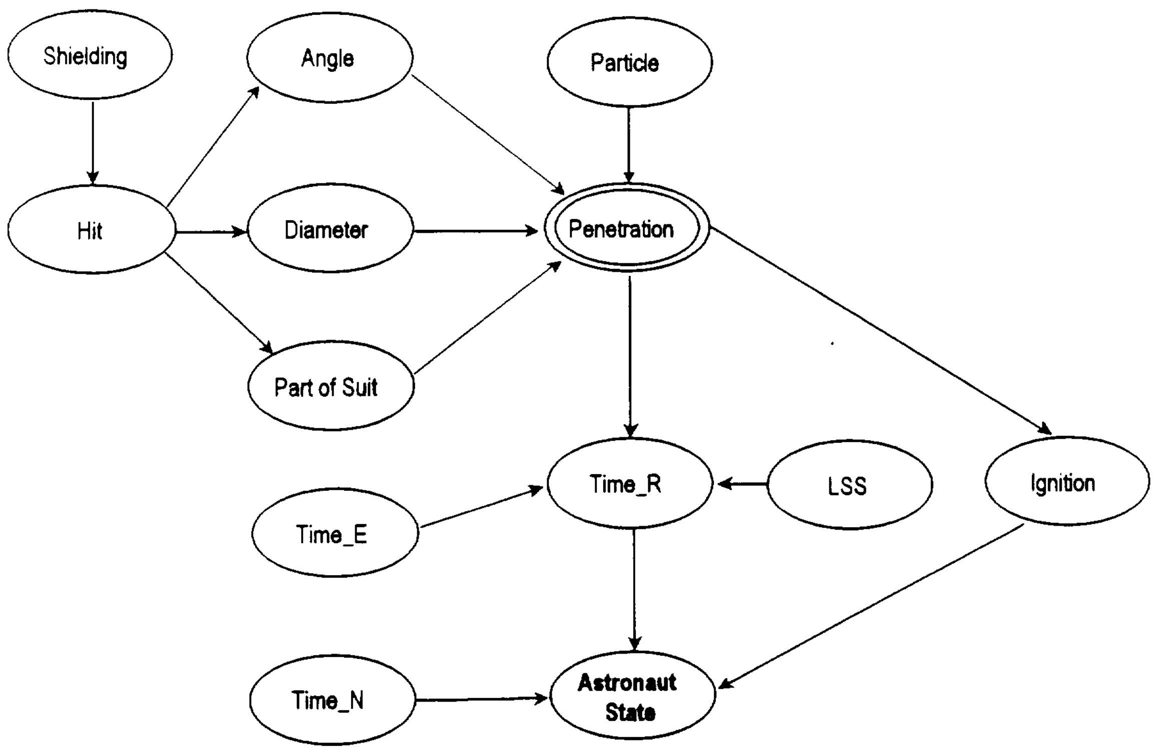


Figure 4.2-1: The PRA Model

[4] An influence diagram is a graphical tool that represents the structural level of the decision problem; it is mainly used for communication purposes between the decision maker and the decision analyst

Model evaluation: Given that an impact occurs[5] we evaluate whether shielding if effective or not. If no shielding is effective, we compute the energy of the impacting particle and identify the part of the suit being hit. Given the impact energy and the part of the suit being hit, we can calculate whether there is penetration or not. If there is penetration, we check whether there is ignition or not. If there is no ignition, we check whether the LSS is working properly or not and we calculate the remaining oxygen supply (in minutes). We then compare this quantity to the amount of oxygen needed to get to the hatch (never more than 30 minutes).

Data sources: Given that an impact occurs (we use the shuttle window impact statistics for the analysis of uncertainties), we use ORDEM96 data and the formulae in SSP30425 to assess the diameter distribution of orbital debris and meteorites respectively. We calculate (by using ORDEM and SSP30425) the flux of particles that are large enough (or larger) to penetrate the soft parts of the EMU. Both ORDEM96 and SSP30425 provide us with cumulative flux estimates, that is, flux data for particles of a given size *and larger*. Based on these flux calculations, we compute the conditional probabilities for each diameter class as its contribution to the overall particle-flux[6]. Throughout these computations, we assume an impact velocity of 10km/s for debris and 20km/s for meteorites. We simulate impacts at various angles and we calculate the *vertical* (normal to the surface) impact velocity[7]. Based on a function the vertical impact velocity, the particle type and diameter and the part of the suit being hit, we calculate the hole diameter (soft parts) or check the ballistic limit for penetration (hard parts). The formulae for the hole diameters due to impacts in soft parts are[8](E_p, the kinetic impact energy[9], measured in [J]):

Hole diameter due to impact by micro-meteorite:

$$D_H = 0.00153 * E_p^{1.344} \ [cm] \qquad (4.2\text{-}1a)$$

Hole diameter due to impact by orbital debris:

$$D_H = 0.00176 * E_p^{1.35} \ [cm] \qquad (4.2\text{-}1b)$$

[5] Based on the data gathered from window impacts on shuttle missions, we calculated a probability of $0.007 m^{-2} hr^{-1}$ for a a particle hit during EVA

[6] We calculate the relative weight of each diameter class within the total flux, e.g. "85% of the total flux is due to particles of size 0.01cm"

[7] The exact formula is $v_{vertical} = [\cos(v)]^{0.2}$ (Hodgeson, 1997, private communication)

[8] Cour-Palais, 1996

[9] $E_p = 0.5 * m * v^2$; m in [kg], v in [m/s]

If a hard part is penetrated, a critical incident occurs. If a soft part is penetrated, we evaluate the distance to the hatch (in minutes) and compare it to the minutes of oxygen left, taking into account the size of the hole. Finally, we introduce a small probability of LSS failure, given that there is a hole in a soft part.

For probabilistic calculations, the flux of orbital debris and micro-meteorites can be assumed to be probabilistically independent. This allows us to model these two phenomena separately and, once this is done, to calculate the overall probability of a particle hit.

We use a cut-off threshold for particles of diameter 0.01cm, i.e. particles of smaller diameters were not considered in this model as their impact energy was below the level of penetration of soft parts. We calculate the percentage of total flux attributable respectively to debris and meteorites by running ORDEM96 and using the formulae in SSP30425 (roughly 60:40). The formulae for meteorite-flux in SSP 30425A are:

$F^{ip}_r(m)$, the interplanetary flux at one A.U.:

$$F^{ip}_r(m) = c_0\{c_1 m^{0.306} + c_2)^{-4.38} + c_3(m + c_4 m^2 + c_5 m^4)^{-0.36} + c_6(m + c_7 m^2)^{-0.85}\} \quad (4.2\text{-}2)$$

c_0	$= 3.156*10^{\wedge}7$	c_4	$= 10^{\wedge}11$
c_1	$= 2.2*10^{\wedge}3$	c_5	$= 10^{\wedge}27$
c_2	$= 15$	c_6	$= 1.3*10^{\wedge}-16$
c_3	$= 1.3*10^{\wedge}-9$	c_7	$= 10^{\wedge}6$

s_f, the shielding factor:

$$s_f = [1 - \cos(\eta)]/2 \quad (4.2\text{-}3)$$

$\sin(\eta) = R_E/(R_E + H)$

R_E = *Earth radius + 100km atmosphere (6478km)*

H = *Height above Earth's atmosphere (height of atmosphere 100km)*

G_E, the focussing factor of the Earth's gravitational field:

$$G_E = 1 + (R_E/r) \quad (4.2\text{-}4)$$

r = *Orbit Radius (6378km + 400km)*

$F_r(m)$, the integral flux of particles of mass m or larger, tumbling surface in Earth's orbit:

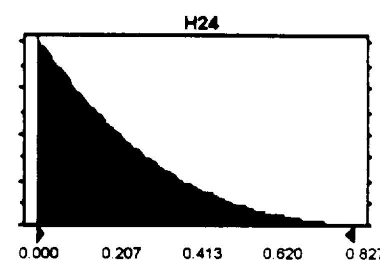
$$F_r(m) = s_f * G_E * F^{ip}_r(m) \quad (4.2\text{-}5)$$

The Probabilistic Risk Analysis in this report includes the probabilities of penetration of hard parts of the Space Shuttle Suit. This had not been done so far, based on the assumption that the hard parts of the suit are not critical (see Section 3 for details). Furthermore, we include the effects of shielding of the astronauts in EVAs. The data that we used can be divided *into flux data* (loads), *suit data* (capacities), and *time* (exposure).

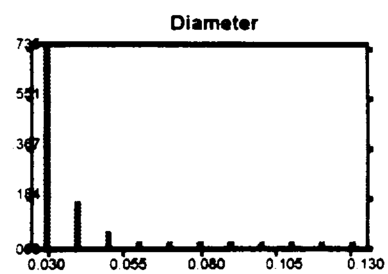
Our model was run on a Pentium Pro with 64MB of RAM and a 200MHz CPU. We used Crystal Ball™, an Excel™ add-on, for the simulation part.

The following list describes each of the variables of the influence diagram in more detail. Random variables are assigned a distribution. Variables that are deterministic are variables that represent results of functional evaluations of other variables. For example, "Penetration" depends on all the variables that are connected to the node ("bubble") that represents penetration in the influence diagram.

- **Hit**: A debris particle or a micro-meteorite hits the space suit; we do not consider particles of diameters less than 0.01 cm as their impact energy is not sufficient enough to penetrate any part of the space suit. Distribution: Bernoulli (p), based on windows impact during space shuttle missions (limitation: no consideration of variation of probability of hit over time)
- **Angle**: The impact angle is measured against the axis perpendicular to the surface being hit; an angle of 0 degree is perpendicular, while an angle of 90 degrees is tangential to the surface area.Distribution: Beta (1, 10), multiplied by 90^0

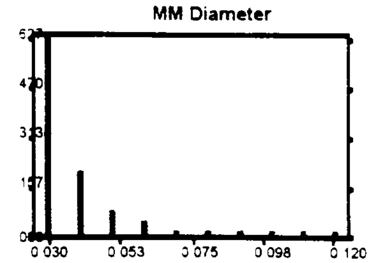


- **OD Diameter**[10]: Particles of different sizes and velocities hit the space suit; we assume an impact velocity of 10km/s for orbital debris. We use the data that we obtained from running ORDEM96 for diameters 0.03cm to 0.13 cm. Any orbital debris particle of diameter larger than 0.11cm has enough kinetic energy to penetrate any part of the EMU. Therefore, we did not deem it necessary to include particle diameters of larger than 0.13cm. Distribution: Custom (discrete)

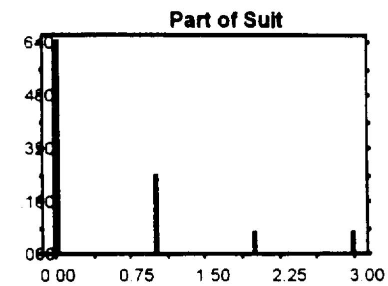


[10] The distribution for the particle diameter was derived from the ORDEM96 output for the ISS orbit. ORDEM96 provided us with flux data for a given diameter size *and larger*(e.g. the flux for particles of 0.03 cm *and larger* is 1.04E-01 $m^{-2}yr^{-1}$, the flux for particles 0.04cm *and larger* is 0.0276 $m^{-2}yr^{-1}$); we calculated the flux for a set of diameters and then calculated the flux for intervals of 0.01cm (e.g. 0.0276 $m^{-2}yr^{-1}$ for the interval 0.03 to 0.04 cm); finally we calculated the distribution to be the percentage of flux, attributable to each of the intervals. We followed a similar procedure for the diameter distribution of meteorites.

- **MM Diameter:** Particles of different sizes and velocities hit the space suit; we assume an impact velocity of 20km/s for micro-meteorites. We calculated the flux for a range of particle diameters, starting at 0.03cm and including 0.13cm. Any meteorite particle of that diameter or larger has enough kinetic energy to penetrate any part of the EMU. Therefore, we did not include any particles of larger diameters. Distribution: Custom (discrete)



- **Part of Suit**: The area of the suit being hit by the particle. We make use of the test data available in Cour-Palais (1996), and we distinguish between 4 different parts of the suit: soft parts, primary GOX, HUT and helmet/visor. We assume that the conditional probability of impact location on the EMU, given there is an impact, is proportional to the percentage of surface area covered by that part of the suit. Distribution: Custom (discrete)



- **LSS**: The performance of the life support system in case of suit penetration, given that the LSS is **not** the EMU part being penetrated. If the LSS is penetrated, then we have a fatal accident and the astronaut is dead before he can reach the hatch. If, however, the LSS is not the suit element that is being penetrated, then we assume its performance to be independent of which part of the suit has been penetrated. By this, we want to consider that there is a chance of malfunction of the LSS when it is called upon in an emergency mode. For this failure, we assume a conditional probability of 2 in 1000 (Paté-Cornell, 1994). Distribution: Bernoulli (0.002)
- **Penetration**: Penetration of the suit depends on 4 variables – "Part of Suit", "Hit", impact energy (which is a function of "Diameter" and "Angle") and "Shielding". If there is no hit, there is no penetration. If there is a hit, but shielding is effective, there is no penetration. Given there is a hit and shielding is ineffective, the probability of penetration depends on impact energy and on the part of the suit being hit. Deterministic Variable (Formula)
- **Time Elapsed (Time_E):** Oxygen time elapsed between start of EVA and particle impact. Since a particle impact can occur at any time during the EVA, we assume a uniform distribution for this variable (we have no data that would indicate otherwise). Distribution: Uniform [0, Total Oxygen]

- **Time Remaining (Time_R):** The time left during which the astronaut will have sufficient oxygen pressure. This variable depends on "Time Elapsed" (Time_E), the state of the life support system "LSS", the amount of oxygen available at the beginning of the EVA "Total Oxygen", and "Penetration". The formula can be found in Appendix C. Deterministic variable (Formula)
- **Ignition**: Because the atmosphere in the suit is composed of pure oxygen, it is highly susceptible to ignitions; this variable captures the possibility of an ignition due to penetration of the bladder. We set this conditional probability to be 1 in 1,000 (Paté-Cornell, 1994). Distribution: Bernoulli (0.001)
- **Time Needed (Time_N)**: Time needed is the oxygen time required for the astronaut to get back to the hatch. We assume it to be the minimum of 30 minutes and the remaining mission time (we assume that at any point during the EVA, the maximum distance between the astronaut and the closest hatch is 30 oxygen minutes). The formula can be found in Appendix C. Deterministic variable (Formula)
- **Astronaut State**: Depending on the possibility of penetration, on the state of the LSS and the time needed to get to the hatch, the astronaut can be OK or severely injured/dead. The formula can be found in Appendix C. Deterministic variable (Formula)
- **Total Oxygen:** Total amount of oxygen available to astronaut at the start of an EVA (excluding the secondary GOX), measured in minutes. Deterministic variable (Parameter)
- **Shielding:** During most of their EVAs the astronauts will be partly shielded against particles by the space shuttle or the ISS. For each of these cases, we define a percentage of flux that can be shielded against by the structure (i.e. if there is no shielding, the astronaut will be exposed to 100% of the particle flux; if there is shielding by the ISS, he/she will be shielded against 1/3 of the incoming meteorites and 9/10 of the incoming debris). The flux factors are listed in table 4.2-1 (Effective Flux = Incoming Flux * Flux Factor). These numbers are the result of an estimated guess, as we had no data on this factor at this point in the study. Distribution: Bernoulli(p)

	MM [%]	OD [%]	Time [%]
Shuttle	0.333	0.100	0.250
ISS	0.667	0.100	0.500
None	1.000	1.000	0.250

Table 4.2-1: Flux Factors

- **Particle:** Micro-meteorite or orbital debris. Due to their different penetration characteristics, meteorite and debris particles have to modeled separately. We use an estimated guess of a 60% and 40% ratio for debris and meteorite percentage of total particle flux. Distribution: Bernoulli(0.6)

Therefore, there are two main points of concern in the data that we used in our model:

a) Flux data: We used flux data from the shuttle window impacts for the impact probability of particles of a kinetic energy of 3J or more (the kinetic energy necessary to puncture the soft part of the EMU – this diameter is the limit below which the formulae of Cour-Palais (1996) indicate no penetration). Since particles with impact energies of less than 3J create visible effects in the shuttle windows, the use of this data might be an overestimation. Also, we used relative weights derived from ORDEM96 data and SSP30425 formulae to estimate the conditional probabilities of particle diameter, given there is an impact (see footnote on page 24).

b) Shielding: We "guesstimated" the effects of shielding as well as the amounts of time spent in each environment (Table 4.2-1). Once reliable data are available, the estimation of these variables can be improved.

SECTION 5

RESULTS

5.1 FINDINGS AND LIMITATIONS OF THE MODEL

In the model that we developed, we used data from different sources (Christiansen, 1996; Cour-Palais, 1996; Hodgeson, 1993; Kessler *et al*, 1996; Simonds, 1997 to name a few).

We improved the existing models in the following way. First, we included in our risk computations the hard parts of the EMU. Second, we considered the effects of shielding. Third, we extended the risk analysis framework to place the risk of particle hits in the perspective of the overall EVA risk. We did not run this overall model (which was outside our scope), but it is clear that particle hits constitute only a part (and probably a minor one) of the overall EVA risk.

The simulation runs of our model show that the overall probability of a fatal or near-fatal accident (i.e. astronaut dead or severely injured) due to a hit by orbital debris or micro-meteorite is below 2% for an exposure of 3,000 hours of EVA. This figure, which includes penetration of both hard and soft parts of the EMU, is below the threshold set by current NASA guidelines and is consistent with NASA findings (Simonds, 1996). Our simulation runs also indicated that the probability of an accident due to penetration of a soft part dominates the probability of penetration of a hard part. The hard parts of the EMU therefore seem to contribute a larger part of risk of fatal accidents than has been previously expected, but this could be attributed in part to the uncertainties regarding the particle flux.

In our simulations, passive shielding reduced by 25% the probability of a critical incident. Given the significant impact of this passive (and largely free of cost) safety measure, time should be spent on mission schedule development to make the most use of possible shielding. The effects of shielding, however, are a function of the actual particle flux in orbit (which itself is uncertain), and of the position of the astronauts relative to any structure that might shield them. In our model, we used a coarse estimate of the latter factor as we did not have access to any conclusive data. Further refinement will be necessary.

A major source of uncertainty is the flux of orbital debris. Current models provide some estimates but they do not necessarily concur with experience. For example, the number of window impacts on the shuttle assessed by simulation is 30% below the actual number measured in orbit. Our simulation indicated that the probability of a critical event is very sensitive to both the probability of a particle hit *and* the size of the particle. An important input is thus the flux distribution, i.e. the distribution of total flux measured by the size (diameter) of the particles. In particular, everything else being equal, a change of 1% in the probability of a particle hit (from 0.9782 to 0.9675) almost doubled the probability of a fatal accident[11]. The same is true for variations of the particle diameter distribution. Uncertainties about the flux of debris of less than 10cm diameter are of particular concern. Further, research indicates that all sources or processes by which debris of this diameter class get generated are not well understood (NRC, 1995). We do know that future space activity will increase the flux of debris in LEO and other orbits. Therefore, we know that the amount of orbital debris will increase, but their actual future flux can only be guessed. In addition, while current flux models predict a very low probability of critical penetration of the EMU, data gathered from space shuttle missions suggest that the current model predictions be reconsidered and that further research into the flux of orbital debris is necessary.

In the long run, the total particle loads to which the astronauts will be subjected in orbit depend on the duration of exposure as well as the debris flux. Unexpected events will most likely increase the number of EVA hours. Reducing the risk of penetration due to particle hits will require a harder space suit – or shielding. NASA has to decide if the development of such an advanced space suit should be a priority item or if it could be delayed.

In our calculations, we performed a sensitivity analysis for the loads (debris flux) because they appear to dominate the uncertainties of the results. We varied the probabilities of impact and the probability distribution for the diameter of the orbital debris. We did not vary the probability distribution for the meteorite diameter, as the research suggests that these data are more reliable than the orbital debris data. The results of this sensitivity analysis are shown in Appendix A, the parameters that we varied are listed in Appendix B.

For a full scale risk analysis, however, a sensitivity analysis of both the loads *and* the capacities has to be performed since both are uncertain: the flux of orbital debris is uncertain and the ballistic limits of various EMU elements have not been established by tests yet. Time

[11] We want to point out that due to the extremely low probabilities involved here, a Monte-Carlo simulation requires a large number of runs. Therefore, these results have to be understood as more relative than absolute.

and budget constraints, however, did not allow us to perform a full-scale sensitivity analysis at this point. Further research is also needed to assess the effects of impacts on soft and hard suits, particularly on the combination of TMG covered aluminum sheets. In addition, the contribution of these uncertainties about capacities to the uncertainties on the risk should be assessed to permit proper interpretation of the results.

Other limitations of our results include the following:

1. Improved data on the relevance of oblique impacts are needed.

2. We used a constant velocity of 10km/s for debris and 20km/s for meteorites. We are aware that the velocity of particles varies and this variation can be represented by a distribution, but we feel comfortable with our simplification after an analysis of the velocity spectra.

3. Better data are needed for $p_{LSS}(F)$, the probability of failure for the life support system given that there is a penetration in another part of the suit. This might prove to be an important variable, since holes of diameter of less than 4mm are more likely that those of larger diameters (we assume that a penetration hole of more than 4mm in diameter results in a fatal accident)

4. Better data are needed for the probability of suit ignition due to particle penetration

5. We needed a better description of the mission profile of EVA missions. We needed to know, in particular, the time spent in each environment to be able to estimate the effects of passive shielding and we needed the distance to hatch over time to be able to assess the time and oxygen necessary to get back to the hatch in the event of an accident.

5.2 Implications for Risk Management

Although during EVAs, the astronauts are unlikely to be "as safe outside [the ISS] as inside", the risks that were computed for the current ISS-related EVA plans seem to be acceptable within the parameters defined by NASA. A number of uncertainties, however, can affect the actual risk levels, including uncertainties about loads, capacities and exposure.

In the future management of such EVAs, these risk analysis results are relevant for a number of decisions still to be made. First, passive shielding by the orbiter or the ISS should be an important part of EVA risk management and taken advantage of whenever possible. The number of EVA hours is also an important component of the risk. The 905 hours of construction should be considered firm at this points but there will undoubtedly be some further unexpected EVAs requirements.

There remains the issue of whether a hard suit should be made available and when. We understand that the time and budget constraints of the ISS did not allow for the full development of a hard suit at the time the final decision was made. It seems however, that additional work in LEO will be needed in the future, whether for the operation and maintenance of the ISS or for other purposes (including perhaps, the repair of satellites). Given the costs and the vulnerabilities of the current EMU, it would be logical to complete the development of a hard suit with proper attention to mass and stowage volume. Such a robust suit could be more easily produced and maintained than the current one, it could probably be produced at lower costs, it could provide a higher level of safety, and it should be able to sustain the higher pressures that are required for an improved level of human performance.

SECTION 6

REFERENCES

Christiansen, E.L., Meteroid/Orbital Debris Model & Uncertainties, June 25, 1996

Christiansen, E.L., Hypervelocity Impact Test Results on EMU Materials, June 25, 1996

Cour-Palais, B.G., A Review of the EMU Ballistic Limit Tests and Analysis Performed in Conjunction with Space Suit Meteorite and Orbital Debris Protection Capability, SwRI Project No. 06-6684, Report No. 6684/002, 1996

Gebicke, M.E., GAO Memo to Daniel S. Goldin (B-248278, April 15, 1992)

Hamilton Standard, EVA Hazard Estimates, June 26, 1996

Hodgeson, E., Micrometeorite and Orbital Debris Hazard Analysis for EMU, Analysis 93-056, Hamilton Standard Division United Technologies Corporation, Contract NAS 9-17873, 1993

Kessler, D.J., Zhang, J., Matney, M.J., Eichler, P., Reynolds, R.C., Anz-Meador, P.D. and Stansbery, E.G., A Computer Based Orbital Debris Environment Model for Spacecraft Design and Observations in Low Earth Orbit, NASA Technical Memorandum 104825, NASA JSC, 1996

Levin, G.M., NASA Orbital Debris Program, Presentation to NASA Advisory Council, October 31, 1996

National Research Council (NRC), Orbital Debris – A Technical Assessment, National Academy Press, 1995

Paté-Cornell, M.E., Risk of Extravehicular Activities and Policy Implications: An Analytical Framework, NASA-ASEE Stanford Summer Faculty Fellowship Program, Final Report, 1994

Simonds, C.H. and Julian, R.L., Assessment of Portable Orbital Debris and Micrometeorite Shield for EVA Crew Protection at the International Space Station, 1997

Simonds, C.H., Revised Thread of EMU SSA Penetration, June 26, 1996

Simonds, C.H., Assessment of Hazard to EVA Crew by Impact of Micrometeorites and Orbital Debris during Assembly and Operation of International Space Station, DRAFT May 8, 1996

ACKNOWLEDGEMENTS:

This study was funded in part by a NASA grant NAG 2-980. We want to thank Mr. Bruce Webbon who initiated this study and Mr. Michael Rouen for their support in this effort. We also want to thank Dr. Christiansen, Mr. Nicholas Johnson and Dr. Simonds for providing us with helpful information.

APPENDIX A: RESULTS

PASSIVE SHIELDING

Probability of Hit: I
Flux Distribution: I

Outcomes:	Frequencies:	Probabilities:
AOK	29,995	99.983%
Penetration Soft Part	2	0.007%
Penetration Hard Part	3	0.010%
	30,000	100.000%

Probability of Hit: II
Flux Distribution: I

Outcomes:	Frequencies:	Probabilities:
AOK	29,991	99.970%
Penetration Soft Part	5	0.017%
Penetration Hard Part	4	0.013%
	30,000	100.000%

Probability of Hit: I
Flux Distribution: II

Outcomes:	Frequencies:	Probabilities:
AOK	29,992	99.973%
Penetration Soft Part	5	0.017%
Penetration Hard Part	3	0.010%
	30,000	100.000%

Probability of Hit: II
Flux Distribution: II

Outcomes:	Frequencies:	Probabilities:
AOK	29,992	99.973%
Penetration Soft Part	4	0.013%
Penetration Hard Part	4	0.013%
	30,000	100.000%

NO PASSIVE SHIELDING

Probability of Hit: I
Flux Distribution: I

Outcomes:	Frequencies:	Probabilities:
AOK	29,994	99.980%
Penetration Soft Part	5	0.017%
Penetration Hard Part	1	0.003%
	30,000	100.000%

Probability of Hit: II
Flux Distribution: I

Outcomes:	Frequencies:	Probabilities:
AOK	29,984	99.947%
Penetration Soft Part	13	0.043%
Penetration Hard Part	3	0.010%
	30,000	100.000%

Probability of Hit: I
Flux Distribution: II

Outcomes:	Frequencies:	Probabilities:
AOK	29,990	99.967%
Penetration Soft Part	9	0.030%
Penetration Hard Part	1	0.003%
	30,000	100.000%

Probability of Hit: II
Flux Distribution: II

Outcomes:	Frequencies:	Probabilities:
AOK	29,984	99.947%
Penetration Soft Part	13	0.043%
Penetration Hard Part	3	0.010%
	30,000	100.000%

Each table represents the results of a simulation run with a set of different parameters. The parameters that were varied were the probability of being hit by a particle (scenarios I and II) and the diameter distribution of orbital debris, given that there is a hit by orbital debris (scenarios I and II). Appendix B shows probabilities for each of the parameters.

APPENDIX B: SENSITIVITY PARAMETERS

- Probability of Hit (total flux consists of MM and OD)

I Unmodified values:

P(No Hit)	0.9782
P(Hit)	0.0218

II Modified values:

P(No Hit)	0.9675
P(Hit)	0.0325

- Flux Distribution:

I Unmodified (taken from ORDEM96):

Orbital Debris	
Diamater [cm]	Percentage of Flux
0.03	7.35E-01
0.04	1.71E-01
0.05	5.31E-02
0.06	2.04E-02
0.07	9.23E-03
0.08	4.58E-03
0.09	2.53E-03
0.10	1.49E-03
0.11	9.33E-04
0.12	6.15E-04
0.13	1.78E-03

II Modified:

Orbital Debris	
Diamater [cm]	Percentage of Flux
0.03	6.00E-01
0.04	1.00E-01
0.05	1.00E-01
0.06	1.00E-01
0.07	1.00E-01
0.08	1.00E-01
0.09	1.00E-01
0.10	1.00E-01
0.11	1.00E-01
0.12	1.00E-01
0.13	1.00E-01

APPENDIX C: PROGRAM CODE

```
REM ===========================================================================
REM THE FOLLOWING FUNCTION EVALUATES IF THERE IS PENETRATION OF THE EMU AND THE
REM DIAMETER OF THE HOLE IF A SOFT PART IS PENETRATED
REM PENETRATION IS SET TO 100 IN CASE OF FATAL ACCIDENT
REM
REM DATA FOR BALLISTIC LIMITS TAKEN FROM COUR-PALAIS, 1996
REM FORMULAE FOR MM AND OD HOLE DIAMETERS FROM COUR-PALAIS, 1996
REM
REM E_IMPACT        IMPACT ENERGY (TAKING DIAMETER AND IMPACT ANGLE INTO
CONSIDERATION)
REM
FUNCTION PENETRATION(ANGLE, DIAMETER, HIT, PARTICLE, SUIT_PART, SHIELDING)
E_IMPACT = 0

IF PARTICLE = 0 THEN
    REM IMPACT BY ORBITAL DEBRIS
    E_IMPACT = 0.5 * (4 / 3 * 3.14159265359 * (DIAMETER / 2) ^ 3 * 2.71) * 100000
* COS(ANGLE * 3.14159265359 / 180)
    IF HIT = 1 AND SHIELDING = 0 THEN
        IF E_IMPACT > 71 THEN
        PENETRATION = 100: REM OD PENETRATES ANYTHING
        ELSEIF E_IMPACT >= 60.4 AND SUIT_PART = 2 THEN
        PENETRATION = 100: REM OD PENETRATES PRIMARY GOX
        ELSEIF E_IMPACT >= 44 AND SUIT_PART = 1 THEN
        PENETRATION = 100: REM OD PENETRATES HUT
        ELSEIF SUIT_PART = 0 THEN
        PENETRATION = 0.00176 * (E_IMPACT ^ 1.35): REM OD PENETRATES SOFT PART,
HOLE DIAMETER
        ELSE
        PENETRATION = 0
        END IF
    ELSE
        PENETRATION = 0
    END IF
ELSE
    REM IMPACT BY MICRO-METEOROID
    E_IMPACT = 0.5 * (4 / 3 * 3.14159265359 * (DIAMETER / 2) ^ 3 * 1.15) * 400000
* COS(ANGLE * 3.14159265359 / 180)
    IF HIT = 1 AND SHIELDING = 0 THEN
        IF E_IMPACT > 170 THEN
        PENETRATION = 100: REM MM PENETRATES ANYTHING
        ELSEIF E_IMPACT >= 75 AND SUIT_PART = 2 THEN
        PENETRATION = 100: REM MM PENETRATES PRIMARY GOX
        ELSEIF E_IMPACT >= 70 AND SUIT_PART = 1 THEN
        PENETRATION = 100: REM MM PENETRATES HUT
        ELSEIF SUIT_PART = 0 THEN
        PENETRATION = 0.00153 * (E_IMPACT ^ 1.344): REM MM PENETRATES SOFT PART,
HOLE DIAMETER
        ELSE
        PENETRATION = 0
        END IF
```

```
    ELSE
        PENETRATION = 0
    END IF
END IF

END FUNCTION

REM ==========================================================================
REM THE FOLLOWING EVALUATES HOW MUCH OXYGEN TIME THE ASTRONAUT HAS LEFT

FUNCTION TIME_R(LSS, SUIT, TIME_E, TIME_MIN, KSI)
REM TIME MEASURED IN HOURS TO BE CONSISTENT WITH PROBABILITIES
    IF LSS = 1 AND SUIT = 0 THEN
        TIME_R = TIME_MIN - TIME_E
    ELSEIF LSS = 1 AND SUIT < 0.4 THEN
        REM LSS OK, SUIT HAS SMALL HOLE: PRIMARY AND SECONDARY GOX CAN BE USED
        TIME_R = 0.5 + (TIME_MIN - TIME_E) * KSI
    ELSEIF LSS = 1 AND SUIT < 100 THEN
        REM LSS OK, SUIT HAS LARGE HOLE: EXPONENTIAL LOSS OF OXYGEN
        IF 0.5 * EXP(0.4 - SUIT) > 0 THEN
            TIME_R = 0.5 * EXP(0.4 - SUIT)
        ELSE
            REM HOLE TOO LARGE FOR OXYGEN PRESSURE TO BE STABLE
            TIME_R = 0
        END IF
    ELSEIF LSS < 1 AND SUIT = 0 THEN
        REM LSS BAD, SUIT OK: LOSING OXYGEN, ABORT MISSION (I.E. NO ASTRONAUT DEAD
DUE TO BAD LSS)
        TIME_R = TIME_MIN - TIME_E
    ELSEIF LSS < 1 AND SUIT < 0.4 THEN
        REM LSS BAD, SUIT HAS SMALL HOLE: SWITCH TO SECONDARY GOX, BUT MIGHT NOT
WORK
        TIME_R = 0.5 * KSI
    ELSE
        REM LSS BAD AND SUIT HAS HOLE LARGER THAN 0.4 CM: FATAL
        TIME_R = 0
    END IF
END FUNCTION

REM ==========================================================================
REM THE FOLLOING FUNCTION EVELUATES THE STATE OF THE ASTRONAUT GIVEN PENETRATION
OCCURS

FUNCTION STATE(TIME, DISTANCE, HOLE, IGNITION)
    IF HOLE > 0 THEN
        IF IGNITION = 0 AND (TIME - DISTANCE) > 0 THEN
            STATE = 1
        ELSE
            STATE = 0
        END IF
    ELSE
        STATE = 1
    END IF
```

```
    IF (TIME - DISTANCE) < 0 THEN STATE = 0

END FUNCTION

REM ==========================================================================
REM THE FOLLOWING FUNCTION EVALUATES IF A HARD OR A SOFT PART GOT PENETRATED

FUNCTION CAUSE(PART, EFFECT)
    IF EFFECT = 0 THEN
        IF PART > 0 THEN CAUSE = 2: REM HARD PART
        IF PART = 0 THEN CAUSE = 1: REM SOFT PART
    ELSE
        CAUSE = 0
    END IF
END FUNCTION

REM ==========================================================================
FUNCTION METEOROID_FLUX(MASS)
    REM METEOROID FLUX IN LEO AT 400KM
    C0 = 3.156 * 10 ^ 7: C1 = 2200: C2 = 15: C3 = 1.3 * 10 ^ (-9)
    C4 = 10 ^ 11: C5 = 10 ^ 27: C6 = 1.3 * 10 ^ (-16): C7 = 10 ^ 6
    METEOROID_FLUX = C0 * ((C1 * MASS ^ 0.306 + C2) ^ (-4.38) + C3 * (MASS + C4 *
MASS ^ 2 + C5 * MASS ^ 4) ^ (-0.36) + C6 * (MASS + C7 * MASS ^ 2) ^ (-0.85))
    METEOROID_FLUX = 0.6680258 * 1.941843 * METEOROID_FLUX: REM 0.66.. AND 1.94..
FOR CIRCULAR ORBIT AT 500KM
END FUNCTION
```

APPENDIX D: MODEL DATA SHEETS

PRA Model

[redacted]

Color Code:

Unconditioned Chance Variables	
Condictioned Chance Variables	
Deterministic Variables (Functions)	
Crystal Ball Simulation Cells	
Data or Estimates	

Model Particle Flux [1/m^2/hr] [redacted]
Shuttle Particle Flux [1/m^2/hr]: [redacted] Data: 313 impacts /(592days*24hours*3m^2)
Area of Space suit [m^2]: [redacted]

Total Oxygen Supply [hrs]: [redacted]

Shielding:	MM [%]	OD [%]	Time [%]
Shuttle	0.333	0.100	0.250
ISS	0.667	0.100	0.500
None	1.000	1.000	0.250
			1

OD ratio of total flux: 0.6000

[redacted]

[redacted]

	1
0	[redacted]
1	

[redacted]

	0
0	0.462
1	0.538

[redacted]

	0
0	0.6000
1	0.4000

OD Diameter
0.003

Orbital Debris	
Diameter [cm]	Percentage of Flux
0.03	7.35E-01
0.04	1.71E-01
0.05	5.31E-02
0.06	2.04E-02
0.07	9.23E-03
0.08	4.58E-03
0.09	2.53E-03
0.10	1.49E-03
0.11	9.33E-04
0.12	6.15E-04
0.13	1.76E-03

MM Diameter
0.120

Meteoroids	
Diameter [cm]	Percentage of Flux
0.03	6.27E-01
0.04	2.04E-01
0.05	8.18E-02
0.06	3.79E-02
0.07	1.95E-02
0.08	1.08E-02
0.09	6.42E-03
0.10	3.99E-03
0.11	2.59E-03
0.12	6.61E-03

Angle
[redacted]
0.0

[redacted]
0.119 [redacted]

Ignition

	0
0	0.999
1	0.001

Part of Suit

	1
0	0.64
1	0.23
2	0.07
3	0.06

[redacted]

	1
0	0.001
1	0.999

[redacted]

[redacted]
Penetration(Angle, Diameter, Hit, Particle, Suit_Part, Shielding)

[redacted]
Time_R(LSS, Penetration, Time_E, Time_Min, ksi)

As[redacted]te
State(Penetration, Time_R, Ignition, Time_N)

[redacted]

Ratio of Orbital Debris Flux and Meteoroid Flux of Total Flux (given same energy spectrum).	
Orbital Debris:	0.52
Meteoroids:	0.48

Total Flux (Diameter >=0.01 cm)

Orbital Debris in LEO:

Data output from ORDEM96 program provided by Nic Johnson of JSC:
The flux calculated by this program shows that the probability of being hit by a particle that is critical is less than remote
A flux of 5 per m^2 per year translates into something even smaller if considering only 3000hrs and the flux of 5 is for particles below the critical threshold of the space suit!

All Flux data given for specified diameter size and larger!

Since the OD impacts are of greater significance we use the condictional probabilities for OD in the model (conditional probabilities for MM are almost identical)

Considering a spacecraft in circular orbit:	
Inclination [deg]:	51.6
Altitude [km]:	500
Time [year]:	2001
F10.7 [10^4 J yr]:	198
DiaMin [cm]:	0.01
DiaMax [cm]:	0.14
nDia [-]:	1
N [-]:	0.2
dV [km/s]:	2
Mass [g/ccm]	2.71

The program ORDEM96 was used to produce these results. The diamater input values were iterated from 0.01cm to 0.14cm.
The generated outputs were then accumulated in the table below (average values).

Diamater [cm]	Kin Energy [J]	Flux [#/sqm/yr]	Differ. Flux [#/sqm/yr]	Percentage of Flux
1.00E-02	7.09E-02	5.21E+00	4.60E+00	8.83E-01
2.00E-02	5.68E-01	6.12E-01	5.08E-01	9.75E-02
3.00E-02	1.92E+00	1.04E-01	7.64E-02	1.47E-02
4.00E-02	4.54E+00	2.76E-02	1.78E-02	3.41E-03
5.00E-02	8.87E+00	9.84E-03	5.52E-03	1.06E-03
6.00E-02	1.53E+01	4.32E-03	2.12E-03	4.07E-04
7.00E-02	2.43E+01	2.20E-03	9.60E-04	1.84E-04
8.00E-02	3.63E+01	1.24E-03	4.76E-04	9.14E-05
9.00E-02	5.17E+01	7.64E-04	2.63E-04	5.05E-05
1.00E-01	7.09E+01	5.01E-04	1.55E-04	2.98E-05
1.10E-01	9.44E+01	3.46E-04	9.70E-05	1.86E-05
1.20E-01	1.23E+02	2.49E-04	6.40E-05	1.23E-05
1.30E-01	1.56E+02	1.85E-04	4.30E-05	8.25E-06
1.40E-01	1.95E+02	1.42E-04	1.42E-04	2.73E-05

Meteoroids in LEO:

Model taken from SSP 30425, Rev. A, 1991, Paragraph 8
The formulae in SSP30425 allow for the calculations of particle flux [#/m^2/yr]
The output of the formulae is the flux of particles of a given size OR larger
We assume the meteoroid particles to be spheres of same density

Meteoroids

Mass density [g/cm^3] 1.17

Diameter [cm]	Mass [g]	Kin Energy [J]	Flux [#/sqm/yr]	Differ. Flux [#/sqm/yr]	Percentage of Flux
0.0083	3.50283E-07	0.07005655	4.79E+00	4.39E+00	9.15E-01
0.02	4.90088E-06	0.98017691	4.06E-01	2.97E-01	6.20E-02
0.03	1.65405E-05	3.30809706	1.09E-01	6.83E-02	1.43E-02
0.04	3.92071E-05	7.84141526	4.07E-02	2.22E-02	4.63E-03
0.05	7.65763E-05	15.3152642	1.85E-02	8.91E-03	1.86E-03
0.06	0.000132324	26.4647765	9.57E-03	4.13E-03	8.62E-04
0.07	0.000210125	42.0250849	5.44E-03	2.12E-03	4.43E-04
0.08	0.000313657	62.7313221	3.32E-03	1.18E-03	2.46E-04
0.09	0.000446593	89.3186207	2.14E-03	6.99E-04	1.46E-04
0.10	0.000612611	122.522113	1.44E-03	4.35E-04	9.08E-05
0.11	0.000815385	163.076933	1.00E-03	2.82E-04	5.89E-05
0.12	0.001058591	211.718212	7.20E-04	1.90E-04	3.96E-05
0.13	0.001345905	269.181083	5.31E-04	1.31E-04	2.74E-05
0.14	0.001681003	336.200679	3.99E-04	9.30E-05	1.94E-05
0.15	0.002067561	413.512133	3.06E-04	3.06E-04	6.39E-05

Note: We set the limit of diameter size at a size that correspinds to a kinetic energy of 0.1 Joule.

Note: Formula for calculation of flux in VB sheet

The following is based on the penetration equation for aluminum sheets, Cour-Palais, 06/96, p. 8

The equation calculates the finite sheet thickness for no leak, given an impact by a projectile of given diameter, mass and velocity.
The projectiles commonly used to simulate orbital debris are aluminum projectiles (2.8 g/qcm) and nylon for micro-meteoroids (1.15 g/qcm).
The impact velocities used are 10km/s for orbital debris and 20km/s for micro-meteoroids.

The calculations show that the Alu plates/sheets used in the space suit will be penetrated by any particle of diameter 1mm or larger (!)

Orbital Debris:

Diameter [cm]	Thickness [cm]	Mass[g]	Energy [J]
0.001	0.0039	0.0000	0.0001
0.01	0.0447	0.0000	0.07
0.02	0.0932	0.0000	0.57
0.03	0.1433	0.0000	1.92
0.04	0.1944	0.0001	4.54
0.05	0.2463	0.0002	8.87
0.06	0.2988	0.0003	15.32
0.07	0.3518	0.0005	24.34
0.08	0.4053	0.0007	36.33
0.09	0.4592	0.0010	51.72
0.10	0.5134	0.0014	70.95
0.11	0.5680	0.0019	94.43
0.12	0.6229	0.0025	122.60
0.13	0.6780	0.0031	155.87
0.14	0.7334	0.0039	194.68
0.15	0.7891	0.0048	239.45
0.16	0.8450	0.0058	290.60

Micro-Meteoroids:

Diameter [cm]	Thickness [cm]	Energy [J]
0.00	0.0000	0
0.01	0.0453	0.120427718
0.02	0.0944	0.963421747
0.03	0.1451	3.251548396
0.04	0.1968	7.707373977
0.05	0.2493	15.0534648
0.06	0.3025	26.01238717
0.07	0.3562	41.30670741
0.08	0.4103	61.65699181
0.09	0.4649	87.7918067
0.10	0.5198	120.4277184
0.11	0.5751	160.2892932
0.12	0.6306	208.0990974
0.13	0.6865	264.5796973
0.14	0.7426	330.4536593
0.15	0.7989	406.4435496
0.16	0.8555	493.2719345

Orbital Debris:

Diameter [cm]	Energy [J]	P(no hit)/m^2hr
0.0001	0.00	0.254141771
0.001	0.00	0.979661725
0.01	0.07	0.999863023
0.1	70.95	0.999999795
1	70947.83	0.999999999
10	70947634.09	0.999999999

Micro-Meteoroids:

Diameter [cm]	Energy [J]	P(no hit)/m^2hr
0.0001	1.20428E-07	0.760352907
0.001	0.000120428	0.979661725
0.01	0.120427718	0.999589126
0.1	120.4277184	0.999999863
1	120427.7184	1
10	120427718.4	1

The following is based on the penetration equations for TMG, Cour-Palais, 06/96, p. 6

Aluminum (OD)

Kin. Energy [J]	Hole Diameter [cm]
3	0.008
4	0.011
5	0.015
6	0.020
7	0.024
8	0.029
9	0.034
10	0.039
11	0.045
12	0.050
13	0.056
14	0.062
15	0.068
16	0.074
17	0.081
18	0.087
19	0.094
20	0.100
21	0.107
22	0.114
23	0.121
24	0.128
25	0.136
26	0.143
27	0.151
28	0.158
29	0.166
30	0.174
31	0.181
32	0.189
33	0.197
34	0.206
35	0.214
36	0.222
37	0.230
38	0.239
39	0.247
40	0.256
41	0.266
42	0.273
43	0.282
44	0.291
45	0.300
46	0.309
47	0.318
48	0.327
49	0.337
50	0.346
51	0.356
52	0.366
53	0.374
54	0.384
55	0.394
56	0.403

Nylon (M-M)

Kin. Energy [J]	Hole Diameter [cm]
3	0.01
4	0.01
5	0.01
6	0.02
7	0.02
8	0.03
9	0.03
10	0.03
11	0.04
12	0.04
13	0.05
14	0.05
15	0.06
16	0.06
17	0.07
18	0.07
19	0.08
20	0.09
21	0.09
22	0.10
23	0.10
24	0.11
25	0.12
26	0.12
27	0.13
28	0.13
29	0.14
30	0.15
31	0.15
32	0.16
33	0.17
34	0.17
35	0.18
36	0.19
37	0.20
38	0.20
39	0.21
40	0.22
41	0.23
42	0.23
43	0.24
44	0.25
45	0.26
46	0.26
47	0.27
48	0.28
49	0.29
50	0.29
51	0.30
52	0.31
53	0.32
54	0.33
55	0.33
56	0.34
57	0.36
58	0.36
59	0.37
60	0.38
61	0.38
62	0.39
63	0.40
64	0.41

Average

Kin. Energy [J]	Hole Diameter [cm]
3	0.01
4	0.01
5	0.01
6	0.02
7	0.02
8	0.03
9	0.03
10	0.04
11	0.04
12	0.05
13	0.05
14	0.06
15	0.06
16	0.07
17	0.08
18	0.08
19	0.09
20	0.10
21	0.10
22	0.11
23	0.12
24	0.12
25	0.13
26	0.14
27	0.15
28	0.15
29	0.16
30	0.17
31	0.18
32	0.18
33	0.19
34	0.20
35	0.21
36	0.22
37	0.23
38	0.24
39	0.24
40	0.25
41	0.26
42	0.27
43	0.28
44	0.29
45	0.30
46	0.31
47	0.32
48	0.33
49	0.34
50	0.35
51	0.36
52	0.37
53	0.38
54	0.39
55	0.40
56	0.41

Source: Cour-Palais Report, Southwest Research Institute, June 1996

Table 1: Shuttle Suit Element Surface Areas

Suit Elements	Material Layup	Failure Criteria	S. Area [m^2]	Total Area [m^2]	Hard Area [m^2]	
Boots	*TMG+Bladder*	*NL & 4mm*	*0.46*	*0.46*		
Gloves	*TMG+Bladder*	*NL & 4mm*	*0.10*	*0.56*		
Lower Legs	*TMG+Bladder*	*NL & 4mm*	*0.60*	*1.16*		
Upper Legs	*TMG+Bladder*	*NL & 4mm*	*0.26*	*1.42*		
Lower Arms	*TMG+Bladder*	*NL & 4mm*	*0.38*	*1.80*		
Upper Arms	*TMG+Bladder*	*NL & 4mm*	*0.28*	*2.08*		
Waist Brief	*TMG+Bladder*	*NL*	*0.23*	*2.31*		
Helmet&Visors	*Lexan+Polys.*	*NPS*	*0.21*	*2.52*	*0.21*	0.0586592
HUT	*TMG+Fibergl.*	*NPS*	*0.12*	*2.64*	*0.33*	
D&CM	*TMG+1.6mm Alu*	*NPS*	*0.05*	*2.69*	*0.38*	
PLSS: Valves etc.	*TMG+1.6mm Alu*	*NPS*	*0.31*	*3.00*	*0.69*	
PLSS: CCC	*TMG+2.3mm Alu*	*NL & 4mm*	*0.07*	*3.07*	*0.76*	
PLSS: Batt Cover	*TMG+0.46mm Alu*	*NPS*	*0.03*	*3.10*	*0.79*	
PLSS: Primary Gox	*TMG+3.6mm Alu*	*NPS*	*0.24*	*3.34*	*1.03*	0.0670391
PLSS: Secondary Gox	*TMG+1.8mm Alu*	*NPS*	*0.24*	*3.58*	*1.27*	
Sizing Rings	*TMG+3.2mm Alu*	*NPS*	*variable*			

Total surface area:	*2.31*	3.58	
Total area soft parts:	*1.27*	2.31	**64.53%**
Total area hard parts:		1.27	**35.47%**

Source: Kosmo, Joseph J e-mail, Subject: Status of EMU Material Sample Impact Tests, 24.02.1997

HITF Shoot	*Mat.*	*Proj. Dia.* [mm]	*Volume* [cm^3]	*Mass* [g]	*Speed* [km/s]	*Energy* [J]	*Angle* [deg]	*Vertical Impact* *Energy* [J]	*Result* [Bladder]
A2905	Al	0.299	0.000112	0.000311	6.85	5.25	0	5.25	No Hole
A2894	Al	0.300	0.000113	0.000314	7.00	5.54	0	5.54	No Hole
A2896	Al	0.392	0.000252	0.000701	6.90	12.01	0	12.01	No Hole
A2897	Al	0.404	0.000276	0.000768	6.68	12.32	0	12.32	No Hole
A2900	Al	0.500	0.000524	0.001456	7.03	25.88	0	25.88	No Hole
A2907	Al	0.600	0.000905	0.002515	6.95	43.70	0	43.70	Pinhole
A2910	Al	0.599	0.000900	0.002503	5.79	30.18	0	30.18	Hole (1.3mm)
A2911	Al	0.520	0.000589	0.001637	4.35	11.14	0	11.14	No Hole
A2912	Al	0.794	0.002097	0.005829	5.23	57.35	0	57.35	Hole (2.5x2.1mm)
A2929	Al	0.407	0.000282	0.000785	6.95	13.64	30	11.81	No Hole
A2930	Al	0.495	0.000508	0.001412	6.84	23.77	30	20.58	Pinhole
A2931	Al	0.608	0.000941	0.002617	7.18	48.53	30	42.03	Hole (0.5mm)
A2932	Al	0.517	0.000579	0.001609	5.66	18.54	30	16.06	Hole (0.8mm)
A2933	Al	0.404	0.000276	0.000768	7.11	13.96	45	9.87	No Hole

Specific Mass Al [g/cm^3]: **2.78**

Kinetic Energy [J]: **(Mass x Velocity^2)/2; [Mass]=kg, [Velocity] = m/s**

Table2: Space Shuttle Suit Ballistic Limits

Suit Element	Failure Mode	Meteoroid BL [J]	Debris BL [J]
Arms&Legs	No Leak	3.4	3.2
Arms&Legs	4 mm Hole	68.0	56.0
Boots&Gloves	No Leak	3.4	3.2
Boots&Gloves	4 mm Hole	68.0	56.0
Sizing Rings	No Spall/Leak	47.6	39.3
HUT	No Spall/Leak	70.0	44.0
Waist(Brief)	No Leak	3.4	3.2
Helmet&Visor	No Spall/Leak	167.0	71.0
D&CM	Not Critical	NA	NA
D&CM	No Spall/Leak	11.5	10.0
PLSS: Primary GOX	No Spall/Leak	76.0	60.4
PLSS: Secondary GOX	No Spall/Leak	15.4	13.4
PLSS: CCC	No Spall/Leak	25.5	21.4
PLSS: CCC	4 mm Hole	172.0	71.0
PLSS: Battery Cover	No Spall/Leak	3.5	3.5
PLSS: Valves etc.	Not Critical	NA	NA
PLSS: Valves etc.	No Spall/Leak	11.5	10.0

Assumptions

Assumption: Diameter **[Final Model.xls]Model - Cell: E23**

Custom distribution with parameters:

	Value	Relative Prob.
	0.030	0.734615
	0.040	0.170769
	0.050	0.053077
	0.060	0.020385
	0.070	0.009231
	0.080	0.004577
	0.090	0.002529
	0.100	0.001490
	0.110	0.000933
	0.120	0.000615
	0.130	0.001779
Total Relative Probability		1.000000

Assumption: Particle Hit **[Final Model.xls]Model - Cell: B23**

Custom distribution with parameters:

	Value	Relative Prob.
	0.00	0.982420
	1.00	0.017580
Total Relative Probability		1.000000

Assumption: LSS Perf. **[Final Model.xls]Model - Cell: K32**

Custom distribution with parameters:

	Value	Relative Prob.
Single point	0.00	0.001000
Single point	1.00	0.999000
Total Relative Probability		1.000000

Assumption: Ksi **[Final Model.xls]Model - Cell: G32**

(random variable used to simulate oxygen left in primary GOX after penetration)

Uniform distribution with parameters:

Minimum	0.00
Maximum	1.00

Assumption: Ignition **[Final Model.xls]Model - Cell: H38**

Custom distribution with parameters:

	Value	Relative Prob.
Single point	0.00	0.999000
Single point	1.00	0.001000
Total Relative Probability		1.000000

Assumption: Part of Suit — **[Final Model.xls]Model - Cell: K23**

Custom distribution with parameters:

		Relative Prob.
Single point	0.00	0.640000
Single point	1.00	0.230000
Single point	2.00	0.070000
Single point	3.00	0.060000
Total Relative Probability		1.000000

Assumption: Shielding — **[Final Model.xls]Model - Cell: B29**

Custom distribution with parameters:

		Relative Prob.
Single point	0.00	0.504167
Single point	1.00	0.495833
Total Relative Probability		1.000000

Assumption: Particle — **[Final Model.xls]Model - Cell: B34**

Custom distribution with parameters:

		Relative Prob.
Single point	1.00	0.635393
Single point	2.00	0.364607
Total Relative Probability		1.000000

Assumption: H2Impact Angle — **[Final Model.xls]Model - Cell: H24**

(the output was multiplied by 90)

Beta distribution with parameters:

Alpha	1.00
Beta	4.00
Scale	1.000

Selected range is from 0.000 to +Infinity

Assumption: MM Diameter — **[Final Model.xls]Model - Cell: E40**

Custom distribution with parameters:

		Relative Prob.
	0.030	0.626761
	0.040	0.203658
	0.050	0.081764
	0.060	0.037889
	0.070	0.019481
	0.080	0.010839
	0.090	0.006416
	0.100	0.003994
	0.110	0.002590
	0.120	0.006607
Total Relative Probability		1.000000