NASA Contractor Report 3855

Space Station Crew Safety Alternatives Study—Final Report

Volume II—Threat Development

R. F. Raasch, R. L. Peercy, Jr.,
and L. A. Rockoff

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Volume II—Threat Development

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ACKNOWLEDGEMENTS

In addition to assessing risks, this report aggregates released data that has been in preparation by the aerospace community since 1968. The report surveys broad areas of interest and calls on reference data to support concept development and risk assessment. Rather than footnoting individual references, each reference is identified by a parenthetical number that correlates with the entry number in the Literature Search printout, appendix A of volume IV of this report.

The co-monitors of Contract NAS1-17242, Bob Witcofski of NASA-Langley Research Center, and Marc Cohen of NASA-Ames Research Center supported the development, data input and direction for this study report. This help was appreciated.

The Rockwell Safety Group contributors included W. W. Gates, H. H. Giar, G. H. Mead, R. L. Peercy, Jr., L. A. Rockoff and P. R. Schwemler.

FOREWORD

This report is one of five documents covering the results of the Space Station Crew Safety Alternatives Study conducted under Contract NAS1-17242. The study documentation is designated as follows:

Vol. I	- Final Summary Report (NASA CR-3854)
Vol. II	- Threat Development (NASA CR-3855)
Vol. III	- Safety Impact of Human Factors (NASA CR-3856)
Vol. IV	- Appendices (NASA CR-3857)
Vol. V	- Space Station Safety Plan (NASA CR-3858)

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1. INTRODUCTION

The Space Station Crew Safety Alternative Study objectives were to develop a threat definition for the space station as concerns crew safety, postulate and assess strategy options to address the threats and develop threat-alleviating safety criteria and guidelines. The special studies of extravehicular activity, escape/rescue and safety impacts of human factors are covered elsewhere in this report:

Extravehicular Activity	- Volume I, Section 6
Escape/Rescue	- Volume I, Section 5
Safety Impacts of Human Factors	- Volume III

APPROACH

The approach used to develop the threats is shown in Figure 1-1. A candidate baseline safety philosophy was presented to NASA-HQ and the safety community in April, 1983. This philosophy, subsequently accepted, is stated as:

> Threats to the space station shall cause no damage to the space station or injury to the crew which will result in a suspension of planned tasks or a loss of the mission.

This selected philosophy was a trade-off between a threat causing no damage to the station and no injury to the crew and a threat forcing crew survival at the cost of the station. The former would probably not be achievable within realistic cost constraints and the latter would pose an extremely high risk to the station. The selected philosophy then allows some risk acceptance and appears to be within reasonable dollar constraints. This philosophy was a guiding factor in assessing configurations, scenarios and operations.

It should be noted that normal mission redundancy requirement that will be levied on space station design does much to alleviate threat impact, and as such, these costs to achieve system redundancy are not wholly chargeable to safety. This assumed redundancy posture is noted in Volume IV, Appendix E of this report.

THREAT DEFINITION

According to the logic flow in Figure 1-1, the configuration, the scenarios and the operations defined a threat posture. Assessment of these three mission elements defined the threat posture as shown in Table 1-1. The candidate space station hazards are subsets of the threat. For instance, the twenty-three threats generated approximately one-hundred fifty candidate hazards. On Table 1-1, the threats marked were selected as being the program cost drivers. This initial preselection had to be made so that the study could stay within its cost and schedule constraints.

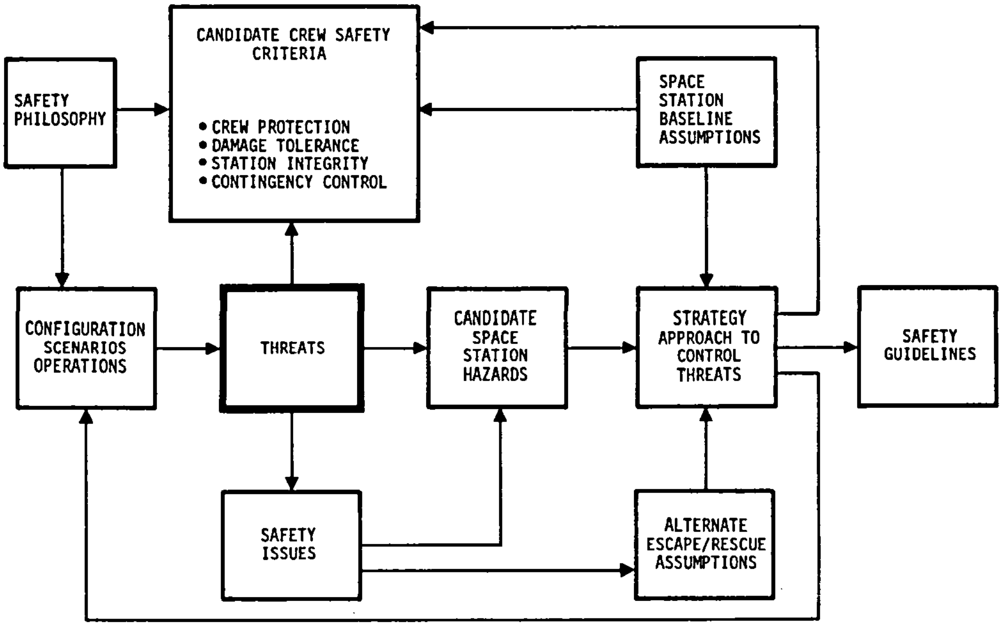

Figure 1-1 Threat Development Approach

TABLE 1-1 SPACE STATION CREW SAFETY THREAT LIST

\- Fire
Leakage
Tumbling/Loss of Control
\- Biological or Toxic Contamination
\- Injury/Illness
Grazing/Collision
Corrosion
Mechanical Damage
\- Explosion
\- Loss of Pressurization
\- Radiation
Out-of-Control IVA/EVA Astronaut
Inadvertent Operations
Lack of Crew Coordination
Abandonment of Space Station
Electric Shock
\- Meteoroid Penetration
Stores/Consumables Depletion
Structural Erosion
Orbit Decay
Loss of Access to a Hatch
Temperature Extremes
\- Debris
Free Orbit (EVA Astronaut)

THREAT ASSESSMENT

Each of the threats highlighted in Table 1-1 is addressed separately in this volume. A summary assessment of the issues, Table 1-2, indicated that not all the selected threats were as severe as anticipated, that is, fire, explosion, loss of pressurization were controllable by design/operational solutions. Both design-to-preclude and design-to-control approaches to resolve these threats appear to be within the state-of-the-art or good design practice. The meteoroid issue appears to be less a driver than is debris. The probability of a large meteoroid hit is about 1 in 10,000 years in the low earth orbit. On the other hand. the "Lack of Crew Coordination", together with "Injury/Illness" prompted a study follow-on task to investigate the safety impacts of human factors (See Volume III of this report).

THREAT IMPACT SUMMARY

Table 1-2 summarizes the major threats that drive program costs and indicates alleviating strategies recommended to address each issue. Strategies whose implementation require further study are discussed in Section 12 of this volume, Section 13 of Volume III and summarized in Section 8 of Volume I.

As stated, this volume addresses the following threats:

SECTION	THREAT
2.	Fire
3.	Biological or Toxic Contamination
4.	Injury/Illness
5.	Explosion/Implosion
6.	Loss of Pressurization
7.	Radiation
8.	Meteoroid Penetration
9.	Debris

In each case, the threat is defined, and the threat background is discussed. Figure 1-2 suggests handling strategies. The strategy options selected drive the criteria definition. Section 10 of this volume shows the relationship of the criteria to the driving threats. The criteria were not developed necessarily on a threat-per-threat basis. That is why the relationships, summarized in Section 10, have one or more threats per criterion.

TABLE 1-2 THREAT SUMMARY ISSUES

ENVIRONMENT (THREATS)	THREAT	STRATEGIES
NATURAL	• DEBRIS • RADIATION	• INTEGRATED BARRIER SYSTEM DEVELOPMENT
INDUCED	• CONTAMINATION	• MATERIAL REQUIREMENTS DEVELOPMENT, SCREENING CATALOGING, REAL-TIME MONITORING, INVENTORYING, DISPOSAL & CONTROL SYSTEM
	• LACK OF COORDINATION* • HUMAN/SOFTWARE SYSTEM INTERACTION • MAN/MACHINE INTERACTION • ATTITUDE ISSUES	• CREW SELECTION ORIENTATION, INDOCTRINATION & TRACKING PROGRAM • CREW (ORBIT/GROUND) TRAINING PROGRAM
INHERENT	• INJURY/ILLNESS	• LOW "G" RESCUE VEHICLE • REAL-TIME HEALTH MONITORING • CREW FITNESS MAINTENANCE • MINIMUM MEDICAL FACILITY

*NOT INITIALLY RECOGNIZED AS MAJOR THREAT

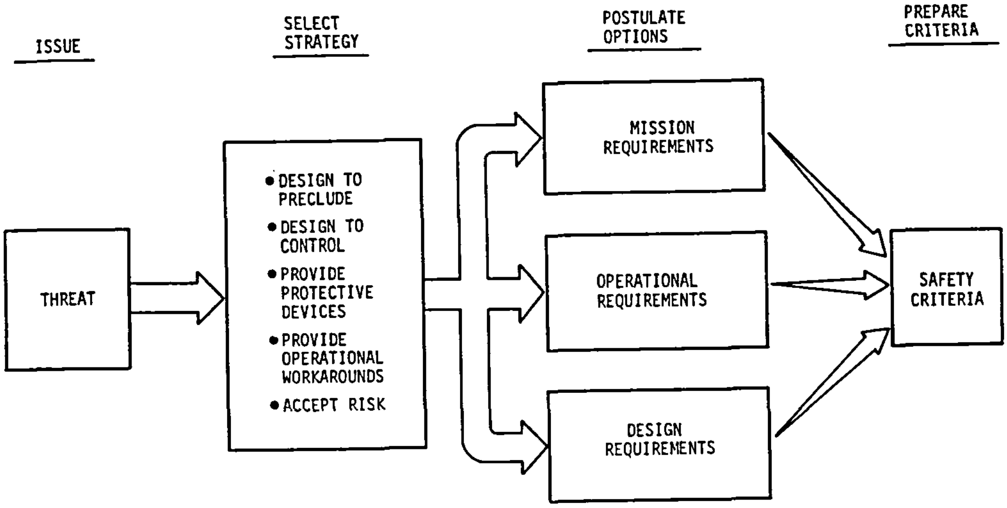

Figure 1-2 Criteria Development

2. FIRE

DEFINITION

Fire threats are associated with an area containing subsystems equipment, electrical wiring, or laboratory equipment, or in personnel areas which damages and puts out of commission unprotected operating equipment in a compartment. Fire prevention in design leans heavily on isolating the elements of combustion: Fuel, Oxidizer and Ignition. In a two-gas system (80% N2 and 20% O2), the fuel is excluded only if all materials are screened for flammability. Applying "NASA MSC Requirements for Materials and Processes", JSC-SE-0006B, through the RI-SD Material Control (MATCO) program, screened shuttle materials for flammability. In a 100% O2 environment (such as in EVA pre-breathing areas), all surface temperatures must be analyzed to ensure that no ignition sources are available and the contained materials are not flammable at high O2 concentrations. "Environment Requirements and Test Criteria for the Orbiter Vehicle", MF0004-014C, cites maximum allowable surface temperatures in each of the compartments based on the potential fluid leaked into the compartment. Fluid leaks are considered credible. Additionally, smoke/fire sensing and supression could be included in Damage Control design.

DISCUSSION

Fire on board the space station is the threat with potentially the most catastrophic consequences. Hence, every precaution must be taken to preclude its occurrence. An added precaution is also essential -- that the adequate strategies exist to mitigate its consequences should a fire occur. The development of strategies requires that one fully understands the causative factors involved in a fire as well as the added parameters that a space station introduces to the problem. First, because there is a zero or micro-g environment, the only convection currents in the atmosphere would be those introduced by fans used in cooling avionics or other hardware which may cause a brief fine intensity. A second difference is that flame fronts behave and propogate differently (more slowly, in general) in a zero or micro-g environment (refs. 271, 272, 269 & 273). A third difference is the proximity to the vacuum of space which has both advantages such as ease of depleting the oxygen level below the oxygen partial pressure (ref. 271, pg.9), which will support combustion, and disadvantages such as a rupture or penetration of a pressure wall that can cause a turbulence in the atmosphere and unpredictable damage. Flashover to adjacent material is also possible (ref. 271, pg. 9). Although these parameters do not present insurmountable issues, they are a portion of the environment and should be considered as a segment of a total strategy.

CAUSES

The following paragraphs summarize three major causes of fire. Similar emphasis is also placed on electrical ignition sources because of the unique characteristic that most electrical ignition sources may result in continuous power application and greater probability of pyrolisis.

These causitive factors and corresponding strategies are shown in Table 2-1. (This is not an all-inclusive list as there are other causitive factors and attendant strategies. For example, among the issues that are not addressed are fire-fighting techniques and attendant limitations. This discussion is beyond the scope of the study.)

TABLE 2-1 STRATEGY DEVELOPMENT FOR THE THREAT OF FIRE

THREAT	CAUSATIVE FACTORS	STRATEGY(IES)
FIRE	GROUND & SPACE HABITABLE AREAS • FUEL/OXIDIZER/IGNITION SOURCES COEXIST	1. EXCLUDE TWO OF THE THREE ELEMENTS 2. WHEN TWO ELEMENTS ARE PRESENT, INERT 3. MATERIALS CONTROLS
	SPACE NONHABITABLE AREAS • FUEL/OXIDIZER/IGNITION SOURCES/ TEMPERATURE/PRESSURE COEXIST	1. EXCLUDE THREE OF THE FIVE ELEMENTS 2. MATERIALS CONTROL
	• CATALYTIC REACTION	1. INERT ENVIRONMENT 2. CONTROL SURFACE TEMPERATURE 3. MATERIALS CONTROL
	• CHEMICAL REACTION	1. INERT ENVIRONMENT 2. MATERIALS CONTROLS 3. EXTINGUISHING AGENTS
	• IGNITION SOURCES (ELECTRICAL/ELECTROSTATIC)	1. PROPER GROUNDING/BONDING 2. WIRING CONTROLS 3. PROPER CIRCUIT PROTECTION 4. ISOLATION OF CIRCUITS FROM COMBUSTIBLE MATERIALS 5. MATERIAL SELECTION

Coexistance of Ignition Source/Fuel/Oxidizer

Consider the first entry in Table 2-1, which is perhaps the most common source of fire particularly in a pre-launch environment. To illustrate the strategy by drawing upon some shuttle experience, visualize a fire triangle consisting of fuel, oxidizer and an ignition source. Generally, one feels comfortable whenever one leg of a fire triangle is broken. However, in the case of the shuttle, it was part of the fail-safe design philosophy to break two legs of the fire triangle so that should another leg occur as the result of a failure or other incident, the vehicle is still safe. Always being "fail-safe" means that if fuel exists, oxidizers and an ignition source are excluded, etc. When two of the three elements exist, then there are other methods of safing, such as inerting. Other options that are available include the judicious selection of materials. Particularly important is the requirement that no flammable materials are selected for use within a habitable area. Another requirement is that flammable fluids or oxidizers be excluded from habitable areas.

The above scenario applies to the fire threat in the pre-launch environment or in a habitable area on orbit. When considering other environments of orbital operations, the fire triangle becomes a penta-ring by expanding it to include the two additional "sides" of temperature and pressure. By the reduction or elimination of one or more sides, a fire can be prevented or extinguished. For example, dumping to vacuum is an accepted technique of quenching a fire for those very limited cases where it can be used.

Generally solids and liquids do not burn by themselves. Except for a few materials such as carbon and some metals, a change of state is necessary. Only gases burn, whether in the free state or released from solids or liquids by an evaporation process. In order for solids or liquids to perform as fuels, the first step is for energy, frequently in the form of heat, to evaporate some of the material to a gas. This energy can be generated by compression or friction with adjacent materials; or supplied by a high-temperature source in conjunction with radiation, convection, or condition; or some combination of these processes may be very complicated. (Ref. 268, pg. 7)

J. H. Kimzey in Reference 268, page 6, indicates: "The conditions to initiate combustion are far more complex than are generally believed. For example, it is misleading to refer to the ignition temperature of a material as if it were a chemical property. The following factors must all be considered in determining whether ignition will occur:

1. Composition and physical state of fuel
2. Composition and physical state of the oxidizer
3. Pressure, stress, or other internal forces
4. Gravitational force field
5. Temperature and enthalpy of container, fuel, and oxidizer
6. Energy media
7. System restraints
8. Surface area, texture, and particle size
9. Degree of mixing or stratification
10. Stability or degress of self-degradation
11. Catalyst
12. Thermal conductivity
13. Time

The above items should be considered in terms of changing conditions as well as the rate of change. This list is not intended to imply that all of the factors are separate effects, nor that all of the factors can even occur, to a greater or lesser degree, at the same time. In some cases, many of these factors are negligible to the extent that their values are not measurable."

Catalytic Reactions

One subject that is quite often overlooked, as design solutions are considered, is the consequence of chemical and/or catalytic reactions. One of the areas with which safety engineering is very much concerned is the number of high-energy fluids that may be used, such as hydrazine, which may impinge upon a metallic or other surface that can cause an increase in temperature. If this surface continues to be exposed to the hypergolics, such as hydrazine as an example, the material will continue to increase in temperature until a thermal runaway occurs. (Ref. A, B, & C). This thermal phenomenon has been named "Thermal Regeneration Temperature" and is described below for hydrazine.

Hydrazine is a simple chemical consisting of two atoms of nitrogen and four atoms of hydrogen. This material is a clear colorless hygroscopic liquid which at standard temperature and pressure is very stable. However, it is both toxic and flammable. Hydrazine is often used as a monopropellant in space operations since it does not require an oxidizer to release its energy. The hazards associated with hydrazine are emphasized by its extremely wide flammability range of 4.7 to 100 percent with a flash point of 100°F. However, its catalytic action is such that the National Fire Protection Association, (Ref. Std. 49), indicates spontaneous ignition temperature varies from 75°F (iron rust surface) to 518°F (for a Pyrex glass surface). Hydrazine may ignite spontaneously in air when in contact with porous materials such as cloth. Spontaneous ignition can occur with oxidants like hydrogen peroxide and nitric acid. Contact with many metallic oxide surfaces may lead to flaming decomposition. (316, 317, 318)

Decomposition - The decomposition reaction of hydrazine is different from the oxidation reaction. This reaction can occur in either the gas or liquid phase. The products of the reaction, and, therefore the energy released, vary with the catalyst design. The maximum energy is obtained when the products are ammonia and nitrogen, although a possible reaction contains no ammonia.

Oxidation - The reaction of hydrazine and oxygen also occurs in either the gas or liquid phase. In air, hydrazine is easily ignited and burns with a blue flame. Again, there are two extremes to consider, depending on whether or not ammonia is a final product. Combinations of the oxidation reactions are typical and are considered rapid as compared to the decomposition reaction, although detonation may occur in both decomposition and oxidation.

Under the direction of Mr. J. H. Kimzey of JSC, a series of tests at WSTF were performed to characterize some of these high-energy fluids for shuttle applications. These test results provide perhaps the best collection of data on the catalytic effects of materials to date. A Minimum Reaction Temperature (MRT), where a specimen showed a 5°F temperature rise when small quantities of hydrazine was injected at rates of 50 microliters each 30 seconds and a Thermal Regeneration Temperature (TRT) where the temperature did not stabilize but continued to rise beyond the autoignition temperature of hydrazine, were defined. Of interest is that all metallics tested exhibited MRT and TRT characteristics, while non-metallics exhibited only a MRT. (Ref. C). See Figures 2-1, 2-2, & 2-3 which characterize the TRT plots of metals. Maximum temperature rises varied with the metal and air flow.

During testing at WSTF per the test plan TP-WSTF-025 dated 5-1-75, the autoignition temperature of hydrazine in air increased from approximately 320°F at 14.7 psia to 550°F at 2.0 psia. (See Figure 2-4). The reactions were generally characterized by a slow start which elevated temperature and pressure so that as a result, it became a rapid detonation. Catalytic effects of the 304 stainless steel test vessel may be a factor in results obtained. Time delays varied from 0.5 to 27 seconds after injection of the fuel that autoignition was detected. All testing at 1 psia was negative. At 2 psia only four of 37 attempts ignited despite varying temperatures and fuel ratios. It was therefore concluded that the lowest pressure at which hydrazine can ignite in air is 2 psia using a 2.8 liter vessel of 304 SS.

The MMH results were comparable but the autoignition temperatures were lower. Autoignition temperature of MMH in air increased from approximately 260°F at 14.7 psia to 420°F at 3.0 psia as in Figure 2-5 (See WSTF Test Reports, TR 205-001 to 005). The rate was similar, starting slowly and evolving into a detonation as the reaction proceeded. Time delays from injection of the fuel to auto- ignition varied from two to 82 seconds. Limiting testing in nitrogen rather than air showed "no indication of any significant decomposition as measured by the test system instrumentation." The lowest pressure at which MMH can ignite in air was found to be 3 psia using a 2.8 liter vessel of 304 SS.

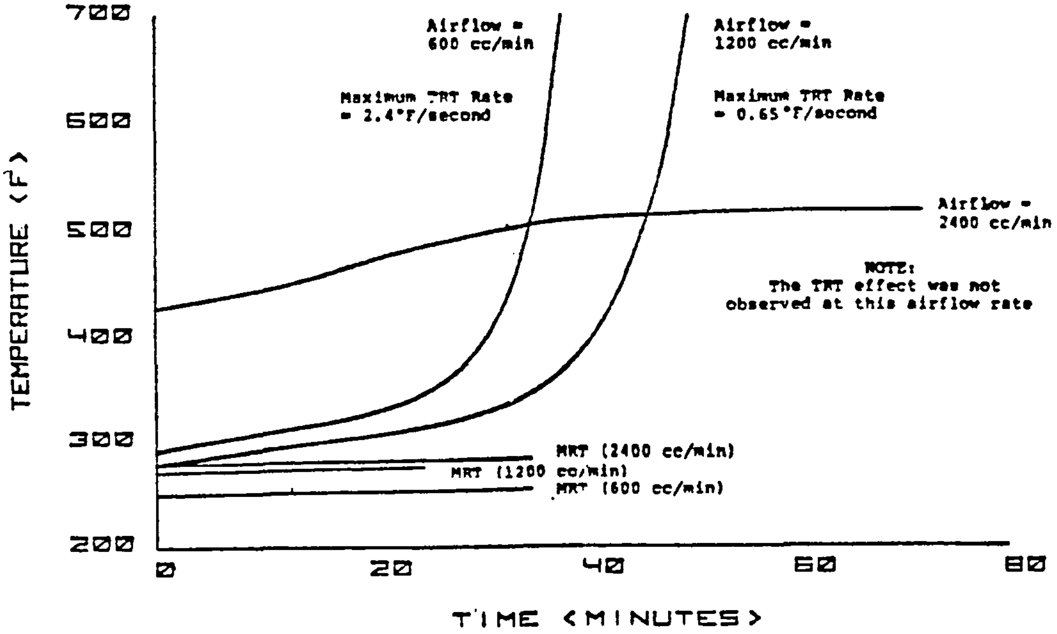

Figure 2-1 Thermal Regeneration Temperature Curves of 304 Stainless Steel: Effect of Airflow Rate

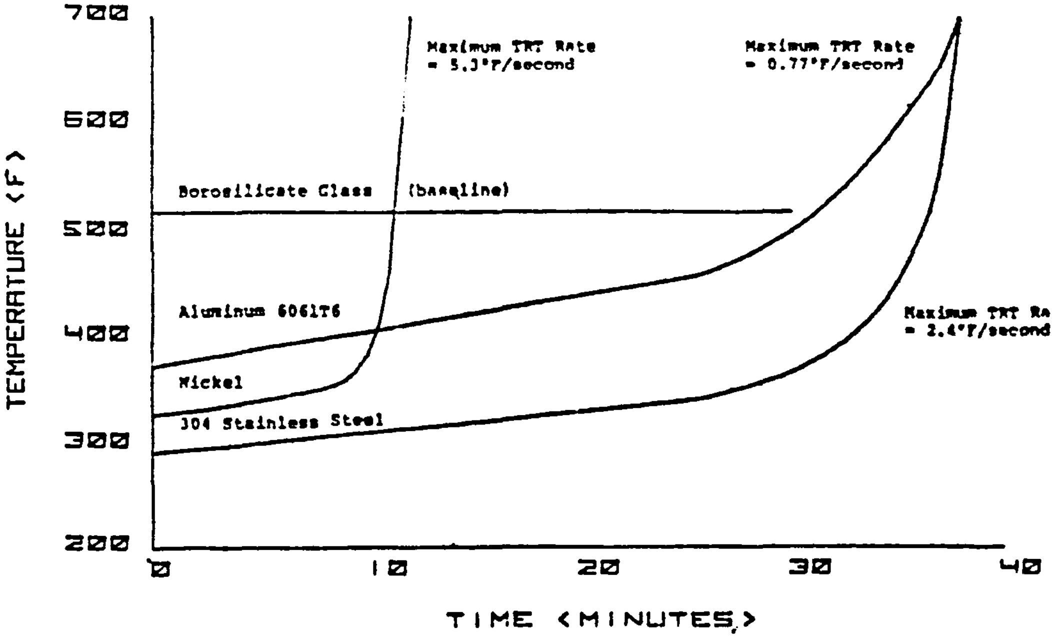

Figure 2-2 Thermal Regeneration Temperature Curves of Various Materials (Air Flow Rate = 600 cc/min)

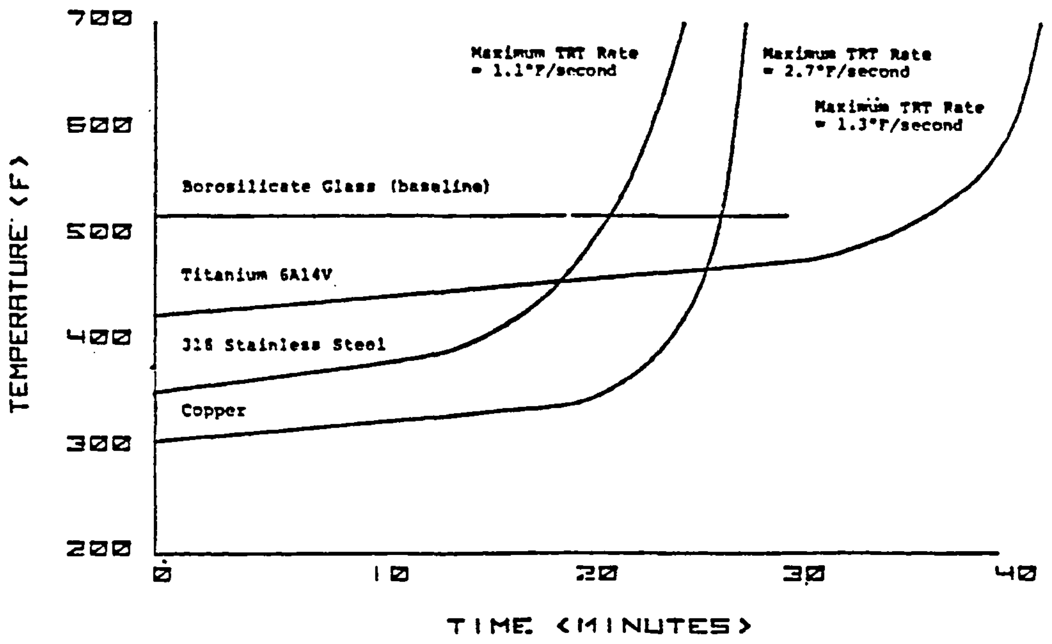

Figure 2-3 Thermal Regeneration Temperature Curves of Various Materials (Air Flow Rate = 600 cc/min)

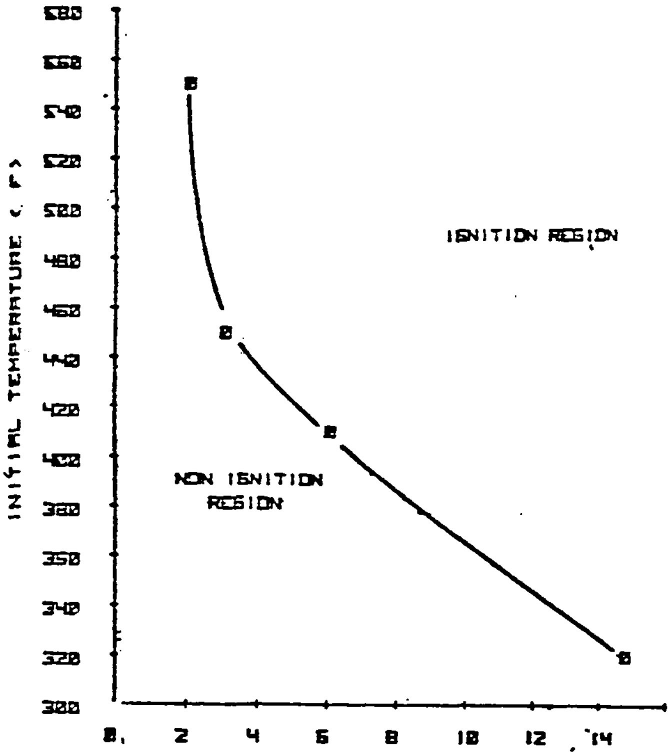

Figure 2-4 Autoignition Temperature of Hydrazine at Reduced Pressure in a closed 304 Stainless Steel Chamber

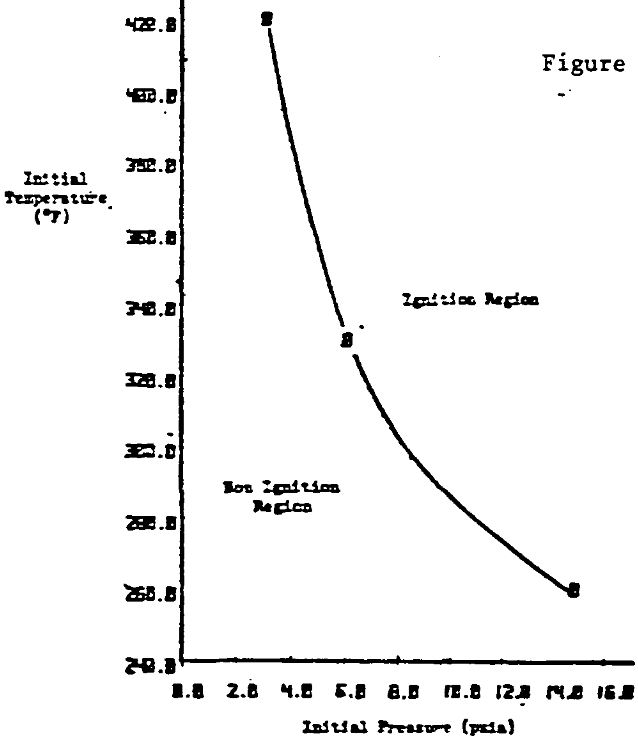

Figure 2-5 Autoignition Temperature at Reduced Pressure in a Closed 304 Stainless Steel Chamber

Chemical Reactions

Two major categories of reactions are of concern; decomposition and oxidation. In the hydrazine and MMH examples discussed earlier, it was noted that both of these mechanisms were of significance. In Table 2-2 below fluids and solids are shown as either oxidizing or reducing agents.

Table 2-2 Oxidizing/Reducing Agents

FLUIDS		MATERIALS	
OXIDIZING AGENTS	REDUCING AGENTS	OXIDIZING AGENTS	REDUCING AGENTS
N_2O_4	HYDRAULIC FLUIDS	NONE	Al ALLOYS
LOX	MMH		STEELS
GOX	N_2H_4		Ni ALLOYS
AIR	LH_2		Co ALLOYS
	F-21		Ti ALLOYS
	FC-40		ADHESIVES
	NH_3		FINISHES
	LUBE OIL		PLASTICS
			POTTING COMPOUNDS

Supporting data for Table 2-2:

1. Rate of reactions is a function of the stability of the agents.

   Very unstable highly reactive oxidizing and reducing agents will react in a rapid and violent manner, such as N_2O_4 and MMH or N_2H_4. However, stable oxidizing and reducing agents produce slow reaction, such as oxygen and iron.

2. Solids are more stable than liquids, and liquids are more stable than gases.

3. The rate of reaction between solid and either a liquid or a gas is quite slow due to the limited exposed surfaces of the solid.

STRATEGY OPTIONS

Some of the strategies that were used on the Shuttle as methods of counteracting the particular threat of fire are shown in Tables 2-3 and 2-4.

The first line of defense should be "design to preclude" as illustrated in Table 2-3. Recognize that there are two types of threats (simple and complex) based on the physics of causitive factors. It should be noted that for a complex threat, the solution is generally complex. The strategy issue is not the fire itself but rather dealing with the causitive factors, such as the ignition sources, fuels and oxidizers. Another point of significance is that there is not one simple solution but rather a family of solutions. Some of the things that are done to preclude fire may be very helpful in precluding some of the other threats as shown in Table 2-3. Consider toxicity and explosion, since some of the measures to lessen the risk of fire will lessen these other threats. However, in some cases the solutions for controlling threats have just the opposite effect. In these cases, whenever one takes certain steps to control a given threat, the consequence may be an adverse response to another threat, creating a worse situation, and some of these will be examined in later sections.

The second line of defense here is "design to control" (See Table 2-4). In essence what this defense presumes is that the design to preclude worked but was not 100% effective. If one assumes that a fire will occur, some of the things one could do are shown in this figure, such as building compartments. Some of the compartments on the shuttle orbiter are there solely to deal with the issue of fire and/or toxicity. Table 2-5 shows the compartments or zones of the orbiter vehicle and some of the data provided to designers to preclude fire generation/propagation. The Table 2-5 compartments were assessed and the highest allowable temperature, for the volatiles involved, were stated.

In the area of strategies it is of paramount importance to fully understand the characteristics of the materials, fluids and gases present within the design solutions. This philosophy is particularly critical when dealing with hydrazine, MMH, Aerozine 50 and other propellants. Designs must consider normal characteristics as well as out-of-tolerance conditions and assure that the configurations selected are tolerant of and forgiving in all postulated events. These are the kinds of issues that require strategies to be considered in the early design portion of the program so that safeguards, such as protective coatings, inert environments, etc., may be created and steps taken to assure that surface temperatures remain sufficiently low that the vehicle will be tolerant of this type of problem.

One of the best summaries discovered by this author was an internal JSC memo prepared by J.H. Kimzey. His eight conclusions are listed verbatim.

Testing is difficult because of the hazards in working with hydrazine. Therefore, there are few places qualified to do the high quality, fully instrumented, tasks as the NASA White Sands Test Facility in New Mexico.

TABLE 2-3 STRATEGIES TO COUNTERACT THREATS - DESIGN TO PRECLUDE

DESIGN TO PRECLUDE

THREAT ELEMENTS THAT PRECLUDE	FIRE	TOXICITY	EXPLOSION	LOSS OF CRITICAL FUNCTION
2-GAS SYSTEM -14.7 PSI	●			
MATERIALS/WIRING CONTROL	●	●	●	
FLUID LINE CONSTRUCTION	●	●	●	
BONDING/GROUNDING	●		●	
IGNITION SOURCE CONTROL	●		●	●
FAIL-SAFE DESIGN & SAFETY FACTORS	●	●	●	●
INTERLOCK/INHIBIT CRITICAL FUNCTIONS				●
PRESSURE VESSELS •FILAMENT WOUND •HIGH SAFETY FACTOR	●		●	●

TABLE 2-4 STRATEGIES TO COUNTERACT THREATS - DESIGN TO CONTROL

DESIGN TO CONTROL

THREAT ELEMENTS THAT CONTROL	FIRE	TOXICITY	EXPLOSION	STRUCTURAL FAILURE
COMPARTMENTATION	●	●	●	
PURGE & HAZARDOUS GAS DETECTION	●	●	●	
ACTIVE VENT SYSTEM			●	
CABIN SMOKE DETECTION	●			
REMOTE & PORTABLE FIRE EXTINGUISHERS	●			●
DAMAGE CONTROL INSTRUMENTATION & ANNUNCIATORS	●	●		●

TABLE 2-5 ORBITER COMPARTMENTS/ZONES
(FROM MF0004-014 & SD74-SH-0223B)

COMPARTMENT (1)	OPERATIONAL FLUIDS NORMALLY PRESENT	ZONE (2)	IGNITION PREVENTION ZONE (6)	MAX ALLOW SURFACE TEMP TO PREVENT AN AUTO IGNITION -DEGREES F (6)
NOSE SPHERE	(NONE)	I	NO	--
FORWARD RCS	N2O4, MMH He	II	YES	352
NOSE GEAR WELL	HYD FL (83282&5606)			
FWD MODULE PLENUM	HYD FL (83282), H2O	III (4)	YES	352
WINDOW CAVITIES	(NONE)			
STAR TRACKER CAVITY	(NONE)			
MID-FUSELAGE	LH2, LO2, HYD FL (83282), MMH, He, N2O4, F21, H2O, N2,FC40(3)			
CREW MODULE	N2/O2, GO2, 1301, H2O	IV	NO	--
WING LEADING EDGE (L&R)	(NONE)	V, VI	NO	--
WING BOX (L&R)	(NONE)	VII, VIII	YES	423
MAIN GEAR WELL (L&R)	HYD FL (83282&5606)			
WING/ELEVON INTERCAVITY (L&R)	HYD FL (83282)			
AFT FUSELAGE	LH2, LO2, HYD FL (83282), MMH, NH3, LUBE OIL, N2H4, F21, He H2O, N2O4	IX (4)	YES	352
VERT. STABILIZER FWD OF REAR SPAR	(NONE)			
VERT. STABILIZER AFT OF SPAR (REAR)	HYD FL (83282)	X	YES	432
OMS/RCS POD (L&R)	N2O4, MMH, He, N2	XI, XII	YES	352
ME LO2 DISCONNECT	LO2	XIII	YES (5)	(5)
BODY FLAP	HYD FL (83282)	XV	YES	432
LH2 UMBIL CAVITY	LH2, HYD FL (83282), F21, He, N2	XVI	YES	432
LO2 UMBIL CAVITY	LO2, He N2	XVII	YES (5)	(5)

It is concluded that the:

1. Ignition temperature of hydrazine varies with:
   a. Materials, clean (in the absence of air)
      1) Aluminum, 2024T-4: 452°F at 350 psia
      2) Stainless steel, 17-7PH: 449°F at 350 psia
      3) Tool steel, M-2: Between 300° and 350° at 350 psia

   Values are lower in air.

   b. Materials, oxidized - The greater (thicker) the oxide the lower the ignition temperature.

   c. Pressure - The lower the pressure, the higher the ignition temperature. Autoignition temperatures of hydrazine in air vary from approximately 320°F at 14.7 psia to 580°F at 2.0 psia in 304 stainless steel. Hydrazine could not be ignited at 1.0 psia in air.

   d. Time - Time delays are typical. For hydrazine ignition in air, values are from 0.5 to 27 seconds, with no apparent relationship to pressure or quantity of fuel injected. Autodecomposition time delays can be very long: 71 to 104 minutes.

2. Adiabatic compression of hydrazine greatly lowers the ignition (autodecomposition) temperature of hydrazine. This is not the case with MMH.

3. Ignition temperature of MMH in air also varies. It was found to be 260°F at 14.7 psia increasing to 420°F at 3.0 psia using a 2.8 liter vessel of 304 SS.

4. Catalytic effects of many materials have been observed when exposed to vapors of hydrazine in air. Both metals and non-metals exhibit a "Minimum Reaction Temperature" (MRT) a temperature at which the material heated five degrees fahrenheit and stabilized.

5. A second catalytic effect, observed from materials exposed to vapors of hydrazine in air, is a "Thermal Regeneration Temperature" (TRT), a temperature at which the temperature continues to rise until ignition takes place. Nonmetallics did not exhibit a TRT value. Values for metals were as low as 314°F for 303 CRES, 318°F for 286 CRES, 322°F for 321 CRES, 343°F for titanium TI-3Al-2.5V, and 354°F for Inconel 600.

6. Coatings can retard catalytic effects, especially Super Koropon primer. Paints containing iron oxide pigment reduce safe temperatures for hydrazine vapors in air, specially Pyromark and brown silicone/glass duct. Also dry film lubricants containing graphite and MoS_2 act as catalysts.

7. The literature contains both correct and incorrect information.

8. The Orbiter has properly designed hydrazine systems from a Materials standpoint. Autodecomposition of hydrazine will not occur in flight if systems are built and operated according to specifications. Leaks of hydrazine (liquid or vapor) will not ignite in the aft compartment if built as designed but may produce damage in electrical insulation.

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3. BIOLOGICAL OR TOXIC CONTAMINATION

DEFINITION

Contamination threats are those associated with biological or toxic contamination of the atmosphere, food or water supply. All similarly packaged food stored in any one area (e.g., all vacuum-packed food stored in one pantry) will be assumed unfit to eat. Similarly, all potable water in connected tanks will also be assumed toxic; the water, however, may be reprocessed through the water purification system and the tanks decontaminated to render water potable. This threat is associated with the release of toxic, flammable, corrosive, condensible, or particulate matter. Contamination is caused by leakage, spillage, outgassing, loose objects, abrasion and from the growth of fungus or release of volatile condensible materials. Leakage of or outgassing of hazardous materials should be prevented by eliminating suspect materials through MATCO screening. Close looks at materials interactions are also required. Where hazardous materials are brought on board, special containment consideration must be given. All materials brought on board should be screened, including astronaut personal effects.

BACKGROUND

Atmospheric Contamination of Spacecraft Habitable Areas is a concern for which procedures must be developed & implemented to determine the identities & quantities of contaminants. Methods & criteria must also be developed to determine external contamination from space debris particles & spacecraft residue.

History: More than 100 contaminant gases have been detected in the Space Shuttle cabin, with most of these concentrations of gases being below a toxicity hazard level.

MATERIALS AND METHODS

Early in the planning of toxicological support for the Shuttle Program, five toxicity areas were identified as of major importance:

1. Establishment of space flight atmosphere toxicity standards:
2. Establishment of a materials selection program.
3. Development of methods for removing spacecraft cabin atmospheric contaminants.
4. Development of procedures and methods for measuring spacecraft cabin atmospheric contaminants.
5. Establishment of procedures and guidelines for conducting toxicological assessments of the spacecraft crew environments.

Establishment of Space Flight Atmosphere Toxicity Standards (312)

A new set of criteria had to be established for space flight which defined the maximum amount of any given contaminant gas or mixtures of gases that could be tolerated in the spacecraft cabin without creating a toxic hazard for the crew. Since the safety of the crew and the success of a mission depends highly on crew performance, the basis for spacecraft toxicity standards were often based upon behavioral toxicity criteria rather than on classical time-weighted averages (TWA) or threshold limit values (TLV).

New inhalation toxicity data were required for space flight, since most existing inhalation toxicity information concerns 40-hr work-week exposures. Since both spacecraft and submarine crews operate in closed environments for long periods of uninterrupted activity, similar atmospheric problems often are experienced. For this reason, the maximum allowable concentration (MAC) value for many atmospheric contaminants for spacecraft and submarine environments are often the same.

Since there was no significant data available for dealing with several days of continuous exposures to trace quantities of many atmospheric contaminants, the National Academy of Sciences was asked for assistance. A list of known spacecraft contaminant gases was submitted to an ad hoc committee composed of governmental, institutional, and industrial toxicologists. The values they recommended were, in most cases, from one-half to one-tenth the values establish for the standard industrial 40-h work-week. These values were designated as spacecraft maximum allowable concentrations (SMAC).

Establishment of a Materials Selection Program (312)

The second area of toxicological consideration involved establishing a program to control the selection of spacecraft materials on the basis of outgassing characteristics. A set of criteria was developed for establishing the means and conditions with which the candidate materials were to be tested. From the toxicity standpoint, the most important information obtained from these tests was to identify and measure outgassed compounds from each material. Further analyses determined the outgassing rates of each identified compound. The criteria for acceptance or rejection of the candidate materials were based upon outgassing characteristics, spacecraft cabin volume, mission duration. SMAC values, and trace contaminant removal capabilities of the spacecraft atmospheric revitalization system (ARS).

Development of Methods For Removal of Spacecraft Cabin Atmospheric Contaminants

The third area of toxicological consideration was to ensure that proper procedures and hardware were incorporated into the spacecraft ARS for the removal and control of outgassed contaminant compounds. This effort required establishing a close working relationship between NASA toxicologists and ARS design and test engineers. As a result of their work, the Shuttle Orbiter ARS removes contaminant gases by three different methods. (312)

The primary method for removal of contaminant gases is by activated carbon adsorption in the ARS carbon dioxide removal bed (lithium hydroxide). Some acid gases are also removed from the cabin air by the lithium hydroxide bed. The second method for contaminant gas removal is in a specially designed cartridge known as the ambient temperature catalytic oxidizer (ATCO), composed of platinum deposited on an activated carbon bed preceeded by another activated carbon bed. The platinum-coated carbon acts as an ambient temperature catalyst to convert cabin carbon monoxide into CO_2. The CO_2 is scrubbed out of the airstream by the lithium hydroxide bed. Some trace contaminant gases are also removed in the activated carbon bed of the ATCO. The third means of trace contaminant gas removal is by the spacecraft ARS dehumidifier system. The relative humidity of the spacecraft cabin is controlled by passing the cabin atmosphere over a cold surface. Water is condensed and eventually removed at this surface. As the cabin trace contaminant gases pass over the same surface, the water-soluble contaminants are carried out of the dehumidifier in the condenser effluent water stream. (312)

Development of Procedures and Methods For Spacecraft Cabin Atmospheric Contaminant Measurements (312)

The fourth area of toxicological consideration concerns the procedures and methods used for conducting analytical measurements of contaminant gases contained in the spacecraft cabin. From previous experiences with analyses of closed environments in ground-based manned chamber tests and in earlier analyses of spacecraft cabin atmospheres, two methods were found to obtain complete qualitative and quantitative information about the spacecraft cabin atmosphere. These two methods have come to be known as the whole-gas and adsorbed-gas sampling methods. Both of these methods are used for ground-based and inflight sampling of Shuttle crew cabin atmospheres. Whole-gas sampling takes instantaneous air samples, while absorbed-gas sampling takes atmospheric samples on a continuous basis.

The ground-based sampling procedure, using the whole-gas method, requires a pressure pump to transfer atmospheric samples into a stainless steel cylinder. The inflight sampling procedure, using the whole-gas method, requires the use of an evacuated stainless steel cylinder. When a sample is to be taken, a valve on the cylinder is momentarily opened and an atmospheric sample is drawn into the cylinder.

The ground-based sampling procedure using the adsorbed-gas sampling method requires pumping cabin atmosphere samples through tubes containing a substrate known as Tenax . This material has a relatively high affinity for most atmospheric contaminant gases, but has the unique property of permitting water vapor to pass through. In flight, space vacuum is used to draw the cabin atmosphere through the Tenax adsorption substrate, which is contained in a tube.

Both the whole-gas and adsorbed-gas samples for the ground-based as well as the inflight samples are returned to the laboratory for chemical analyses by gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS). Quantitative analyses mainly use standard GC-MS procedures, while qualitative determinations use standard GC procedures. Because of the concentrating effect of the adsorbed-gas sampling method, this technique is mainly used for qualitative analyses. The whole-gas samples are the most accurate means of determining quantitative values for the atmospheric contaminants since cylinder samples contain concentrations exactly as they existed in the atmosphere at the time of sampling.

Establishment of Procedures and Guidelines For Conducting Toxicological Assessments of Spacecraft Crew Environments (312)

In most toxicity evaluations involving contaminant gases, only one gas is normally considered at a time. As many as 100 contaminant gases may be present during a mission which, for the Shuttle Orbiter, may last up to 7 days. The SMAC values established for space flight were based upon the following set of criteria.

1. Continuous exposures for 24 h/d for periods up to 7 days.
2. Exposure to a single contaminant gas.
3. No other physiological stressors, e.g. heat, cold, illness, injury, etc.
4. Where toxicity data is not available for a given compound, a SMAC value may be assigned for the compound at a level equal to the toxicity for the most toxic compound in the compound family.

In order to conduct toxicity assessments of data obtained from outgassed samples taken from the Shuttle spacecraft, contaminant gases were categorized into groups according to their relevant toxicological effects on humans. These groupings were:

1. Irritants: e.g. aldehydes and ammonia.
2. Asphyxiants: e.g. carbon monoxide and methane.
3. Central Nervous System Depressants (anesthetics and narcotics): e.g. ethers, ketones, alcohols, and halogenated hydrocarbons.
4. System Poisons: e.g. benzenes, phenals and napthalenes.
5. Particulates: e.g. silicon and asbestos.

Depending upon concentration, the examples shown above in these categories can change from on grouping to another or even exhibit physiological effects in more than one category at the same time. Furthermore, the physiological effects can be additive, synergistic, or subtractive within a given category. Scientific information does not exist for dealing with the possible synergistic effects of the some 100 gases detected in the Shuttle spacecraft cabin.

However, in order to arrive at an overall assessment of the Shuttle cabin atmosphere, only the additive effects in a given physiological category have been considered. Since the Shuttle ARS contains a particulate filter for removing micron-sized materials, particulate matter is not monitored during a mission. For this reason, this category is not addressed in crew cabin toxicity assessments.

Table 3-1 lists the contaminants found in the Shuttle Orbiter in the first five STS flights.

Table 3-1 CONTAMINANTS FOUND IN SHUTTLE ORBITER ATMOSPHERIC SAMPLES (370)

	STS Mission Number				
Compound Identity	1	2	3	4	5
Acetic Acid, n-Butryl Ester	X				
Acetic Acid, 2-Ethoxyethlyester	X				
Benzaldehyde		X			
Benzene	X	X	X		X
Bromotrifluoromethane			X	X	
1-Butanal	X	X	X		
1-Butanol	X	X			
2-Butanone	X	X	X		X
Butene					X
n-Butylbenzene	X				
Carbon Disulfide		X			
Carbon Monoxide	X	X	X		X
Cyclohexane		X			
Decane		X			
Dichlorodifluoromethane				X	
1,1-Dichloroethene		X			
Dichloromethane	X	X	X		X
1,2-Dimethylbenzene	X	X	X		
1,3-Dimethylbenzene	X	X	X		X
1,4-Dimethylbenzene	X				X
1,1-Dimethylethanol	X				
Ethanal	X	X	X		X
Ethanol	X	X	X	X	X
Ethylbenzene	X	X	X		
2-Ethylhexanal		X			
1-Heptanal	X				
Heptane		X	X		
2-Heptanone	X				
3-Heptanone	X				
Hexamethylcyclopentane		X			
Hexamethylcyclotrisiloxane	X				
1-Hexanal	X				
Hexane	X	X			
Indian		X			
Methane	X	X	X	X	X
Methanol	X	X			
2-Methyl-1,3-Butadiene	X				
Methylcyclopentane	X	X			
Methylethylcyclopentane			X		
6-Methyl-2-Heptanone		X			
2-Methylpentane		X			
2-Methyl-1-Propanol		X			
2-Methyl-2-Propanol		X	X		
4-Methyl-2-Propantanone	X		X		
Napthalene		X			
Nonane		X			
Octane		X			
1-Pentanal	X	X	X		
Pentane		X	X		
1-Propanal	X	X	X		

Table 3-1 (Continued)
CONTAMINANTS FOUND IN SHUTTLE ORBITER ATMOSPHERIC SAMPLES

Compound Identity	STS Mission Number 1	2	3	4	5
2-Propanol	X		X		X
2-Propanone	X	X	X	X	X
Propylbenzene	X	X			
Toluene	X	X	X		X
1,1,1-Trichloroethane	X	X	X		
Trichloroethane		X	X		
Triochlorofluoromethane	X	X	X		
1,1,2-Trichloro-1,2,2-Trifluoroethane	X	X	X	X	X
Trimethyl Silanol		X			
C_7-Aliphatic Hydrocarbons (1)*		X			
C_8-Aliphatic Hydrocarbons (7)		X			
C_9-Aliphatic Hydrocarbons (9)		X			
C_{10}-Aliphatic Hydrocarbons (8)		X			
C_{11}-Aliphatic Hydrocarbons (8)		X			
C_{12}-Aliphatic Hydrocarbons (8)		X			
C_{13}-Aliphatic Hydrocarbons (1)		X			
C_{14}-Aliphatic Hydrocarbons (13)		X			
C_8-Alkane (1)				X	
C_9-Alkane (4)				X	
C_{10}-Alkane (6)	X		X		
C_{11}-Alkane (5)	X		X		
C_{12}-Alkane (4)	X		X		
C_8-Olefinic Hydrocarbon (1)		X			
C_9-Olefinic Hydrocarbon (2)		X			
Siloxane (3)					X
C_3-Substituted Benzene (11)	X				
C_4-Substituted Benzene (6)	X				

*Denotes number of different compounds identified for each given category.

MATERIALS & PROCESS CONTROL

Materials and process control applies to the proper selection, usage evaluation, documentation and the tracking of materials and processes to avoid or reduce the risks of system performance failures from flammability, toxicity, thermal/vacuum stability, corrosion, fluid incompatbilities, fatigue, oxygen impact sensitivities, contamination control, etc.

Materials will also be compatible, in that electrical currents (induced or other) will not create electrolysis that will degrade &/or erode structures.

A total material and process control system consists of two elements:

1. An Engineering Review/Evaluation System
    - Program Requirements
    - Design Review/Approval
    - Materials/Contamination Test Programs
    - Specifications
    - Hazard Removals
    - Failure Analysis
2. An Engineering Data Management And Tracking System
    - Materials Selection Lists
    - Properties Manual
    - Material/Contamination Identification & Tracking
    - As/Built Controls "Built per Specification" Controls
    - Completeness Verification

A comparison of present technology with new requirements is shown in Tables 3-2 and 3-3. Columns two and three relate to capabilities of equipment to handle the contamination problem.

TABLE 3-2 CONTAMINATION CONTROL ISSUES*

Issues	Current Data Base To Resolve	Control W/Current Technology	New Technology
o Inherent Hardware Contamination Levels	60%	X	
o Ascent/Launch Drag Along/Induced	20%		X
o Orbital Debris	?		X
o Operations/Cross Contamination	?	X	X
o Materials Degradation	20%	X	X
o Maintenance Procedures	30%	X	X
o Problem Anticipation/Tracking Monitoring	30%		X

TABLE 3-3 MATERIALS AND PROCESSES ISSUES*

Issue	Current Data Base To Resolve	Control W/Current Technology	New Technology
o Advanced Engineering Materials Tracking Data Base System	70%	X	-
o Improved Materials Age Life Data Base	40%	X	X
o Effects Of Radiation On Material Properties	30%	X	X
o Integrated Logistical Data Bases	?	X	-
o Material/Configuration Mapping (Locator)	?	X	X

* Based On Apollo/Shuttle Program Experience 1960-1984

MATERIAL CONTROL AND VERIFICATION PLANNING

Material Selection and Control Requirements

Materials used in the design and fabrication of space hardware should be selected with consideration of the environmental and operational requirements for the particular application and the design engineering properties of the candidate materials.

Presently the Shuttle Orbiter materials are rated and are listed on material selection lists. These lists serve as the basis for all material selections.

Minimum information contained on these lists include:

A. Metallic/Non-Metallic Materials
   (1) Material Code (assigned)
   (2) Material Description
   (3) Material Specification
   (4) Minimum Operating Temperature
   (5) Material Rating
   (6) ... (264)

A description of material rating is necessary as there are several levels of acceptance:

(A) Acceptable; (B) Acceptable With Specific Controls; (C) Acceptability Must be Demonstrated; (D) Not Rated; (X) Unacceptable: Materials with this rating have failed the material screening requirement and may be used only if they can be accepted at the configuration level as meeting a program requirement. (264)

See Table 3-4 for Materials for Orbiter, to date, that have X-rating in toxicity.

See Table 3-5 for Materials for Orbiter, to date, that have X-rating in stress, corrosion, cracking susceptibility.

MATERIAL SELECTION

Materials should be selected from a list of materials where the key properties are:

Toxicity
Flammability
Total Volatile Solids
Stress Corrosion Cracking
Etc.

Precedents Have Been
Established for Test
Procedures & Acceptance
Environment & Habitable Areas

This list should be available during detail design and supplemented as new materials become identified for new applications.

Good/Bad Materials

In general, certain guidelines have been established such that materials that are unacceptable when tested as ran may be retested in configuration and pass.

Material Classification	Habitable Areas	Non-Habitable Areas
Epoxy Laminates (0.080 in.)	Fails Flam.	---
Silicones (Lubricants, etc.)	Pass Tox, Flam.	Fails TVS
Metals	Pass	Pass
Ceramics, Glass	Pass	Pass
Non-Teflon Fabrics & Films	Fails Flam.	---
Teflons	Pass	Pass
Polyurethane (Insulation)	Pass Tox, Flam.	Fails
Polyurethane (Coatings)	Pass Tox, Pass Flam.	Fails
Rubbers	Fails	Fails
Paints/Primers	Fails	Fails

Tox - Toxicity (includes total organics, outgassing, odor)
Flam - Flammability
TVS - Total Volatile Solids

TABLE 3-4 MATERIAL CODES RATED X IN TOX.

U719-10-203 TOX RATINGS FOR NON-METALS BY MATERIAL CODE 03:44 AM PAGE 1

00010	X	INK 73X	05483	X	TAPE SCOTCHLITE 3270 VINYL/PS	06370	X	INK S66-13 ROCKET RED
00013	X	PRIMER M602 EPOXY-PHENOLIC	05490	X	INK 977-9	06391	X	TAPE SCOTCHCAL 3652 VINYL YEL
00140	X	DELRIN ACETAL	05499	X	RUBBER NITRILE	06472	X	POTTG CPD PTK 16000-0002 SIL
00172	X	PRIMER SS4004 SILANE	05525	X	ADHES STABOND T-190 NEOPRENE	06489	X	POTTG CPD RTV 3112 SIL/CAT F
00440	X	PRIMER EC766 NITRILE/PHENOL	05553	X	POTTG CPD COX 28 EPOXY	06523	X	ADHES EPIBOND 1210A/CAT 1210B
00509	X	ADHES FM-123-2 FILM EPOXY	05556	X	CTNG EPOXY AMINE	06584	X	CTNG SCOTCHGARD EC4101-C-16
00552	X	CTNG 150-W-8 HYPALON	05584	X	POTTG CPD C15-015 EPOXY	06624	X	PRIMER 421-03 AUTOMOTIVE GRAY
00591	X	ADHES EASTMAN 910 CYANOACRYLAT	05593	X	INK 6811 FRS BLACK	06647	X	TAPE CW-3 POLYETHYLENE ACRL AD
00708	X	ADHES FM1000 EPOXY/NYLON	05605	X	ADHES P460 EPOXY	06652	X	INK 42-11FD MARKING BLACK
00895	X	ADHES DC 281 SILICONE	05616	X	TAPE SCOTCHCAL 3651 RED	06662	X	ADHES CHEMLOCK 222
01336	X	GERMICIDE PHENYLPHENOL PROPYL	05638	X	LUBE DRY TRANSLUBE 20204	20022	X	TUBING RNF-100 POLYOLEFIN
01843	X	CTNG PRIMER WASH	05656	X	FOAM ABLEFOAM #1 EPOXY	20026	X	LAURIC ACID
02055	X	CTNG A423/T252 EPOXY	05662	X	PRIMER E42GP22/V66KP46 EPOXY	20027	X	PARAFFIN WAX
02231	X	ADHES CHEMLOCK 205/220 NEOPREN	05669	X	VARNISH RED GLYPTAL CAT N090-2	20038	X	CTNG ACRYLIC ENAMEL SW J5-5226
03374	X	SEALANT LOCTITE ALL GRADES	05698	X	FOAM LUNAR F-20 A/B EPOXY	20046	X	ROYALITE R-54 ABS
03398	X	PRIMER DC Z6020 SILANE	05715	X	VARNISH INSULON 100 EPOXY	20047	X	INK TROJAN OPAQUE SILVER
03422	X	LAMIN MYLAR/PROPYLENE	05716	X	CTNG XR 5133 EPOXY	20070	X	CTNG EPOX POLYAM RED (#21105)
05000	X	PRIMER SS4155 SILANE	05726	X	INK WORNOW SERIES M9N WHITE	20095	X	LUBE DRY ELECTROFILM 4306
05002	X	RUBBER NITRILE	05741	X	ADHES STABOND N-125 NEOPRENE	20105	X	POTTG CPD SYLGARD 182 SILICONE
05004	X	PRIMER FM47 VINYL/PHENOLIC	05778	X	CTNG PLY TILE EPOXY	20115	X	GREASE ANDOC C
05015	X	PRIMER 515-700 SUPER KOROPON	05788	X	PRIMER CHEMLOCK 607	20120	X	TAPE 76593 POLYESTER/GLASS
05019	X	ADHES WS 1183 CB5 EPOXY	05792	X	ADHES TY-PLY S	20128	X	ADHES EPON 8 EPOXY
05034	X	FILM AN 16,AL/TEDLAR/NYLON	05805	X	CTNG DEPTHANE GLOSS#1 POLYU	20143	X	CTNG ER 41 POLYURETHANE
05071	X	PRIMER A-934BX AMINO SILANE	05809	X	CTNG QR-4-3117/XY176 SILICONE	20148	X	POTTG CPD SCOTCHCAST 280A/B
05073	X	VELCRO MID-TEMP NOMEX/METAL	05814	X	RUBBER 3177 EPR	20169	X	CTNG 463-6-5/463-3-8 EPOXY
05097	X	ADHES PLASTILOCK 731/PL727EPOX	05815	X	POTTG CPD ABLECAST 402	20177	X	CTNG PT-401/PT-402 EPOXY
05099	X	RUBBER TIRE TREAD 17149	05831	X	TAPE G404200/G404202TFE/AG/SIL	20185	X	GLYPTAL 1202 ALKYD
05110	X	FOAM STEPANFOAM BX 249N POLYUR	05850	X	ADHES THIXON 806 (AP1442) NEOP	20191	X	CTNG ENAMEL ALKYD LUSTRLESS
05129	X	ADHES M-BOND 610,EPOXY	05862	X	ADHES ABLEBOND 293-1FT	20192	X	SEALANT MICROSEAL
05135	X	PRIMER EPOXY/POLYAMIDE	05878	X	SEALANT PR1750 POLYSULFIDE	20198	X	ADHES EC1357 NEOPRENE CEMENT
05150	X	TAPE MYSTIK 6402 PROPYLE/ACRYL	05889	X	RUBBER RTV 60 SILICONE	20203	X	INK F-100 BLACK
05154	X	PEN F30 J FELTED TIP BLACK	05928	X	POTTG CPD STYCAST 2741/15 EPOX	20205	X	VARNISH MOISTURE FUNGUS RESIST
05155	X	ADHES DAPCOTAC 3001	05929	X	POTTG CPD FM1132 PHENOLIC	20214	X	PRIMER WASH
05173	X	TAPE 465/467/468 ACRYLIC FILM	05955	X	TAPE G401902 FEP/467 ACRYL PS	20216	X	SEALANT LIQUID SCREW LOCK
05193	X	NAMEPLATE ASSY ACRYLIC ADH/AL	05961	X	CTNG SILANE Z6070	20234	X	RUBBER EPR E798-70
05199	X	SEALANT DC 94-002 FLUOROSILIC	05963	X	ADHES CYCLEWELD 55-9	20237	X	RUBBER E740-75
05204	X	RUBBER NITRILE (NRB)	05971	X	ADHES EA919 EPOXY	20254	X	CTNG PT750 POLYU/PT402 PRIMER
05216	X	VARNISH PHENOLIC ELECTR INSUL	05993	X	CTNG EPOXY -GRAY COLOR#36118	20351	X	SEALANT THREAD LOCK #271
05224	X	CTNG THERMAL CONTROL POLYURETH	06014	X	ADHES THERMASIL TYPE II/CAT S	20402	X	SEALANT EC-1103
05226	X	ADHES EC2214(HI FLEX)EPOXY/AL	06026	X	TISSUE MT5 DRY MOUNT	20438	X	FILM STABILENE DIAZO
05231	X	INK WORNOW 50-000 SERIES	06069	X	PRIMER A-4094 SILICONE	20456	X	TAPE P-910
05238	X	PLATE ID AL FOIL/PS ADHES 467	06072	X	CTNG CTL-15/C-15 CAT EPOXY BLK	20485	X	ADHES LOCTITE 242
05297	X	ADHES EPOCAST 212 EPOXY	06093	X	CTNG INSULATING DC 1107 FLUID	20514	X	PRIMER QUICK 65918
05299	X	ADHES METBA-SET BLUE LABEL	06095	X	TAPE POLYIMIDE CLEAR ACRYL ADH	20515	X	INK JUSTRITE INDELIBLE
05315	X	SEALANT 71-Y-1 CORR INH EPOXY	06096	X	TAPE POLYIMIDE AU/AL PS ADHES	20527	X	SEALANT PR 1201-HT POLYSULFIDE
05357	X	CTNG 683-3-3Y POLYURETHANE	06104	X	PRIMER PR-420 URETHANE	20534	X	FOAM MOLECULON FR302 POLYU
05359	X	CTNG EPOXYLITE 9653 EPOXY	06223	X	TAPE T-3596 TEFLON/ACRYLIC PS	20542	X	CTNG EPOXY ENAMEL 66208 WHITE
05369	X	MOLD CPD DIALL 52-01 DAP	06307	X	CTNG POLYU DEPTHANE NO.1 GLOSS	20543	X	DEODORANT ALMAY CHEQ SOLID
05375	X	VARNISH DC-997 SILICONE	06321	X	TAPE SCOTCH 853 POLYESTER	20574	X	FOAM ENSOLITE TYPEAH
05454	X	LUBE DRY LUBRIBOND A	06369	X	INK S66-17 SATURN YELLOW	20639	X	RUBBER TA 96 SILICONE

TABLE 3-4 (CONT'D)

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U719-10-203                 TOX RATINGS FOR NON-METALS BY MATERIAL CODE          03:44 AM     PAGE 2

20703   X   LACING TAPE TG-30              *
20711   X   ADHES 520 NEOPRENE             *
20745   X   CTNG POLYU PLENUM .0575 THK    *
20746   X   CTNG CHEMGLAZE Z853/CAT 9986   *
20747   X   CTNG CHEMGLAZE Z752 POLYU BLUE*
20748   X   CTNG CHEMGLAZE Z651 POLYU GREN*
20777   X   ADHES FLEXICRAFT 868 URE VINYL*
20779   X   ADHES ZIPGRIP 10 CYANO ACRYLIC*
20794   X   ADHES SR 529 SILICONE RUBBER   *
20795   X   CTNG PT 805 SILICONE WHT GLOSS*
20799   X   CTNG EPOXY POLYAMIDE BLK 37038*

TOTAL/REPORT    (161)
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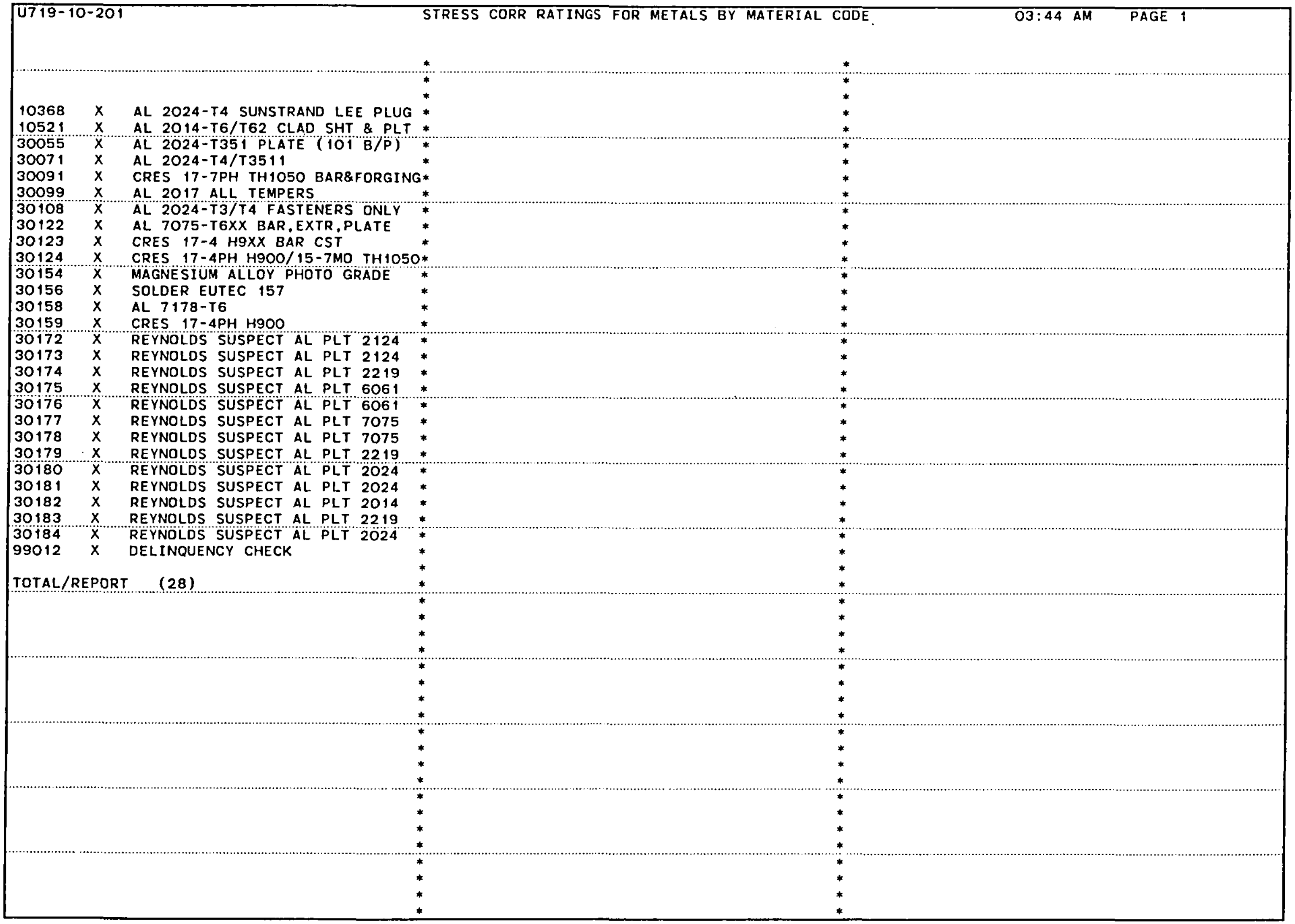
TABLE 3-5 MATERIAL CODES RATED X IN SCC.



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U719-10-201                                           STRESS CORR RATINGS FOR METALS BY MATERIAL CODE              03:44 AM     PAGE 1

10368    X    AL 2024-T4 SUNSTRAND LEE PLUG *
10521    X    AL 2014-T6/T62 CLAD SHT & PLT *
30055    X    AL 2024-T351 PLATE (101 B/P)  *
30071    X    AL 2024-T4/T3511              *
30091    X    CRES 17-7PH TH1050 BAR&FORGING*
30099    X    AL 2017 ALL TEMPERS           *
30108    X    AL 2024-T3/T4 FASTENERS ONLY  *
30122    X    AL 7075-T6XX BAR,EXTR,PLATE   *
30123    X    CRES 17-4 H9XX BAR CST        *
30124    X    CRES 17-4PH H900/15-7MO TH1050*
30154    X    MAGNESIUM ALLOY PHOTO GRADE   *
30156    X    SOLDER EUTEC 157              *
30158    X    AL 7178-T6                    *
30159    X    CRES 17-4PH H900              *
30172    X    REYNOLDS SUSPECT AL PLT 2124  *
30173    X    REYNOLDS SUSPECT AL PLT 2124  *
30174    X    REYNOLDS SUSPECT AL PLT 2219  *
30175    X    REYNOLDS SUSPECT AL PLT 6061  *
30176    X    REYNOLDS SUSPECT AL PLT 6061  *
30177    X    REYNOLDS SUSPECT AL PLT 7075  *
30178    X    REYNOLDS SUSPECT AL PLT 7075  *
30179    X    REYNOLDS SUSPECT AL PLT 2219  *
30180    X    REYNOLDS SUSPECT AL PLT 2024  *
30181    X    REYNOLDS SUSPECT AL PLT 2024  *
30182    X    REYNOLDS SUSPECT AL PLT 2014  *
30183    X    REYNOLDS SUSPECT AL PLT 2219  *
30184    X    REYNOLDS SUSPECT AL PLT 2024  *
99012    X    DELINQUENCY CHECK             *

TOTAL/REPORT   (28)
```

MATERIAL EXCEPTIONS

Certain exceptions break the general guidelines such that all materials should be tested and subsequently be approved or rejected. Some materials may be fail-tested, but approved based on configuration or small volume/surface area.

Metals: Do not use magnesium, beryllium or titanium over 165 Ksi, ultimate strength in structural applications.

Do not use zinc or cadmium.

Non-Metal: Do not use ceramics in structural applications.

Materials Programmatic Requirements

The complex and sophisticated technology of manned spaceflight requries strong and effective engineering management. The effectiveness of that management is related to the design of the engineering data management system. The Space Station technology will require more sophisiticated systems than currently in-place.

Materials & Process Control applies to the proper selection, usage evaluation, documentation and the tracking of materials and processes to avoid or reduce the risks of system performance failures from flammability, toxicity, thermal/vacuum stability, corrosion, fluid incompabilitites, fatigue, oxygen impact sensitivities, etc.

A unitized material and processes control reporting system was developed to support the Space Shuttle program and has served to identify and track all materials usages with the flexibility of discreet configuration control. This is accomplished by a data base information managment system called MATCO.

A total Material & Process Control system consists of two basic elements:

1. An engineering review/evaluation system

    Program requirements
    Design review/approval
    Materials Test programs
    Specificatons
    Hazard removals
    Failure Analysis

2. An engineering data management and tracking system.

    Material selection lists
    Properties Manuals
    Material identification and tracking
    As/built controls
    Completeness verification

Materials & Process Control (MATCO)

A central computer system is used for the identification, tracking, retrieval, control, documenting and reporting of all material usages, both as-designed and as-built configurations, for the space shuttle program.

As-Designed -	Original engineering design releases and any engineering change documentation (Engineering Orders, etc.)
As-Built -	Material changes resulting from, material reviews (MR's), discrepancy reports (DR's), test and checkout procedures, etc.

Advanced Materials & Process Control Areas:

o Age Life - Current data base's are limited and detailed engineering analysis is required for future long duration applications.

o Maintainability - Space environmental effects are showing new perspectives needed in materials usage evaluation/analysis.

o Radiation - Effects of material exposure to radiation is currently a limited data base.

o Material/Configuration Locator - Computer aided locator system for tracking material usages is required for more complex space systems.

o Integrated Logistics - Hardware logistics control data bases need to be integrated with engineering materials data bases.

Advanced Contamination Control System Requirements:

o Real time monitoring and data aquisition/management system.

o Computer aided contamination modeling system.

o Integrated contamination control tracking system.

o Contamination control design standard manual.

Suggested material control requirements for the space station are shown in Figure 3-1. For clarity, the following acronyms are defined:

SCC - Stress Corrosion/Cracking
VCM - Volatile Condensable Material

SUGGESTED MATERIAL CONTROL REQUIREMENTS

CLASS I) BASIC CONFIGURATION
CLASS II) LRU
CLASS III) CONSUMABLES, MOVABLE

			MATERIAL CONTROL REQUIREMENTS																	
			NONMETALLIC											METALLIC						
APPLICATION	LOCATION		FLAMMABILITY	TOXICITY/OFF-GASSING	THERMAL VACUUM STABILITY	AGE LIFE	RADIATION	LOX	HIGH GOX	COMPATIBILITY	BIOLOGICAL	LH_2	HYDRAULIC FLUID	CORROSION	SCC	GOX	LOX	FRACTURE CRT	LOH_2	HIH_2
CREW MODULES	CABIN INTERIOR		●	●		●	●				●			●	●			●		
	EXTERIOR	WINDOW CAVITY	●		●	●								●	●			●		
		ALL OTHER AREAS	●			●	●							●	●			●		
TRANSFER MODULE	AIRLOCK/TUNNEL		●	●	●	●					●			●	●			●		
	OTHER AREAS		●		●	●								●	●			●		
EXTERNAL MODULES			●		●	●								●	●			●		
			●			●								●	●			●		
CONSUMABLE STORAGE	INTERIOR		●		(2)	●	●			●	●			●	●			●		
	EXTERIOR		●			●	●			●				●	●			●		
OTV			●			●								●	●			●		
PLATFORM	UPPER SURFACE		●		●	●								●	●			●		
	REMAINDER		●			●								●	●			●		
SOLAR PANELS	INTERNAL SURFACE		●			●	●							●	●			●		
	EXTERNAL SURFACE		●		●	●	●							●	●			●		
LOX	FLUID SYSTEMS					●		●			●			●	●		●			
>20 PSIA O_2	↓					●			●					●	●	●				
WATER	↓					●				●	●	●		●	●			●		
H_2	↓					●					●	●							●	●
HYDRAULIC FLUID	FLUID SYSTEMS					●							●	●	●					
INERT CONTAINERS	ALL LOCATIONS					●								●	●					

(2) VCM REQUIREMENT IN WINDOW CAVITY IS 0.01 PERCENT

Figure 3-1

OXYGEN BOMBARDMENT

During flight in low Earth orbit, a space vehicle experiences bombardment with highly energetic atmospheric species, the principal of which has been determined to be atomic oxygen. This constituent is known to be chemically reactive with many materials. For sufficiently high fluxes of atomic oxygen, chemical changes can be expected for spacecraft surfaces oriented in the "wind ward" direction.

Opportunities to examine surfaces that have been exposed to space conditions, but protected during reentry heating, have been few. Those samples that were returned from low Earth orbital conditions were contaminated by spacecraft sources during exposure and, therefore, slight changes in these surfaces were not observable. Surfaces returned from lunar exposure were also affected by contaminating lunar dust agitated by the nearby landing of the Apollo lunar module. With the flight of Space Shuttle, uncontaminated surfaces have provided an opportunity for examination.

The current knowledge of high energy O atoms surface chemistry and physics is severely limited. One of the reasons for this is the difficulty of producing a fast oxygen atom beam in the laboratory.

As a vehicle travels through space in relatively low orbit, it experiences bombardment by fast (8 km/sec) oxygen atoms by virtue of its orbital velocity. As the period for which space missions are required to function increases, so also the importance of the long term/effects of exposure of spacecraft materials to the upper atmosphere increases. The advent of the shuttle orbiter, operating at relatively low altitudes, places further importance upon the action of atmospheric species because of the higher atmospheric density encountered in low Earth orbit. The composition and density of the atmosphere above 120 km are functions of several variables: local time, day of the year, geographic latitude, sunspot activity, radio solar flux and magnetic index. Neutral atmospheric species above 120 km include O, N_2, He, O_2, Ar, and H atoms. Molecular nitrogen dominates below about 200 km, while atomic oxygen dominates above this altitude.

The atmosphere bombarding a spacecraft may interact with the surfaces of the spacecraft in a number of ways which effect the surface properties. Among these effects are: condensation, luminescence, sputtering, volatilization of weakly bound surface deposits and chemical reactions with the surface or with impurities deposited thereon.

Evidence for atomic oxygen interactions with various materials was apparent during shuttle flights 2 through 4. (See Table 3-6). Postflight inspection of orbiter payload bay surfaces and spaceflight hardware indicated that significant changes had occurred for thermal control paints used on noninsulated surfaces and handrails and thermal blankets used to insulate payload bay television cameras. The normal glossy appearance of Kapton films used to insulate these cameras was converted to a flat, light yellow hue. Strong shadow patterns, indicating the direction of atomic oxygen bombardment, were evident on these film surfaces. Both A-276 thermal control paint and A-971 identification paint lost their gloss and became dull in appearance, an indication that rapid "aging" had resulted from atomic oxygen bombardment. (261)

More pronounced effects were observed on two metal spheres associated with a space sciences plasma experiment conducted during STS-3 mission. Aerodag, a carbon suspension coating was completely removed from the tops of these spheres, indicating prominent interactions with the atomic oxygen environment. Material disc specimens flown on STS flight 4 showed similar degradation. Silver, osmium, and carbon specimens were similarily affected. (261)

TABLE 3-6 ATOMIC INTERACTIONS WITH SHUTTLE MATERIALS

- Significant effects of environment on payload bay materials observed on all flights
- STS-1
  - Forward bulkhead kapton camera blanket was milky yellow after flight
  - Yellow paint aged rapidly
- STS-2
  - Camera blankets - loss of 4.8% on kapton outer surface; all cameras affected
  - Paint similar to STS-1
- STS-3
  - Camera blankets - mass loss of 35% (0.1 mil) on surfaces of essentially all cameras
  - Torlon thermal blanket button had white deposit on surface
  - Paint similar to STS-1 except white paint on sill longeron also aging rapidly
  - OSS-1 kapton had loss of 22% (0.22 mil)
  - PDP (Plasma Diognositc Package) spheres had complete loss of aquadag on upper surfaces
  - OSS-1 (Office of Space Sciences Mission-1) paint surfaces also affected
- STS-4
  - Kapton affects minor on both camera and payload surfaces
  - Coated kapton had resistance changes
  - Witness samples of four materials flown on IECM (induced environment contamination monitor) had loss ranging from .033 mil for teflon to .07 mil for kapton and mylar
  - Witness samples of carbon coating 2000A completely removed

(262)

Flight tests were performed during the STS-5 misison to evaluate the interactions of atomic oxygen with various spacecraft materials. (See Table 3-7 (261)). To achieve the desired exposure conditions, thin-film material samples were attached to thermal plates mounted on a carrier within the orbiter payload bay. This carrier placed the samples above the Orbiter longerons to allow for direct impingement of oxygen atoms and limit interactions with atomic oxygen reflected from interior surfaces. Orbital attitudes and 44 hours of exposure time acquired during this mission produced a fluence (integrated incident atomic oxygen flux) of approximately 1×10^{20} atoms/cm^2. Postflight laboratory tests revealed significant mass erosion for Mylar, Tedlar, and Kapton films. Scanning Electron Microscope (SEM) examinations showed significant surface morphology changes after exposure to the atomic oxygen environment. Materials such as Teflon were not as susceptible to atomic oxygen reaction as nonflourinated materials such as Kapton and Mylar. The reaction rates for these materials appear to be nontemperature dependent over a temperature range of 24°C to 121°C, which is most likely due to the high kinetic energy (5eV) of the oxygen atoms (261).

TABLE 3-7 STS FLIGHT 5 SAMPLE DESCRIPTION
ATOMIC OXYGEN INTERACTION

Temperature Controlled Trays

- Kapton (Clear and Black)
- Mylar
- Teflon - FEP/TFE
- Kevlar
- Epoxy
- Polysulfone
- Tedlar (White and Clear)
- Paints
  - A276
  - 302
  - 306
  - 401-C10
  - S13-GLO
- Graphite Epoxy
- Graphite/Polymide
- Aluminum
- Silver
- Overcoats (on Kapton or Mylar)
  - Silicone Base Coatings
  - Indium-Tin Oxide
  - Gold
  - Aluminum
- Cables
  - Graphite
  - Kevlar

Temperature Uncontrolled Areas

- Germanium
- Zot
- Silver Foil
- RTV
- Alclad AL with AU/MO
- Silicone Coating
- Fluorinated Polyurethane
- A-276
- Iridium
- Z306
- MS74
- P1700
- S-13GLO
- Indium-Tin Oxide
- Glassy Carbon
- RTV-560
- V2000
- Osmium
- Candidate Antenna Materials
- P1700

(261)

Findings To Date

A) Material reactivity - is presently being measured in three categories: reactive, minimally reactive and non-reactive.

B) Mechanisms - To date, all data collected and analyzed is consistent with a mechanism involving oxygen atom interaction with surfaces.

C) Solar Activity - an assumption can be drawn; if the mechanism is based on atomic oxygen, then solar activity will effect reactivity very strongly since oxygen density is strongly dependent on solar activity. Density from solar minimum to solar maximum can vary by one to two orders of magnitude depending on altitude. Density is also dependent on attitude and flux is dependent on surface attitude.

D) Temperature dependence - Measurements from the STS-5 experiment indicate no surface temperature dependence within the measurement errors.

E) Effects on Spacecraft - Impacts on spacecraft surfaces can be predicted from oxygen atom influence data (takes into account flight date, altitude, attitude, and atmospheric density) and reaction rates. Using reaction rates that have been measured for Kapton and Mylar, consideration of oxygen effects on such surfaces should be taken into account for long-lived, low altitude spacecrafts, especially, if flight occurs during solar maximum. Spacecraft hardware with high sensitivity to surface changes should also be evaluated. Also impact on maintainability should be evaluated.

Strategy Options

The oxygen nuclei bombardment phenomenon severity is inversely proportional to the altitude and directly proportional to the ambient nuclei count. Resolution options to minimize oxygen nuclei bombardment is to maintain the space station in an orbit as high as possible, considering other threat trades (i.e., radiation).

INTERNAL ATMOSPHERE CONTAMINATION

A space station internal atmosphere monitor will have to function in real time. Off-the-shelf equipment for this purpose is not readily available today. The Shuttle gas sampling approach is summarized in Table 3-8.

TABLE 3-8. SHUTTLE INTERIOR ATMOSPHERE SAMPLING APPROACH

- Whole gas samples.
- Three times during mission the cylinder valve is opened to permit the inflow of cabin atmosphere into the evacuated cylinder.
- The sample is trapped upon closing the cylinder valve.
- Toxicology laboratory performs analysis after the flight.
- Gas chromatography.
- Mass spectrometry for compound identification.
- Gas chromatography for quantification.

The problem with the present Shuttle sampling system is that contaminant identification does not take place until after landing. Sometimes it may extend to days or weeks before the community knows the contaminant air parcel make-up. A summary of the contamination monitoring issue follows:

Issue: No real-time monitoring of cabin containments.

Hazard: Loss of crew capabilities due to increased toxicity levels producing short/long term effects.

Present System: See Table 3-8.

Figure 3-2 shows a sketch of the Shuttle cabin air sampling system. Table 3-9 summarizes the safety concerns of the present system.

TABLE 3-9 SAMPLING CONCERNS

1) Insufficient sample bottles to provide the necessary data to make an adequate assessment of the cabin atmosphere throughout the mission.

2) Use of sample bottles for qualification/verification for new equipment or changes in operating conditions.

3) If the crew capability were to be degraded (physically or mentally during the flight) adequate post flight data would not be available to make an assessment of the cause and initiation of corrective action would be difficult.

4) No control on carry-on items. First exposure to cabin environment is during flight without prior evaluation or real time monitoring.

5) Halon 1301 leak/discharge could exceed SMAC level unrecognized.

6) Synergistic effects of cabin contents is unknown.

7) Abuse of Lioh cannisters may create a single point failure which could release a corrosive/toxic material.

8) Under current situations, missions must be aborted if the donning of masks is required.

9) Cabin atmosphere cannot readily be altered, cannot vent to vacuum.

Safety Issues

Because there is no present real time air composition monitoring system available, as state-of-the-art equipment for the space station an analogous issue may be derived from the Shuttle. These safety issues are noted in Table 3-9 above.

Contaminants found in the Shuttle Orbiter to date are listed in Table 3-1.

Recommendation:

Strategy Option

Develop and implement an on-board real time monitoring system for the space station using, at least, the following approach:

1. Look at state of the art equipment available
2. Assess for STS application
3. Design package orbiter experiment
4. Process through Orbit Experiment (OEX) acceptance route
5. Assess real-time test data
6. Recommend prototype design
7. Prepare equipment specifications

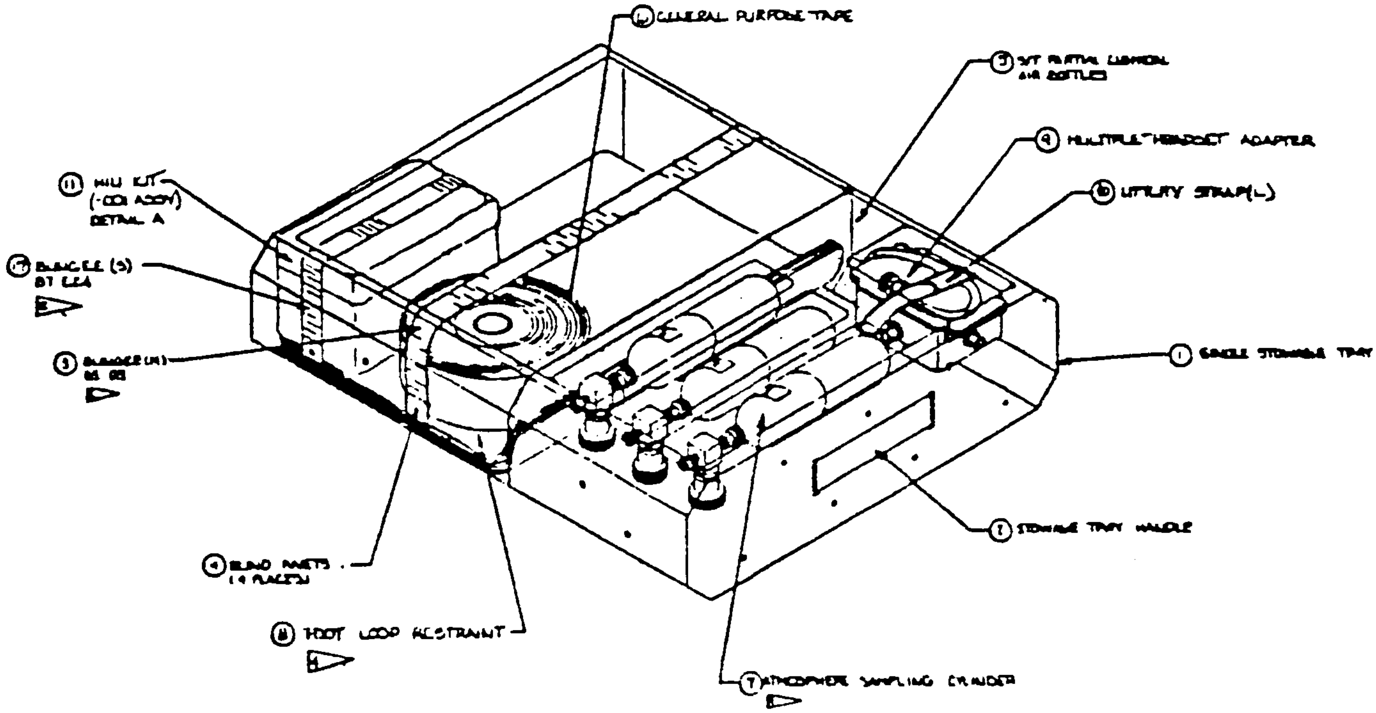

Figure 3-2 Shuttle Cabin Air Sampling System

An optimum unit/system would have the following characteristics:

- o Small Size
- o Light Weight
- o Passess toxicity, odor, flammability
- o Passes qual test
  - Vibroacoustic
  - G Force/Zero G
  - Calibration/Performance
- o Real time data readout and telemetry
- o Storage

Some candidates could include, if size/weight optimized:

- * H-P Model 5992, 3 pieces, $24 ft^3$
- * Finnigan OWA
- * Shimadzu GC + Data system, $1 ft^3$
- * Finnigan ion trap detector, $8 ft^3$

DEBRIS CONTAMINATION IN CREW CABIN

Background

Considerable amount of debris has been collected from subsystem screens and filters during post flight cleanings and inspections of both OV-102 & OV-099 vehicles. The quantity of debris has caused concern based on the possibility of filter clogging with resultant air flow restriction and/or migration of debris matter through systems vulnerable to particulate matter induced malfunctions.

Problem History

STS-5 (OV-102) ECLSS H_2O water separator "B" operated at reduced efficiency, post flight examination revealed a high level of contamination throughout the unit with plugged water drain and transfer holes. Separator "A" was also contaminated but still met the Acceptance Test Procedure (ATP).

During the flight of STS-7, the urinal filter had to be replaced numerous times; a prior failure of the Waste Control System (WCS) urine-air separator had been attributed to this excessive contamination.

During ground checkout of OV-102 cabin positive relief valves, both valves failed to reseat properly due to contaminates entrapped on the valve seats by the reseating valves.

Black box debris screens, in many cases, have been completely covered with lint like materials.

- o No significant reduction in air flow cooling has thus far been noted.
- o Cooling effects under 10.2/8.0 PSI cabin unknown.

Current Action Being Taken

H_2O separator - MCR 10308 authorizes redesign of filter for air entering the cabin fan and debris trap assembly.

Positive Pressure-Relief Valves Awaiting authorization for design of filters to replace present debris screens.

Avionics Screens - OMI 6018 requirements changed to require screens cleaning every 1000 hours or between flights whichever occurs first.

Open Concerns

Contamination could worsen to a point where positive preventative action must be taken. Some of these concerns are:

1) Normal wear/deterioration of cloth materials could generate an increasing amount of lint.

2) Laxity in control of ground support personnel cleanliness procedures could introduce undesired debris/contamination into crew compartment.

3) Manufacturing and modification rework activities at all sites may be a significant contributor to the overall contamination problem.

Analysis of Debris

Materials gathered from OV-102 & OV-099 have been identified and itemized to facilitate determination of origin.

A basic categorization of the materials collected appear to be as follows:

1) Lint-Astronauts Garment, Sleeping Bags, ETC.
2) Manufacturing Debris - Rivets, Washers, Wire, Paint Chips, ETC.
3) Carried Onboard Debris - Popcorn, Apple Stem, Dog Hairs, Small Particulate Matter, Sand, ETC.

The above categorization can be utilized to formulate practical control measures and to monitor their effectiveness.

Strategy Options

Using historical data, screen out the debris generators where possible (clothing, filter cleaning, etc.). Also, a concerted house-keeping plan for the space station should be devised.

SPACE STATION CONTAMINATION

This new technology involving "Micro-G" and the related pollutants, should be investigated and assessed. Use of previous measurements and existing reports should be considered to establish baseline parameters and identify any similar possible contamination. Investigate all materials, both new and existing, hardware, software and orbiting terms that may impact personnel living conditions or degrade space station systems.

There should be a complete analysis of the dispersion rate, concentrations and other factors, which may establish a criterion to identify necessary controls of contaminants and pollutants. This analysis should also encompass hardware/software and avionics areas of reliability, should the effects of contamination not readily be controlled or dispersed.

The flow chart (Figure 3-3) is an example of the methology needed to control, reduce or eliminate contamination of orbital space.

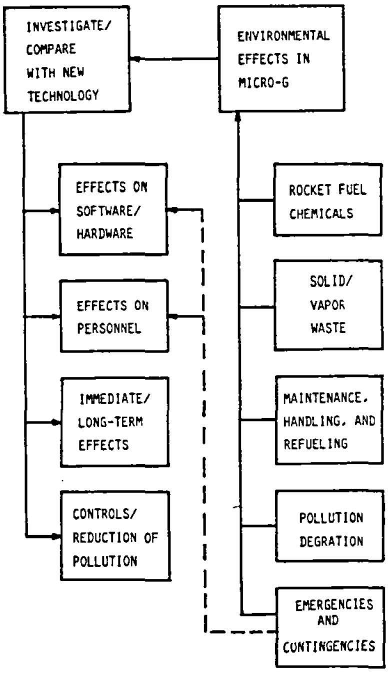

Figure 3-3 Contamination Impact Analysis

Strategy Options

As indicated in Figure 3-3 a contamination impact assessment should be made. Design of a "clean" station would be most helpful. But the problem of "no g assist" to settle dust and allow convenient clean may not have been addressed in the detail necessary to postulate the problem in sufficient detail. The cleaning issue is discussed peripherally in Volume III of this report.

TOXIC CONTAMINATION OF FOOD

Background Precedent (371)

British Airways warned its flight crews about hazards of food contamination after more than 75 crew-members were stricken with suspected Salmonella poinsoning over a four or five-day period in mid-March of 1984.

The airline believes about 120-130 passengers, all of whom had ridden in the first-class sections of at least 13 different British Airways flights between March 12 and March 14 or 15 were also affected.

The contamination had been tentatively traced to the aspic glaze on hors d'oeuvres prepared in the British Airways flight kitchen at Heathrow Airport here.

The airline said that all suspected stocks of the foodstuff were immediately removed from the kitchen and destroyed, and the kitchen has been inspected and approved both by the airline's own safety and medical departments and by the British Dept. of the Environment.

In at least two cases both the pilot and first officier scheduled to fly the same flight became ill. The airline has a standing rule that the two pilots must eat separate meals in flight, and these meals are prepared specifically for the flight crew. They are not drawn from meals prepared for the first-class passengers.

Most of the 75 crew who were stricken were cabin attendants who eat the same meal served to passengers and would normally be expected to be affected by any contamination in the passenger food.

At least two flights, however, including a Washington-to-London Concorde service, had to be canceled after illness hit more members of the flight crew than could be replaced on short notice. Another flight was a Lockheed L-1011 TriStar flight from Nairobi to London.

British Airways officials said there is no record of both pilots on one aircraft later becoming ill.

The airline is uncertain whether one member of some flight deck crews ate snacks prepared for passengers, or whether some of the meals prepared for the crews might have been contaminated.

The high incidence of flight and crew illness was the first indication that the airline had of a problem with the food being served. "Normally, symptoms of the illness do not appear for about 24 hours after the food is eaten," an airline official said. "In some cases, it may have been longer."

Safety Issue

Will space station personnel be supplied with two independently prepared meal lockers?

Strategy Options

Several approaches could be considered. One could include the obvious: have two crew elements, each fed from different galleys. A more subtle alternative would be to select foods with the least probability of pathogic development.

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4. INJURY/ILLNESS

DEFINITION

Physical injuries may be caused by impact or collision with stationary objects having sharp edges or protruding parts or with shrapnel or projectiles from exploding tanks or accelerated loose objects. Physical injuries may also be caused by ingesting particulate matter, touching hot or cold surfaces, and by breathing oxygen deficient air. Care and control to prevent sharp and abrading protrusions and the inclusion of hand holds and other convenient restraints for astronauts minimized exposure to injury. Crew illesses could result from exposure to pathogenic bacteria, toxic materials, or to excessive radiation levels. The physiological/behavioral impact of microgravity on the crew for long time exposure is not clearly understood. Personal hygiene and close control of food prepartion minimize exposure to illness. Crew illness and injury must be treatable within the Space Station. The sophistication of medical facilities is yet to be determined. Death of an astronaut cannot be ruled out, raising the question of what procedure is to be followed for the disposition of the remains, i.e., return to earth or burial in space - burial at sea precedence.

HISTORICAL

Health of space crewmembers has been closely monitored since the beginning of the manned space flight. Treatises have been written on man's capability to adapt to the space environment. That will not be discussed here except where it relates directly to the threat of injury/illness. Essentially man, physiologically, has shown a degree of adaptability to the space environment for periods of time planned for the space station missions; namely, 90-days. Impacting man's orientation in space are the phenomena of:

Weightlessness
Ionizing Radiation
Temperature and Humidity
Accelerations
Circadiac Rhythm Disruption
Noise and Vibration
Atmospheric Composition

Of these phenomena, weightlessness appears to be unique to space. Ionizing radiation at specific altitudes and sectors, as well as solar flares, are more intensified in the space environment, however, experience has been gained on Earth in their handling and study. Similarly, circadian rhythm disruption, although more intensified in space, has been and is being experienced in the Antarctic scientific stations as well as with a sizeable population involved with commercial transportaton.

Predicted and known effects of the space environment include (308):

Amphoria
Nausea
Disorientation
Sleepliness
Sleeplessness
Fatigue
Restlessness
Euphoria
Hallucinations
Decreased G Tolerance
Gastrointestinal Disturbance
Urinary Retention
Diuresis
Muscular Incoordination
Muscle Atrophy
Demineralization of Bones
Motion Sickness
Pulmonary Atelectasis
Tachycardia
Hypertension
Hypotension
Caridac Arrhythmia
Postflight Syncope
Decreased Exercise Capacity
Reduced Blood Volume
Reduced Plasma Volume
Dehydration
Weight Loss
Infectious Illness
Agonal Calculi

The Life Sciences program in Skylab revealed that the zero-gravity environment of space induces a wide range of adaptive changes extending throughout the biological systems of the body. The detailed physiology behind some of these changes has been defined by experiments. However, taking an overview of the program as a whole, two features have emerged. First, Man can adapt to, and live in, the zero-gravity space environment for extended periods of time. But second, and therefore above all, none of the measured changes so far seen in missions extending up to 84 days have proved irreversible after return to Earth. There may be conjectural indications that the 211-day Russian stay in space could have had some irreversible effects on the cosmonauts.

THE SPACE PHYSIOLOGICAL ISSUES

Data today appears to support the belief that man in his space environment is physiologically different from man in his Earth environment. Weightlessness impacts the cardiovascular system and the skeletal system directly. Figure 4-1 summarizes the weightlessness effect on the body while in space and also post landing. Additionally, without constant isometric or simulated physical stress, the skeletal system would tend to atrophy. The motion sickness issue is not a safety matter as it can be accommodated and when evident, lasts only a few days into the mission.

At an early stage of orbital flight, the cosmonauts consistently developed a number of changes that manifested as unusual and sometimes unpleasant sensations, such as autonomic and motor disorders. A state similar to motion sickness usually developed during mission day 1 and gradually diminished during mission days 3-7. Motion sickness symptoms (vertigo, deterioration of health condition, hypersalivation, nausea, and sometimes vomiting, etc.) of various degrees occurred in one-third of the cosmonauts. Frank motion sickness also developed in some cosmonauts. Out of the 10 crew members who participated in Salyut-6/Soyuz flights, four showed autonomic disorders both during the first days and after the flight.

Symptoms of cranial blood redistribution were subjectively noted by nearly all cosmonauts. They emerged during the first day in orbit and then gradually disappeared, but sometimes incompletely at different time intervals, usually during the first week. During this period, the cosmonauts reported increased blood flow to the head and head fullness; nasal congestion; wrinkle relaxation and face puffiness; scleral hyperemia; increased blood filling and pressure in neck veins and increased head blood filling; decreased leg volume and, in most cases, reduced body mass; pastiness of above-the-heart-tissues. Postflight eye examinations demonstrated residual signs of blood redistribution in the form of enlargement of eyeground vessels (engorgement in the papilla area). In addition, there was a decrease in hemodynamic changes during head-down tilting.

Changes in the motor function during the first mission days manifested as a mismatch of the motor stereotype evolved on Earth compared to the weightless environment. Due to this, it was difficult to estimate the muscular efforts required for motor acts (e.g. movement in the cabin) and to perform accurately the necessary muscle movements. All this led to disorders in movement coordination and required a longer time to perform certain preparatory and working operations in the weightless state. However, during the first flight days, movements became adequately precise, efforts associated with them decreased, and efficiency of motor performance increased. (308)

Once acclimated to space, the remaining body system issues are as those summarized in Figure 4-1 and the skeletal maintenance issue (ADH refers to plasma vasopressin).

Strategies

The Russians have developed a preventive program to promote good health. In order to maintain good health inflight and to facilitate readaptation postflight, it was necessary to provide a normal environment, adequate nutrition, a rational work-rest cycle, and different countermeasures. The environmental parameters of the crew module approximated the Earth's atmosphere. The contaminant concentrations were within the limits allowed for long-term flights. Meals were selected from a 6-day menu containing 70 food items. The caloric value of a daily diet was 3150 kcal on Salyut-6 compared to 2800 kcal in Salyut-4 flights. The daily diet was composed of the following nutritional and mineral ingredients: protiens, 125 g; fats, 110 g; carbohydrates, 380g; calcium, 800 mg; potassium, 3.0 g; phosphorus, 1.7g (normal 1.2-1.5); sodium 4.5-5.0 g (normal 4.0-6.0); magnesium, 0.4 (normal 0.3 g); iron, 50 mg (normal 15 mg). Among the various food items there were 25 meat dishes, 5 dairy products, 5 bread and bakery products, 10 varieties of sweets, 12 fruits and juices, 4 warm beverages, 2 dressings, and 6 kinds of soups. The daily diet was supplemented with multiple vitamins. (372)

On request of the crew members, the cargo vehicle, "Progress," as well as the transportation spacecraft supplied fresh fruits and vegetables, spicy dressings, confectionery, and other items. The fresh water supply was obtained from stored silver-treated water and from water reclaimed from atmospheric condensate. The crew members could obtain hot water.

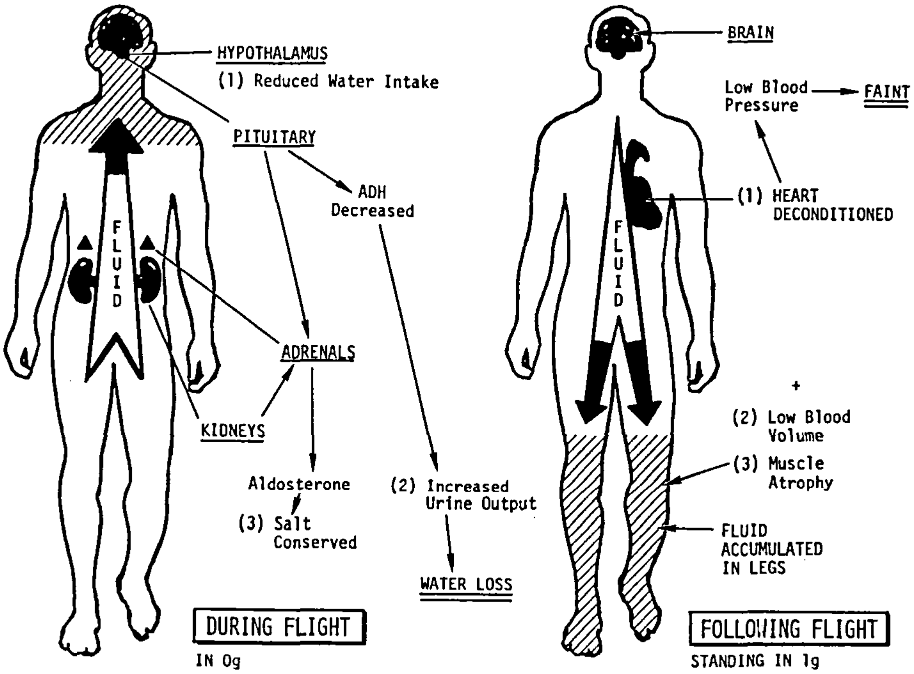

Figure 4-1 Impact of Micro-G on Body Systems (174)

According to the time-schedule, the crewmembers were allowed 9 hours of sleep from 2300-0800, Moscow time, 2.5 hours for exercise, 2.5 hours to take four meals a day, 8 hours to perform various experiments and other activities, and 2 hours of private time, of which an hour was normally spent as a after-lunch nap. Saturdays and Sundays were days off.

Beginning with mission days 4-7, the crew members were scheduled to exercise every morning and evening using a bicycle ergometer and a treadmill equipped with a pulling system that provided a load of approximately 50 kg directed parallel to the long axis of the body. The exercises were performed on a cyclic basis, i.e., for 3 days according to a specially developed program and the fourth day as ad lib.

Each day, the crew members donned Penguin suits that provided an axial load upon the musculo-skeletal system. These suits were removed before going to bed. Two days before recovery, the crew members used a chibis vacuum suit to apply lower body negative pressure (LBNP). On the day of recovery, they ingested three doses of a water-salt supplement composed of 3.0 g NaCl in 300-400 mg water. Immediately before reentry, the cosmonauts donned a pneumatic anti-G suit whose bladders were inflated upon landing. The suit was used both to improve venous return of blood and to enhance orthostatis tolerance in the upright position.

During flight, many measures were taken to fill leisure time, including conversations with family members, scientists, actors, sportsmen and other celebrities. In addition, there were broadcasts of movies, concerts, variety shows, the daily news, press reviews, and consultations by prinicpal investigators, using the television and radio Earth-station-Earth communication channels. This would tend to put off fatigue resulting from boredom. (308)

Medical Investigations included (308):

- Measurements of variations in body mass and leg volume;
- Electrocardiographic examination at rest using the standard 12-lead system;
- Central and regional hemodynamics at rest and during provocative tests using rheography; of blood pressure (including mean pressure) using tachyoscillography; of arterial pulse using sphygmography; and systolic and diastolic time intervals using kinetocardiography;
- Measurements of venous pressure in the juglular vein (phlebography in combination with lower body negative pressure) and in leg and forearm vessels (plethysmography);
- Dynamic electrocardiographic examinaton;
- Hematological examination (blood withdrawn from the finger) and biochemical examination of the urine (using indicator paper strips);
- Study of fluid-electrolyte metabolism and renal function (analysis of urine samples stored inflight);
- Hearing tests using sudiometry;
- Microbiological investigations (skin smears, or nasal smears and smears from the cabin interior surface).

Postflight examination included the following:

- Clinical examination;
- Investigation of the cardiorespiratory system and hemodynamics at rest and during provocative tests;
- Evaluation of motor activity, motor control system, and vestibular function
- Investigation of fluid-electrolyte metabolism, renal function, and bone density
- Biochemical investigations (blood enzymes, and blood and urine lipids, carbohydrates, nitrogens, vitamins, and hormones); indices of the sympathoadrenal and cholinergic system of blood);
- Hematological investigation;
- Immunological investigation;
- Microbiological investigations.

SPACE PSYCHOLOGICAL ISSUES

Although psychological issues impact health maintenance, they are not discussed here. Volume III of this report, "The Safety Impacts of Human Factors" addresses these issues. In Section 2 of Volume III, NASA-ARC presents an interaction model whereas stressors, both physiological and psychological, are addressed. Strategies to address psychological issues are also covered in Volume III.

Strategies

Screening and training of space crewmembers appears to be the best preventive means to avoid psychological illnesses. Once a psychological aberrance is noted, depositioning the problem may require chemical or physical restraint. The better strategy of the two would appear to be handling the problem by screening or training before the fact.

HEALTH MAINTENANCE STRATEGY (368)

For the crew, a health maintenance facility, somewhat analogous to a "clinic" in the usual work setting, will be required. It should contain the necessary capabilities to maintain a sick or injured crewman until he or she can be returned to duty or safely to Earth. This capability may evolve over the course of the space station program.

The overall space station system must provide certain capabilities to perform the work outlined herein. The means by which these capabilities are provided is not important; but in some cases, the method may be limited by available technology. Nonetheless, the capabilities should include:

- On-board crew physical fitness provisions
- Maintenance of the psychological well being of the crew
- Measurement of crew performance
- Maintenance of living organisms from 20 days to over a year in zero gravity with no health risk to crew
- Artificial gravity for controls and partial gravity experiments
- Automatic operation or visitation by the crew on a regular basis to the animal and plant habitats with proper crew safeguards
- On-board sample analysis for certain samples, tissues, and effluents
- On-board storage of and capability to update procedures for medical and experimental protocols
- Data transmission to the ground, (some of it in real time) of video and other data streams

While not inherent in the capabilities outlined above nor in the needed capabilities aboard the space station, there are some interface requirements between the subsystems and the facilities that are key to successful life sciences missions.

For example, since we assume the station will be permanently in orbit, there is a need for periodic resupply of food, water, and station laboratory expendables. Similarly, moving expendables to the station and returning samples or specimens to the ground laboratories requires special transfer and STS equipment.

Since EVA is assumed to be a routine space station operation, facilities for treating decompression sickness should be considered. A life support system is required for all habitable areas of the station. The habitat design should feature maximum habitability. Compartmentalization of the habitat, rescue and escape routes, havens, visable/audible caution/warning systems with sensors, and habitat purge and recompression capability should be considered.

If the space station is to be used as a way-station for longer missions involving returned craft or samples from other solar-system bodies, quarantine facilities should be considered. Similarly, if a crew member becomes ill with a communicable disease, quarantine could be required. A hazard analysis of station operations should be performed to allow medical personnel to plan for treatment of any resultant trauma. Thus some of the requirements for health maintenance and treatment must be left open for now.

Key Personnel

Trained personnel will be needed to provide health and maintenance to the crew and to perform life sciences and other experiments. Some tasks or experiments will require surgical or other manipulations or specimens, collection of samples, or performance of special protocols/procedures. The number and types of skills will be determined by overall mission objectives and station architecture.

Some first-aid can be performed by the crew. However, for a long-stay with no chance of return for many days, some specialized medical training could be required for selected crewmembers. Initial health care might require little more than elaborate first-aid kits derived from present shuttle or past Skylab programs. Later in the space station mission a health maintenance facility, and perhaps even a full-scale clinic ("sick bay") including trained medical personnel, would be required.

Operational Considerations (368)

Operational medicine objectives for the space station are:

- To ensure maintenance of crew health
- To establish on-board capabilitiess for trauma, and cardiac life support, and medical care to the point of stabilization
- To broaden the health data base for an expanded population group of space station passengers including Principal Investigators of experiments

A life scientist, preferably a physician, should be a team member aboard the space station when the crew size reaches about eight individuals. He would provide medical care for the crews, perform biomedical observations, and test medical procedures.

The areas listed and discussed below should be considered in the initial planning phases:

- Zero "g" physiological problems
- Life sciences-medical information system (medical computer)
- Accidents/risks
- Disease prevention
- Diagnosis
- Medical/surgical treatments
- Health monitoring
- Medical crew duties
- EVA crew rescue
- Crew patient transfer in orbits/Earth return
- Crew rotation cycle
- Psychological support
- Ground operational support, resource requirements and effectiveness analysis
- Medical standards
- Medical training and certification
- Medical care technology issues
- Operational medicine/medical care technology experiments

INJURY/ILLNESS RISK ISSUES

Accidents (368)

Many accidents may be possible with the projected complexities and increased varieties of hazardous space station operations. Operational medicine considerations deal with the principles of occupational medicine and environmental health (OMEH) which encompass prevention, monitoring, and countermeasures to ensure the safety of the crew members. The statistics for injury and medical problems suffered in analogous terrestrial operations should be useful in projecting similar problems in Earth orbiting space station. Administering a program of space station health maintenance should remain within space station program jurisdiction.

Disease Prevention (368)

The space station, as a closed or semi-closed ecosystem, makes the crew members a major source of the microbial load and distribution within the space station habitat. Once a crew member develops a communicable disease, its rapid spread among the crew may occur. Disease prevention involves proper crew selection, pre-flight crew health stabilization, on-board food system, personal hygiene, waste management, and possibly the transfer of disease between animal and man if experimental animals are introduced into the station. Disease prevention also concerns the exposure to possible toxic materials, radioisotopes, and biologically active material. In this context, the bioisolation technology incorporated with the space station environmental control and life support system (ECLSS) is needed. Isolation of humans from animals, and healthy crew members from those who have contacted communicable disease, may be required.

MEDICAL PLANNING

Diagnosis (368)

Medical diagnosis of a crew member who is ailing from trauma or disease opens a new technological challenge which encompasses a range from basic physical examination to electronic and clinical chemistry laboratory tests. As stated, we are dealing with physiological baseline changes and physiological norms from those on Earth. Hence, intravenous fluid therapy can be monitored by measuring the body mass or shifts in the body's center of mass.

Another concern is a decision to return the crew to Earth. There may be cases involving patients who cannot immediately be returned to Earth due to the seriousness of the trauma or illness, and other cases in which the 14 to 21 day delay in rescue capability may not be medically acceptable. The level of onboard medical capabilities versus the cost per rescue mission needs further, careful tradeoff considerations.

Based on the current estimate of STS turnaround capability, the minimum arrival time for a rescue vehicle after notice is now projected at 21 days. Since a patient's condition will vary, medical criteria must be determined for committing the patient to reentry and landing without endangering his or her condition.

Medical/Surgical Treatment (368)

Medical and surgical treatment capability aboard a space station is enhanced by a better understanding of physiological "space norms" (hence, a need for experiments) and the feasibility demonstration of therapeutic equipment and procedures in weightlessness. Projected medical problems, or the statistics compiled on medical problems (trauma and illnesses) on Earth, and benign medical problems encountered on past manned space missions, are rather misleading in defining future medical care capability in the space station era.

Medical treatments include pharmacokinetics affected by the space sation environment, the concerns about drug shelf-life, drug potency, on-board processing capability of intravenous fluid, and blood bank technology. It may be useful to select space station crew members in pairs, based on their blood types and titers, as the living blood banks for possible transfusion to another crew member and to abrogate the need for a blood bank facility. Autotransfusing and other techniques should be considered.

Medical Crew Duties

Nominal duties for the medical crew aboard the space station should encompass, but not be limited to the following functions:

- Routine out-patient care, including dental, x-ray and clinical laboratory
- Surgery with computerized intravenous general anaesthesia
- Medical traiing and educational materials
- Communicable disease patient isolation
- Clinical laboratory tests

- Emergency medical care
  - Rescue, CPR, stabilization, and transfer
  - Life sustenance, intravenous (IV) injection, electrolyte balancing
  - Orthopedic treatment
  - Decompression sickness care using the airlock module
  - Burn care
- Vital signs monitoring and treatment of critically ill patients with direct communication with ground for consultation as required
- Crew operations/construction performance monitoring and human factor/man-machine interface analyses (time and motion studies including physiological cost of work using videotape)
- Medical communications
  - Image transmission of x-ray, microscope slide, and patient's appearance (such as skin lesions) for consultation as required
  - Routine crew health status report to ground support center
  - Real-time medical emergency communication with ground
- Monitoring of crew radiation exposure and EVA crew workload/metabolic rates
- Potable water and food testing
- Drug potency testing using animal models
- Psychological crew support
- Equipment and medical facility maintenance
  - Preventive maintenance
  - Checkout and repair
  - Cleaning
  - Calibration
  - Inventory
  - Automated readiness status display
- Microbiological and chemical analysis/monitoring of space station environment
  - Microbial sampling, culture
  - Air sampling/toxicological analysis
  - Light, noise, and temperature
- Human deconditioning trends measurements
- Medical records and data managment/periodic crew health status reporting to the Space Station Commander and the Ground Space Station Operations Support Center
- Decontamination - radiological, chemical, and microbiological contamination
- Biological, radiological, and chemical waste storage, processing and disposal
- Zero-g medical procedures/medical equipment performance verification (video) using human and/or animals model
- Regenerative life support system (RLSS) research

Extravehicular Activity (EVA) Crew Rescue (368)

Long term space station operations may expand EVA to the point of routine and give rise to multi-crew EVA thus increasing the possibility of hazards to the EVA crew. Therefore, various EVA tools, manned remote work stations, manned maneuvering units, extravehicular mobility units, and personal rescue systems have been assumed to be provided.

Possible medical problems during EVA, however remote, include decompression, life support system failure, vomiting, physical fatigue, myocardial infarction, collison with subsequent tumbling and unconsciousness, and cuts and breaks.

On past missions, a skin-attached hypodermic injection kit was devised for medication during EVA. When an EVA crew works several kilometers from the mother station, a pressurized remote-size first-aid station may be required to ensure their safety. There are a number of past and current EVA rescue systems and concepts. These could be analyzed against possible crew hazards in various planned space station operations. The analysis can be used to develop strategies for improved EVA crew safety and rescue.

Crew Patient Transfer in Orbit/Earth Return

Medical treatment and patient transportation in space, or from space to Earth, encompass much broader and sometimes unusual problems not encountered on Earth. Patient handling under such a system can be divided into three categories: (1) illness or injury treated and crewman is returned to duty; (2) first-aid care given for injury or illness and care provided for several days, with return to Earth for more definitive treatment; and (3) more extensive treatment only for conditions that do not permit reentry (e.g., crewman requiring immediate major surgery or more sophisticated diagnosis and treatment will be transferred to a space base station that has more sophisticated medical care facilities). (368)

If patient transfer is required, modular equipment for monitoring and treatment could be installed in the space shuttle or an orbital transfer vehicle for enroute medical care. The acceleration/deceleration loads and durations for the crew patient should not be harmful to his or her ailment. (368)

Figures 4-2 and 4-3 indicate injury/illness drivers that may require return to Earth. Those illnesses or injuries suggesting immediate return to Earth indicate the need for a low-g rather than a high-g rescue level. This tends to support the recommendation to employ Orbiters or Hermes type vehicles.

Build-up Considerations for Medical Planning (372)

The space station developed and placed into orbit by the United States will involve a sequential buildup with limited but increasing manning and operational capabilities at each phase of the buildup. To be effective and useful, the health maintenance and medical care requirements for space stations must take into account this buildup sequence.

Categories have been established for planning purposes in order to define various levels of space station buildup. Each category defines a manning level and operational capability that will require an increasing level of medical support. It is believed that the categories presented will permit various levels of medical operations to be established and provide for most foreseeable space station buildup sequences. The medical operations requirements for each category are presented in this document. Table 4-1 summarizes the medical facilities and operations to be conducted during space station buildup.

Although the timing of the buildup is not established, some preliminary concepts have indicated that Category I activities will last only a few months and involve mainly activiation of the power, communications, and support systems. Thus, there will be little time and need for health maintenance beyond that afforded by an enhanced docked Orbiter. Category II activities may last two or more years. During this period, there may be substantial time

SEVERITY	CONSEQUENCES	EXAMPLES OF POSSIBLE INJURY	SPECIAL TREATMENT & PROVISIONS REQUIRED
MAJOR INJURY	BED REST	FRACTURE OF BACK, LEG, OR CRANIUM; CHEST WOUND; POISONING	X-RAY; TRACTION DEVICES, BRACES, CASTS; CLINICAL LABORATORY TESTS; GASTRIC LAVAGE; ANTICONVULSANTS; SURGICAL CLOSURE PROVISIONS
	RETURN TO EARTH	FRACTURE OF NECK WITH PARALYSIS, HEAD INJURY, COMA, FOREIGN BODY IN TRACHEA, THIRD-DEGREE BURNS	X-RAY; TRACTION DEVICES, BRACES; BLADDER CATHETER; ANESTHESIA; BLOOD TRANSFUSION; CLINICAL LABORATORY TESTS; FLUOROSCOPE; INTRAVENOUS FEEDING & FLUID REPLACEMENT
MINOR INJURY	NO LOST TIME	ABRASION, BLISTER, MINOR LACERATION	COMMON FIRST-AID-KIT PROVISIONS
	LIMITED DUTY	SIMPLE FRACTURE OF WRIST OR ARM, JOINT SPRAIN, MINOR MUSCLE STRAIN, MINOR BURN	X-RAY, PRESSURE BANDAGES, COLD PACKS, SPLINTS & CASTS, ANALGESICS, ANTIBIOTICS

Figure 4-2 Possible Crew Injuries and Required Treatment and Provisions

SEVERITY	CONSEQUENCES	EXAMPLES OF POSSIBLE ILLNESS	SPECIAL TREATMENT & PROVISIONS REQUIRED
MAJOR ILLNESS	BED REST & LOST TIME (>1 WEEK)*	APPENDICITIS, BRONCHIAL PNEUMONIA; INFECTIOUS HEPATITIS, MENINGITIS-EPIDEMIC, PROSTATITIS, THROMBOPHLEBITIS	ANTIBIOTICS, INTRAVENOUS FLUIDS, SURGERY, X-RAY, EXPECTORANTS, CLINICAL LABORATORY TESTS, STEROID THERAPY, ANALGESICS, CATHETERIZATION, INTENSIVE CARE, ISOLATION; ANTICOAGULANT
	RETURN TO EARTH	ENCEPHALITIS, MYOCARDIAL INFARCTION, ILEITIS	INTRAVENOUS FLUIDS, TRACHEOTOMY, SEDATIVES, OXYGEN, ANTICOAGULANT, CLINICAL LABORATORY TESTS, ANTISPASMODICS, SPECIAL DIET
*SERIOUSNESS & EXTEND OF THESE ILLNESSES MAY REQUIRE RETURN OF CREWMEN TO EARTH			
MINOR ILLNESS	NO LOST TIME	ATHLETES FOOT, DERMATITIS, CONJUNCTIVITIS, RHINITIS, URETHRITIS, PHARYNGITIS, ABSCESS OF MOUTH & GUM	FUNGICIDES, STEROIDS, ANTIBIOTICS, ANTIHISTAMINES, NOSE DROPS, DECONGESTANTS, ANALGESICS, ANESTHETIC LOZENGES, IMPROVED HYGIENE PRACTICES
	LIMITED DUTY OR MINIMUM LOST TIME (<1-WEEK)	BRONCHITIS, CYSTITIS, DIARRHEA, DYSENTERY, FEVER, COMMON COLD OR INFLUENZA, GASTRITIS	ANTIBIOTICS, DECONGESTANTS, ANTITUSSIVES, ANALGESICS, CATHARTICS, ANTISPASMODICS, ANTIPYRETICS, ISOLATION, ANTIEMITICS, SPECIAL DIET

Figure 4-3 Possible Crew Illnesses and Required Treatment and Provisions

for medical research. The medical equipment in the first aid station can be used for human research but will have to be always ready for operational medical treatment. Dedicated laboratory space for medical research with animals would be available when the Life Sciences Research Module is added.

Category I - A single habitable work area is assumed with an airlock and living facilities for two persons. When this phase is in orbit, the Orbiter crew may be able to be increased to eight. This station would be utilized for short duration missions and require the Orbiter to be docked or in orbit nearby to provide for crew safety during crew occupancy. Medical equipment would consist of that avilable on the Orbiter with additional supplies and equipment necessary to support the habitat development. At least one crewmember would be trained as an emergency medical technician (EMT) and would have this task as one duty. The EMT will have sufficient training to use a portion of the prescription medical supplies prior to consultation with a mission control center surgeon. Depending upon training and experience, various prescription drugs and surgical supplies could not be used by the EMT until after consultation with a mission control center surgeon. Depending upon training and experience, various prescription drugs and surgical supplies could not be used by the EMT until after consultation with a mission control center surgeon. The entire crew will be trained in first aid techniques. The EMT will be able to draw blood specimens for later analysis in ground-based laboratories.

Category II - Additional work areas and airlocks would be added to increase facility size and provide redundancy. A four-person crew is assumed which would occupy this configuration for stay times to 90 days. A docked Orbiter would not be needed, and the remaining Orbiter crewmembers would return to Earth. Emergency rescue capability would be fairly slow, probably 14 to 21 days. Assembly tasks would be included during EVA. Simple satellite preparation, refueling, repairing; materials processing and observational activities would occur. A dedicated exercise and first aid area would be available. Medical equipment would include a duplication of that in the Orbiter as in Category I plus the equipment and supplies necessary to care for the well-being and medical problems of the crew over a three-month period. Routine simple diagnostic equipment would be available to process specimens. One crewmember would be a trained EMT with long experience as a medical assistant. Medical care and crew health maintenance would be his primary duty, but not his only duty. The remainder of the crew will be trained in first aid techniques.

Category III - Work and habitation areas would be added to Categories I and II. It is assumed that Category III will provide for an eight or more person crew with prolonged stay times as a standard. Four or all eight crewmembers could be changed with each Orbiter visit. EVA activities could include satellite servicing and construction projects. Complex satellite repair and materials processing would be a regular activity. Emergency rescue capability would remain at 21 days. Total emergency evacuation of the facility would be a planned option. For adequate health maintenance, dedicated medical facilities would resemble those available in a physician's office clinic or in a two-bed field hospital. The sophisticated medical care facilities would then be available to be cross utilized in medical research and would be designed to solve the medical care problems caused by the interaction of industrial activities with the physiologial changes of microgravity. A research trained physician would be included to take advantage of the medical operational research and have as a primary duty, the health care of the crew.

He will have surgical training because of the industrial activities. He would have other duties. When a physician is not available, a medical technician with extensive experience in medical care, e.g., physician assistant, would operate the medical facilities.

Health Maintenance Facilities (372)

Category I - Augmented Shuttle Orbiter Medical System, (SOMS), kit both in the Orbiter and the Station plus exercise facilities. Equipment to obtain biologic specimens.

Category II

1. First Aid Station - A location in the module where a sick/injured crewman can be restrained and treated. The station will have ready access to essential equipment such as physiological monitors, intravenous fluids, oxygen, suction, defibrillator, etc. Capability to perform simple diagnostic procedures and obtain routine biologic specimens.

2. Space Station Medical Kit (SSMK) - An expanded version of the SOMS with additional drug supplies and some additional surgical supplies.

3. Hyperbaric Treatment Facility - A facility designed to withstand a minimum of 3 atmospheres (absolute pressure) for treatment of most cases of decompression sickness and able to accommodate two individuals, i.e., patient and attendant.

4. Exercise Facility - An integral part of the recreational area consisting of a treadmill, friction based exerciser, and/or bicycle ergometer, etc.

Category III - Health Maintenance and Treatment Facility (HMTF)

Dedicated HMTF area increased in size. All features listed under Categories I & II will be available and expanded to accommodate additional crewmen. Table 4-1 shows possible health maintenance facility development.

Preventive Medicine

To protect the health of the crew, both physiological and psychological problems that are caused by isolation in space must be anticipated and countered. Methods for maintaining both physical and mental health are often intertwined. Some of these procedures are:

a. Recreation - This should include a large library (perhaps computer contained), exercise equipment, videotape and music libraries, and games to be played alone or with others

b. Work - All on board should have sufficient tasks to make their stay a challenge, yet not so much work that their tasks are burdensome and thus counterproductive

c. Architecture and Engineering - At least two roles are evident: First, to avoid injury and discomfort, safety and ease of operation should be considered in the layout of the station and station systems. Second, the creation of a pleasant place to live and work which would include a private space for each crewmember. Space for personal use would add to the well-being of the crew.

d. Communication - Private two-way video communication with friends and family on Earth and open communication between crewmembers on board could boost morale. Noise level should not be so high that shouting is necessary.

e. Stress Mangement - Crewmembers should be trained to deal with the stress of the long stay in the isolation and close quarters of a space station (e.g. training in social support techniques).

f. Clothing - Should be comfortable, abundant, and not monotonous. Keeping clothing clean should be simple and not require large amounts of water. The design of both clothing and equipment should take into account the possibilities of 1) preventing trauma (e.g., flak jacket), and 2) causing trauma (sharp corners, tight fit). These include all designs within and without the space station.

g. Sleeping - Facilities should be comfortable, with low level noise background, and also darkened.

h. Health Monitoring - Private medical conferences, biomedical and physical testing, and self-assessment should be part of an operational schedule. The macho image must be replaced by intelligent regard to individual health.

i. Nutrition - The food should be high in nutritive value as well as appetizing. The diet should be varied enough to make the crew look forward to mealtimes. Vitamins may be needed as supplements. Food flavor may have to be enhanced. Appetite stimulation may be needed early in flight. Recreational type food may be required. It is unknown whether high or low fiber is necessary for crew health.

j. Normal ranges of all physiological parameters for individuals living in microgravity must be established to aid medical personnel in the determination when disease is actually present.

Table 4-2 shows the preventive medicine implications in space station development.

TABLE 4-1 PROGRESSIVE MEDICAL SUPPORT AS SPACE STATION DEVELOPS

CATEGORY	MEDICAL FACILITIES[1]	MEDICAL OPERATIONS[1]
I - Single module with docked Orbiter.	Augmented SOMS (first aid kit), and exercise facility.	Observing and monitoring the crew, collecting, and storing of blood, excreta, and toxicology specimens to establish normal ranges of biochemical tests.
II - Second module on core space station. No docked Orbiter.	Equipped first aid station area, hyperbaric treatment facility, expanded health maintenance, and exercise facilities.	Initial utilization of onboard diognostic instrumentation which has preventive medical care as its primary function.
III - All-up core space station.	First aid station expanded to dedicated medical area with expanded treatment capability, e.g., anaesthesia, minor surgery, and biochemical analysis.	Medical documentation not requiring animal specimens but including invasive studies to solve medical care problems of microgravity.
AUGMENTED III	Expansion of the medical treatment area and its laboratory equipment making it similar to a small hospital with an enclosed emergency room.	Sophisticated clinical testing and medical research.
	* * * * * * *	
ADD-ON DEDICATED LIFE SCIENCES MODULE (Added during any of the above categories.)	A dedicated separate structure of laboratory space, primarily for biologic research.	Biological research using animals and plants in a separate dedicated laboratory area, not part of the medical treatment facility.

[1] Each category includes all previous features.

TABLE 4-2 SPACE STATION SYSTEMS WITH PREVENTIVE MEDICINE IMPLICATIONS

LIFE SUPPORT

- Structure, Power and General Communications
- Environmental Control Life Support Systems, ECLSS (air, water, temperature control, etc.)
- Food and Nutrition (inludes storage, food preparation, galley, consumption, taste enhancement, cleanup, etc.)
- Waste Management (wet and dry, excreta and packaging materials, etc.)
- Hygiene (hands and body washing, shaving, toothbrushing, etc.)
- Sleep Stations
- Environmental Status Monitoring (could be in HMF or in separate command station)
  - Atmospheric quality (CO_2, O_2, N_2)
  - Trace gas analysis
  - Toxic compounds
  - Water Quality
  - Ambient microbial load (air, water, surfaces)
  - Temperature
  - Humidity
  - Noise Level
  - Acceleration and vibration
  - Radiation
  - Odor

LIVING AND WORKING SUPPORT

- "Housekeeping" (environmental cleaning, clothes washing, etc.)
- Clothing
- EVA Equipment
- Safety Provisions (equipment and procedures)
- Hold Hand, Intravehicular Activity Mobility Aids, Foot and Body Restraints
- Crew Stations
- Man-Machine Integration (includes tools to match the job)
- Work Planning
- Quality Control
- Communications
- Hygenic Needs

HEALTH MAINTENANCE FACILITY (preventive medicine)

- Exercise (fitness - legs, arms, back)
- Physiological Status Monitoring
  - Cardiovascular condition (heart rate, blood pressure, EKG, echocardiography, etc.)

TABLE 4-2 (Continued)

    - Metabolism
    - Pulmonary function
    - Immune competence
    - Blood chemistry records and evaluations
    - Urinalysis
    - Microbial load
    - Anthropometry and mass
    - Bone density
- Thermometry
- Radiologic, ultrasonic, and nuclear imaging
- Visible Light Imaging Device (high resolution color TV or equivalent)
- Tonometry (fluid shift)
- Audiometry (noise and fluid shift)
- Health records (trend analysis)
- Private Medical Communications

SOCIAL-PSYCHOLOGICAL SUPPORT (habitability factors)

- Rest (Earthviewing ports, body position holders, etc.)
- Recreation and Entertainment (electronic games, board/card games, physical games, i.e., library, "darts" puff ball, music, TV, hobbies, diary writing, etc.)
- Work/Rest Timeline Programming (includes circadian rhythm considerations)
- Private Quarters
- Clothing (style, color, selection, fit)
- Private Communications (family and friends)
- Architecture (includes color, local vertical, volume, layout, lighting, noise minimization, stowage, etc.)
- Social Support Aids (computerized library to supplement ground-training, communication with professional psychological support team, etc.)
- Human Performance Measurement

RESEARCH LABORATORY AND EQUIPMENT (add-on modules assumed; not necessarily permanent)

- Human Biomedical Research Laboratory
- Life Sciences Research Laboratory
- Vivarium
- Materials Processing Lab(s)
- Orbital Quarantine Facility

5. EXPLOSION

DEFINITION

In the event of an explosion whereby the damage will be confined to one compartment and will consist of overpressure, heat, shrapnel, and atmospheric contaminants. Equipment in the compartment may be damaged and made inoperative, unless armor-plated for protection. Violent release of energy as a result of equipment overpressurization, fire, chemical reaction, excessive temperature, equipment malfunction or structural failure are candidate causes for explosion. For instance, an explosion of .025 lb TNT equivalent, releasing 50 BTU of energy in the form of heat, shock waves and kinetic and thermal energy of shrapnel damage could be confined to one small compartment and would consist of overpressure, heat, shrapnel and atmospheric contaminants. The equipment would require repair/replacement, depending on the damage an explosion can produce. Further hazards which can result in a compartment by such an explosion, such as fire, etc., should also be considered as part of the threat. Walls and primary structure, or equipment outside the affected compartment, would probably not be damaged (021). Equipment which can disintegrate explosively includes pumps, motors, blowers, rocket motors, generators, laser, etc. In excluding equipment and materials from Space Sation habitable volumes whose TNT equivalency exceeds .01, explosion impact can be minimized. Equipment and material mounted externally to the Space Station habitable volumes that exceed the threshold .01 TNT equivalency should include shrapnel diverter shields to protect the habitable volumes from catastrophic penetrations.

DISCUSSION

An explosion is a phenomenon resulting from a sudden release of energy. The release, however, must be a sudden one, happening so rapidly that a local accumulation of energy occurs at the site of the explosion. This accumulation is then rapidly dissipated in various ways such as by an explosive blast wave, or by the propulsion of missiles or debris. An implosion is a similar phenomenon except that the energy release is initially directed inward.

The magnitude of an explosion is established by the amount of energy that is released. This may be expressed directly in energy units - calories, for example. But a relative, rather than an absolute, measure for explosion size may be both more meaningful and more practical. This requires that some sort of standard be defined; a generally accepted standard is the energy released by the explosion of TNT (symmetrical trinitrotoluene), selected as a standard because chemically pure material is readily available for calibration purposes. By measurements of the energy in its blast wave it has been determined that the explosion of one gram of TNT generates a blast energy of about 1120 calories. This is identified as the explosive yield from that quantity of material. The explosive yield from some other material, relative to that obtained from TNT, is taken as its relative explosive strength. With regard to both laboratory and field tests, there is always some uncertainty in the measured values, even for calibrating blast waves as generated by standard TNT. This situation has led to the acceptance of an arbitrary standard for blast waves - the defined ton of TNT. This corresponds to an explosive energy release of one million kilocalories. An energy release of this amount represents (1,000,000 x 1000)/(2000 x 454) = 1100 calories per gram of TNT, which is an approximate agreement with average experimental values.

Damage from an explosion is a result of energy that is transmitted from an explosion to a target. The mechanism for the transmission may be any of several types, the most severe of which is a direct mechanical coupling. This produces a shattering action, and is related to the shattering power, or "brisance" of the explosion, as described briefly below. Transmission of energy from explosion to target by indirect means occurs through the action of flying missiles and of the blast wave. The relative importance of these damage mechanisms varies considerably with circumstances and depends on the nature of the explosive, the magnitude of the explosion, and the medium in which it occurs. Damage by flying missiles is relatively more important for small explosions in the air than for large ones and for explosions in the vacuum of space, although the blast wave is the major mechanism for destruction in large explosions. Direct energy transfer from an explosion to target also occurs by thermal radiation. This damage mechanism is important only for the large nuclear explosions, and is best considered separately. Ionizing radiation may be considered as a mechanism for the transfer of energy from an explosion to target. This may be a direct transfer at the moment of the explosion, or an indirect one associated with fallout of radioactive debris, but is beyond the scope of this study (293).

Missiles/debris are solid objects flying away from the explosion. The cumulative action of missiles may well be the major damaging effect from small explosions such as those from the container. Or missiles may be formed from material located originally at the site of an explosion; examples are pieces of a structure, parts of a barricade, or some casual object included by chance. The impact energy of a missile is the kinetic energy of its relative motion. For a missile with relative velocity u and mass m, this may be expressed as $.05mu^2$. Like other energy items, this impact energy may also be expressed in terms of its TNT equivalent.

There is an interesting relationship between missiles and barricades. A barricade may act as a sort of armor plate and protect a person or a structure from flying missiles in an explosion. As such, it may be a convenient item to have available. But if a barricade is used in an attempt to confine or contain an explosion, the barricade itself may well be broken up in the explosion and so serve as an additional source for missiles. In this situation, the barricade may actually assist in the transfer of energy from explosion to target.

Brisance, the rapidity with which the energy is released in an explosion, may be an important factor. Its influence can be illustrated by considering the release of energy stored within the compressed air of a pneumatic tire. When sudden, as in a blowout, the effect is that of an explosion. A slow leak can dissipate the same energy but would not be classed as an explosion. Furthermore, two energy releases each sufficiently rapid to cause an explosion may show differences with regard to the intensity of the explosion that they produce. This intensity is evidenced as a shattering power, and is termed "brisance". Any item in contact with exploding material receives a mechanical shock of such intensity that it could well be broken into small fragments long before it has opportunity to move away. Thus dynamite, a detonating material, when placed on top of a boulder may shatter it even though the explosion is completely unconfined (293).

The pressure-time history of a typical blast wave in atmospheres as observed at a location removed from the center of explosion is shown in Figure 5.1. At an arrival time of t_x seconds after the explosion, the pressure at this removed location suddenly jumps to a peak value of overpressure. An

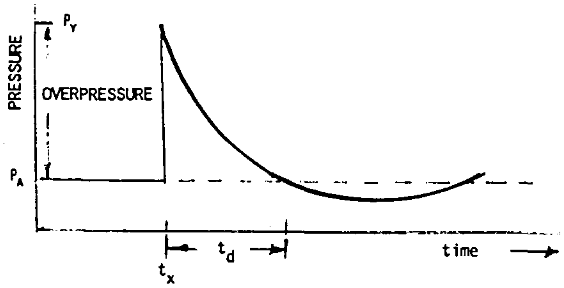

Figure 5-1 Typical pressure- time curve for an explosive blast wave (293)

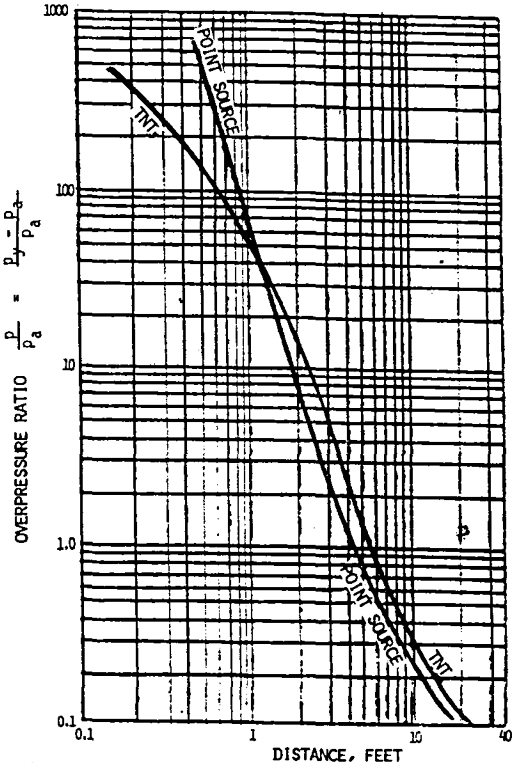

Figure 5-2 **Peak Overpressure Ratio vs. Distance for Explosions with a yield of one pound of TNT (293)**

object at this location is then subjected to an instantaneous lateral force equal to the product of this overpressure and the projected area in the plane of the blast wave. But this is not a stable condition, and the overpressure immediately begins to decay, following a pressure-time relation such as illustrated in the figure and described as quasi-exponential in character.

Blast waves of the type shown in Figure 5-1 require that three independent characteristics be specified in order to describe them completely. One of these is the initial shock intensity, specified perhaps by the peak overpressure, but also by any related intensity item such as Mach number or particle velocity. A second is the duration of the blast wave. A third characteristic is the impulse (force-time product) for the pressure forces in the blast. In addition, for some purposes, such as for the planning of evasive maneuvers, it is desirable to know arrival time; that is, the time required for the explosive shock front to travel from the center of explosion to the location of concern. Both experimental and theoretical means have been utilized to obtain the various characteristics of the blast wave from explosions in atmospheres. A theoretical analysis for peak shock overpressure, that is, the pressure jump in the blast wave face, utilizes the same mathematical approach as for normal shock. It is, however, more complex because of the spherical divergence and because of a transient nature. Values, for the peak overpressures generated in a nominal standard atmosphere and as computed for the blast wave from a one pound spherical charge of TNT, are shown graphically in Figure 5-2.

STRATEGY OPTIONS

Approach

In comparing incidents that can precipitate emergencies the space station is most vulnerable to an explosion. See Table 5-1. Not only is the reaction time zero, other ancillary issues are involved. Because of the risks associated with explosion, a reasonable approach is to cascade prevention and containment techniques. That is, every effort should be made to prevent exposure to the threat and then to accept its possibility of occurrence by including containment techniques in space station designs and operations.

TABLE 5-1 - ASSUMED EFFECTS FOR VARIABLE LEVEL
CREDIBLE EMERGENCIES (016)

	Minimum Reaction Time (Minutes)	Need To Evacuate Compartment	Injured/ Incapicitated Personnel	Restoration to Shirtsleeve Environ.	Can Cause Other Listed Credible Emergen.
Fire/Toxic Environment	0.5	Yes	No	Yes	Yes
Explosion	0	Yes	Yes	No	Yes
Emergency Evacuation	5	Yes	No	No	No
Loss of Pressurization	2-8	Yes	No	No	No

Explosion Prevention

For space station applications, the classical fire triangle should be expanded to an explosion penta-ring, see Figure 5-3, to exploit the advantage of operation in a space environment. This expansion of concept from a three-to-five element approach allows concentration or applying strategy options that work with, not against the space environment. That is, "temperature" and "pressure" are elements extracted from "ignition" in the fire triangle because there is a space advantage in their handling: absence of pressure and an infinite radiative heat sink.

The classical approach for fire/explosion prevention of breaking one or more legs of the fire triangle/explosion penta-ring is equally valid in space station explosion prevention. Guidelines concerning 1) physical and chemical screening to prevent and/or isolate reagents, 2) pressure sensing, relieving and control and 3) system heat sensing and rejection are techniques that can be applied in preventing exposure to explosion risks.

The matrix shown in Table 5-2 indicates explosion prevention options or strategies. Many are desirable design considerations all of which are not mandatory. Using single string tankage, lines, sensing valving and use system as a baseline, one or more options may be considered with its respective cost impacts and synergies.

Table 5-3 shows typical Orbiter compartmentation criteria. Table 5-4 indicates typical gas autogenous ignition temperatures that may be considered for temperature control maximum threshold levels. The designer is advised that equipment in the compartments may not exceed the temperatures noted (spot or surface).

Explosion Containment

Explosion impact is related to four issues: 1) Intensity expressed in TNT equivalency; 2) Direct contamination by explosive parcel; 3) Secondary effects (debris and overpressure); and 4) Preventive and corrective damage control.

TNT Equivalency - The Shuttle approach in isolating crew members from the threat of explosion was to limit systems/equipment into habitable areas to those with a TNT equivalency of 0.01 or less. Those items of equipment exhibiting more than a TNT equivalency of 0.01 were external to the habitable volume. As a result, except for walk-around O_2 bottles, all pressure tankage was excluded from the cabin. Figure 5-4 shows two options in handling the installation of explosion generators in the space station. If adjacent mounting is chosen, it may be wise to consider an adjacent shirtsleeve airlock, pressurizing the critical volume with an inert gas. This would allow IVA (non-pressure suited) crewman to retain tactile dexterity to conduct maintenance tasks in an inert environment while wearing an oxygen or two gas helmet. The adjacent mounting approach with proper shrapnel shielding and inert pressure/depress options would be the lower risk exposure approach for critical, high TNT equivalency equipment by allowing for masked but not shirtsleeve access.

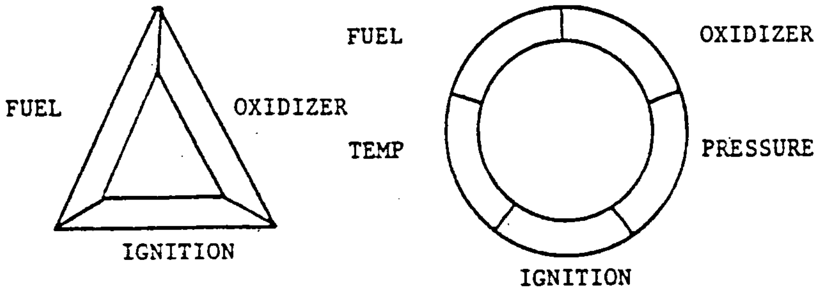

Figure 5-3 Fire Triangle and Explosion Penta-ring

Table 5-2 EXPLOSION PREVENTION OPTIONS

PENTA-RING ELEMENTS	SCREENING	PRESSURE HANDLING	TEMPERATURE HANDLING
FUEL * OXIDIZER * IGNITION TEMP. PRESSURE	o Protect tankage lines from failure, corrosion or erosion o Multistep control of critical consumable transfer/ignition o Purge of interfaces o Explosion proof in-atmosphere components o Electrostatic controls (bonding and grounding) o Compartmentation o Thermal protection of sensitive elements o Providing expansible inner bladder/tanks to accommodate expansion without heat build-up	o Pressure sensing and valving o Vent onverboard of consumables for pressure increase o Blow out disks o Vent to expansion tank for subsequent consumable recovery o Auto level/immediate action o Provide cascade tankage: storage or standby pressure level vs. more confined volume for operating level	o Consumable auto dump into heat exchanger/ radiator loop for temperature rise trends o Maintain system or part of system below autogenous ignition temperature o Size heat rejection system for worst case conditions: maximum insolation, highest internal pressure, adverse "lightside" orientation

* HYPERGOLS

(FROM MF0004-014 & SD74-SH-0223B)

TABLE 5-3 ORBITER COMPARTMENTATION CRITERIA

COMPARTMENT (1)	OPERATIONAL FLUIDS NORMALLY PRESENT	ZONE (2)	IGNITION PREVENTION ZONE (6)	MAX ALLOW SURFACE TEMP TO PREVENT AN AUTO IGNITION -DEGREES F (6)
NOSE SPHERE	(NONE)	I	NO	--
FORWARD RCS	N204, MMH He	II	YES	352
NOSE GEAR WELL	HYD FL (83282&5606)			
FWD MODULE PLENUM	HYD FL (83282), H20	III (4)	YES	352
WINDOW CAVITIES	(NONE)			
STAR TRACKER CAVITY	(NONE)			
MID-FUSELAGE	LH2, LO2, HYD FL (83282), MMH, He, N204, F21, H20, N2,FC40(3)			
CREW MODULE	N2/02, GO2, 1301, H20	IV	NO	--
WING LEADING EDGE (L&R)	(NONE)	V, VI	NO	--
WING BOX (L&R)	(NONE)	VII, VIII	YES	423
MAIN GEAR WELL (L&R)	HYD FL (83282&5606)			
WING/ELEVON INTERCAVITY (L&R)	HYD FL (83282)			
AFT FUSELAGE	LH2, LO2, HYD FL (83282), MMH, NH3, LUBE OIL, N2H4, F21, He H20, N204	IX (4)	YES	352
VERT. STABILIZER FWD OF REAR SPAR	(NONE)			
VERT. STABILIZER AFT OF SPAR (REAR)	HYD FL (83282)	X	YES	432
OMS/RCS POD (L&R)	N204, MMH, He, N2	XI, XII	YES	352
ME LO2 DISCONNECT	LO2	XIII	YES (5)	(5)
BODY FLAP	HYD FL (83282)	XV	YES	432
LH2 UMBIL CAVITY	LH2, HYD FL (83282), F21, He, N2	XVI	YES	432
LO2 UMBIL CAVITY	LO2, He N2	XVII	YES (5)	(5)

Direct Contamination - Contamination by the explosive air parcel relates more to prevention than containment. Prevention of contamination relies heavily on an in-place space station material control system. Containment centers on the ability to decontaminate the volume. Both approaches, the ability to vent contaminants to space, shown in Figure 5-4 support this concept.

TABLE 5-4 TYPICAL AUTOGENONS IGNITION TEMPERATURES

FLUID	TEMP	FLUID	TEMP
JP-4	468^{0}F	ETHYLENE OXIDE	804^{0}F
JP-5	473		
JP-6	450	HYDRAZINE	518
KEROSENE	444	MMH	382
		UDMH	482
METHYL ALCOHOL	800-870	MAF	480
ETHYL ALCOHOL	700		
ISOPROPYL ALCOHOL	750	HYDROGEN	1075
FORFURYL ALCOHOL	915		
AMMONIA	1204	METHANE	1000
BORANE	68 (PYROPHORIC)	METHYLENE CHLORIDE	1033
PENTABORANE	78 (PYROPHORIC)	PERCHLOROETHYLENE	1224
		TRICHLOROETHYLENE	770-786

OBJECTIVES: MOUNT HAZARDOUS ELEMENTS EXTERNAL TO CREW USE OR HABITABLE AREAS WITH PROPER SHRAPNEL SHIELDS TO PREVENT ADJACENT PRESSURE VOLUME PENETRATION

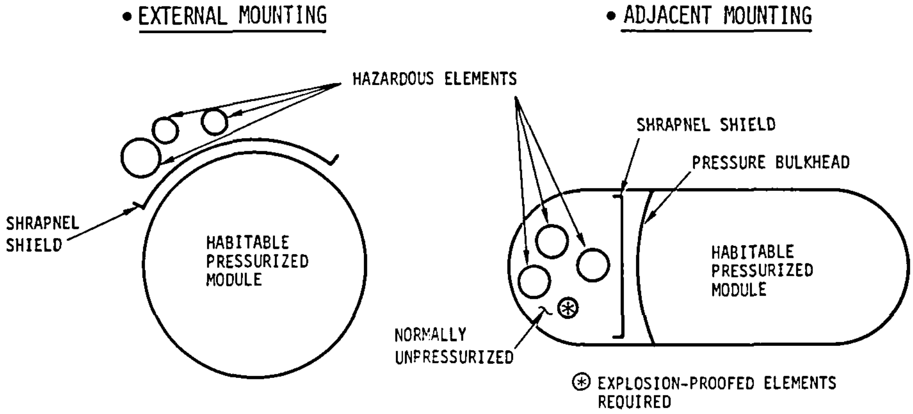

Figure 5-4 Two Options for Explosion Containment

Debris and Overpressure - Containment of debris relies on shrapnel shields or detectors. Overpressure in normally unpressurized volumes is less a problem than in habitable volumes. The control option then would be to locate explosion generators in normally unpressurized volumes or volumes pressurized with inert gas.

Damage Control - An active Damage Control System is mandatory for a long term operable orbital facility. This system would handle all emergencies, not just explosions. Accepting the damage control concept, not only fire control, the space station designer must accept the fact that damage control equipments (shoring, patching, repair) must be inventoried and space provided for their installation and storage. Damage control is an umbrella concept within which emergency procedures are developed and refined.

Containment Strategy Summary - Explosion containment strategies are summarized in Table 5-5.

TABLE 5-5 - EXPLOSION CONTAINMENT STRATEGIES

DAMAGE CONTROL	ISOLATION
o Machinery inspection and servicing, verifying guards in place	o Peripheral containment rings for high energy rotating parts
o Provide damage control lists (structural leak/tear repair) in major modules	o Compartmentation Active (latches) Passive (structural webs)
o Close active latches during explosive risk operations	o Provide shielding/shrapnel deflectors (See Figure 5-4)
o Provide maximum access to module pressure walls	

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6. LOSS OF PRESSURIZATION

DEFINITION

A loss of pressurization in a habitable volume may be caused by an accidental penetration of an outside wall or bulkhead. Pressure sensing, leakage and maintenance imply the need for a Damage Control System on-board the Space Station. Such a system would include pressure, temperature and toxicity sensing with additional capability for smoke sensing and fire suppression for each insolable compartment in the Space Station with primary and back-up readout panels located in separate Space Station areas. If compartment size and criticality so indicate, a need may exist for automatic control of hatch actuation. These design constraints are dependent upon assumed penetration size, size of each isolatable volume, use frequency of the compartment and criticality of the adjacent compartments.

DISCUSSION

The Environmental Control and Life Support System provides the Space Station crew with a conditioned atmospheric environment that is both life supporting and within crew comfort limitations. Loss of pressurization is an extremely critical problem since the provision of an atmosphere of suitable pressure and composition is one of the most immediate requirements of the life support systems. It must supply the oxygen which the blood must absorb and the total pressure required to maintain normal physiologic function. In addition, absorption or elimination of respiratory contaminants and toxic materials must be accomplished.

Decompression problems are similar to those encountered in high altitude aircraft flight. Atmospheric pressure falls with ascent to altitude as shown in figure 6-1. As total pressure falls, the partial pressures of the constituent gases also fall. Therefore, even though the oxygen percentage found in the atmosphere remains relatively constant throughout, the partial pressure of oxygen (pO_2) becomes inadequate to sustain normal physiologic function as total pressure decreases. It, therefore, follows that if adequate atmospheric pressure can be maintained with normal composition, crewmembers can be expected to function without resort to supplementary procedures. However, it may not always be feasible from an engineering or operations standpoint to maintain sea level equivalent pressure within the life support system.

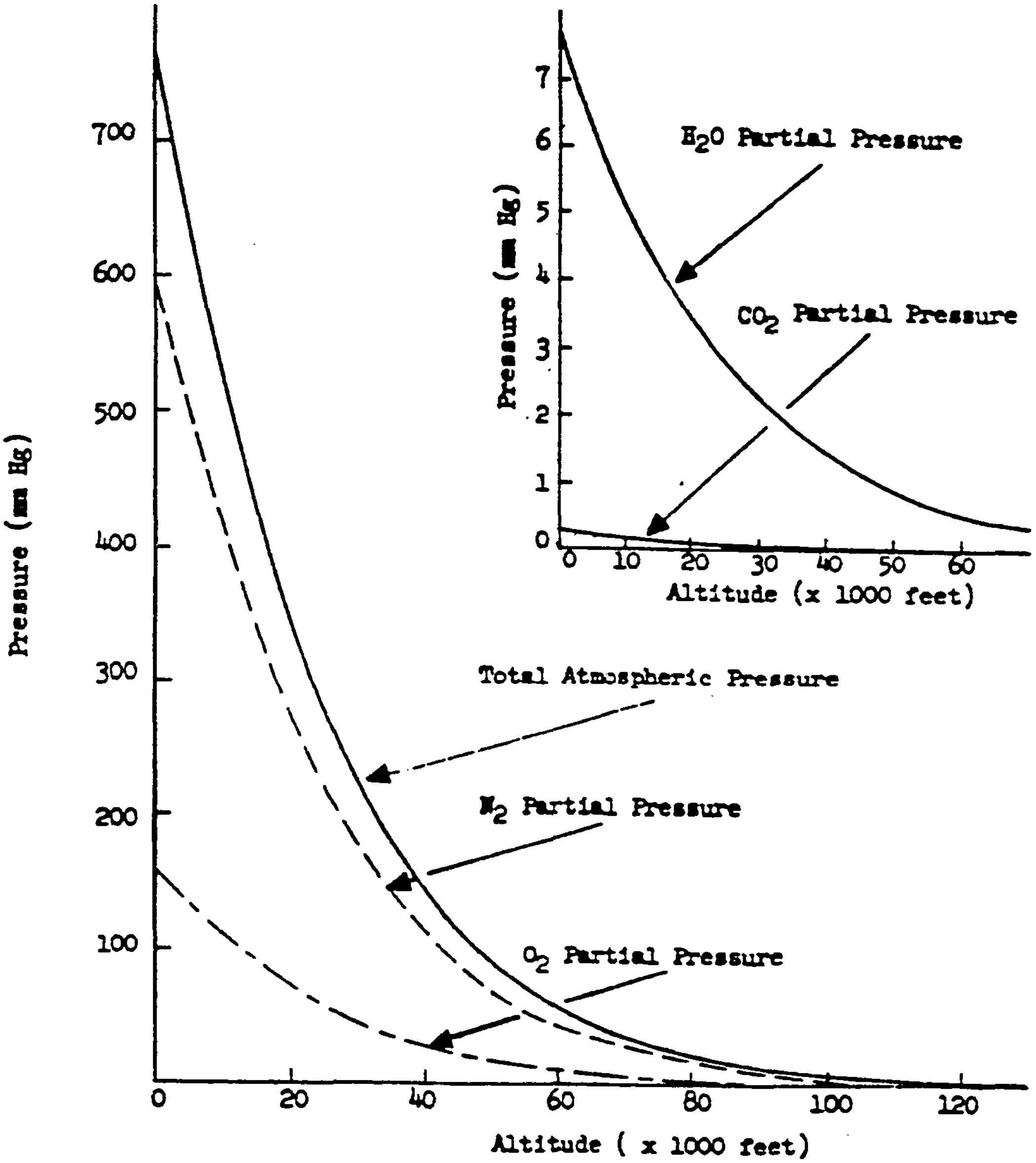


Figure 6-1 Natural Pressure Environment

Emergency Depressurization (025)

The following analyses were performed for situations in which a major penetration has occurred in the Space Station wall:

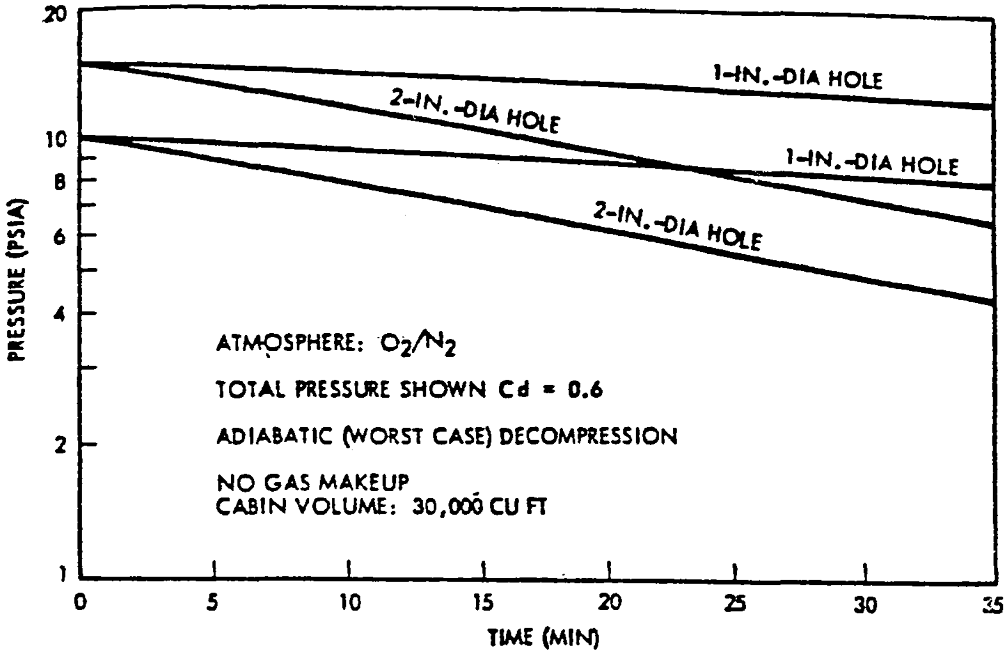
1. Time to depressurization.
2. Wind velocity in the vicinity of the leakage.
3. Loads on a man in the vicinity of the leakage.
4. Wind velocity through the internal hatches.
5. Loads on a man in the internal hatches.
6. Loads on the hatches.

The lowest acceptable pressure level for personnel to function safely must be defined before defininte answers can be given for the time available. A minimum partial pressure of oxygen (pO_2) of approximately 1.9 psi is generally considered to be required to preclude hypoxia (insufficient O_2 in the inspired air), and to permit an acceptable level of crew performance. (384) The visual functions appear most sensitive to hypoxia, and visual performance becomes generally unacceptable at pO_2 of less than 1.9 psi. Unacclimatized persons breathing air (20.9 percent O_2, 79.1 percent N_2), at total pressures less than approximately 6.0 psia (equivalent to approximately 23,000 foot altitude), will lose consciousness after a variable period of time (individual susceptibility varies widely), and total pressures less than 6.9 psia (equivalent to approximately 19,500 foot altitude) in an air environment are considered physiologically unacceptable.

Assuming a homogenous gas mixture and no gas makeup provided, a minimum pO_2 of 1.9 psia is reached at a total (cabin)pressure of 9.1 psia in a 14.7 psia system, and at a total pressure of 6.15 psia in a 10.0 psia system.

Decompression sickness (bends) should not be considered to be a problem because of the pressure drop required to induce the symptoms and the time element involved. Generally, a pressure drop to one-half the atmosphere of prior exposure is considered to be the threshold of decompression sickness, which would be 7.35 and 5.0 psia respectively for 14.7 and 10.0 psia systems. Hypoxic levels would therefore be reached prior to the onset of decompression sickness. Furthermore, for any one individual, decompression sickness is unpredictable in its onset and course, though symptoms are rarely seen during the first few minutes of exposure to low barometric pressure.

The results are presented in Figures 6-2, 6-3, 6-4, 6-5, and 6-6. In these, it was assumed that hatches between the two volumes are left open, so that both hatches are bled down. If the hatches are closed so that only one volume is depressurized, the times shown should be halved. For different volumes, the times should be adjusted proportional to the volume.



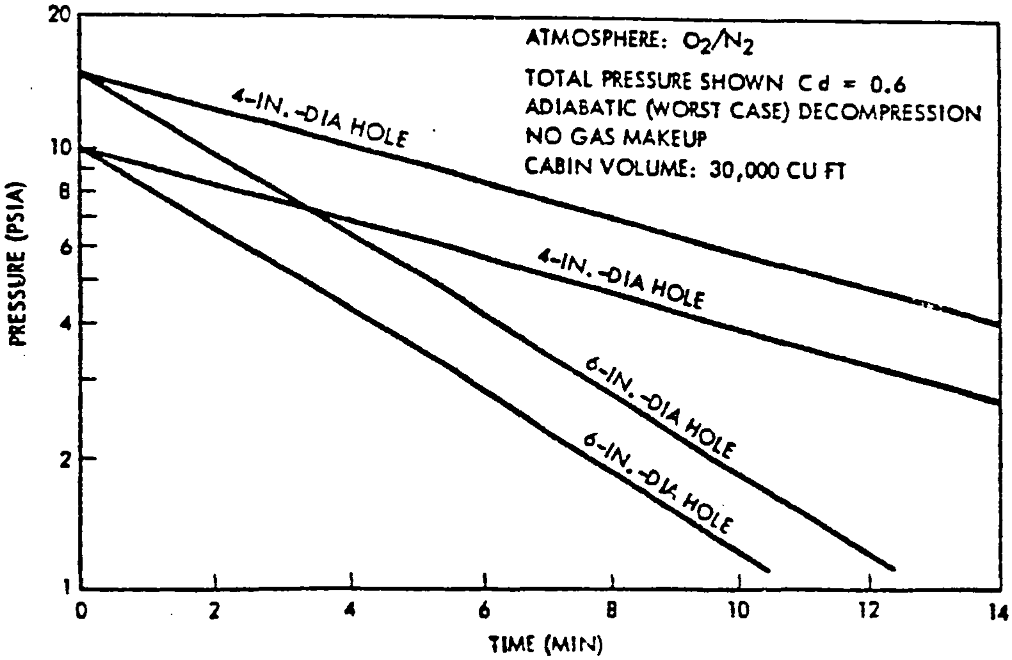
ATMOSPHERE: O_2/N_2

TOTAL PRESSURE SHOWN Cd = 0.6

ADIABATIC (WORST CASE) DECOMPRESSION

NO GAS MAKEUP
CABIN VOLUME: 30,000 CU FT

Figure 6-2 Pressure Drop Following Structural Leak - 1 and 2 Inch Holes (cd = discharge coefficient)



ATMOSPHERE: O_2/N_2
TOTAL PRESSURE SHOWN Cd = 0.6
ADIABATIC (WORST CASE) DECOMPRESSION
NO GAS MAKEUP
CABIN VOLUME: 30,000 CU FT

Figure 6-3 Pressure Drop Following Structural Leak - 4 and 6 Inch Holes (cd = Discharge coefficient)

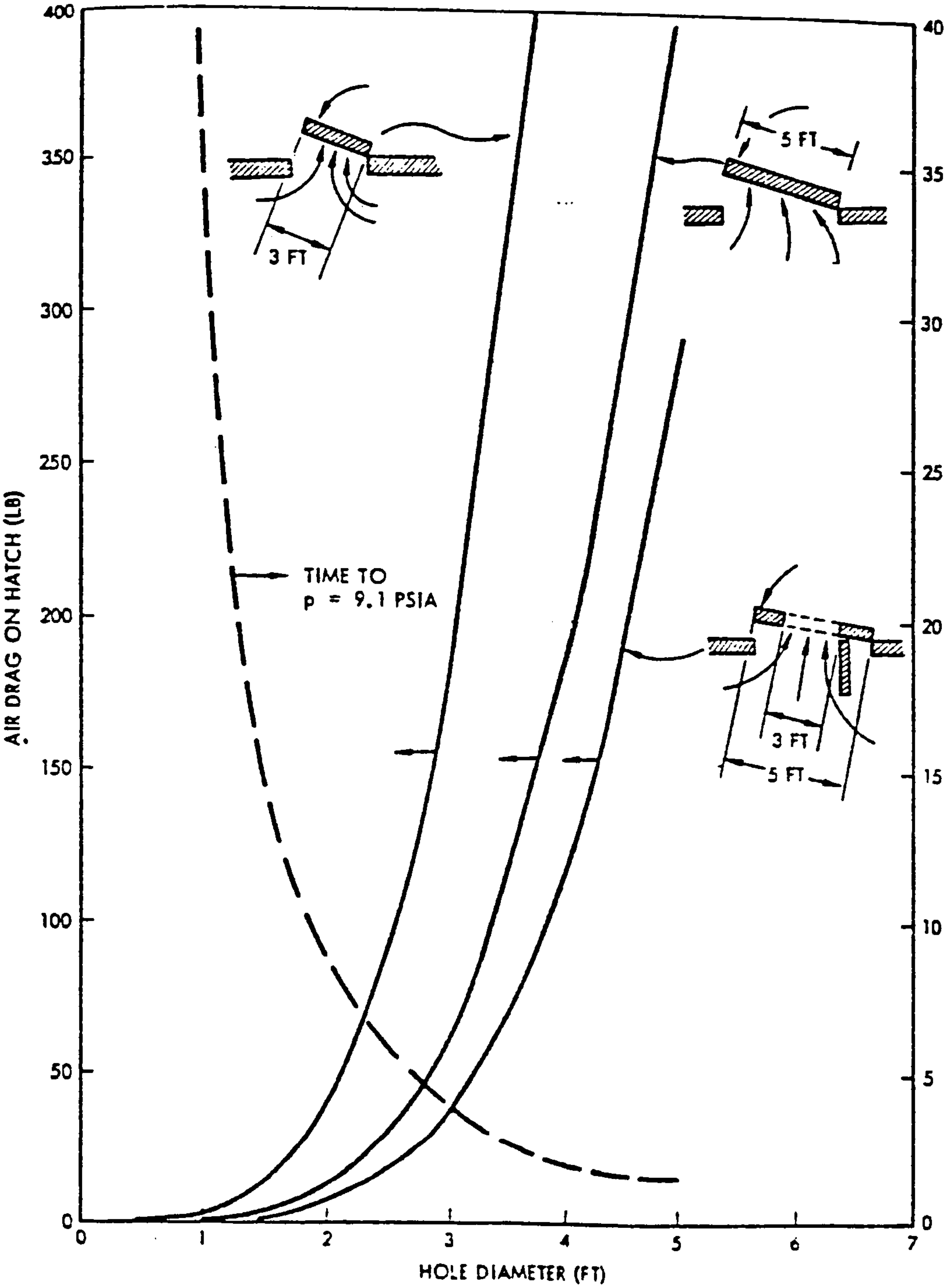


Figure 6-4 Air Drag on Hatch and Time Available Following Structural Leak

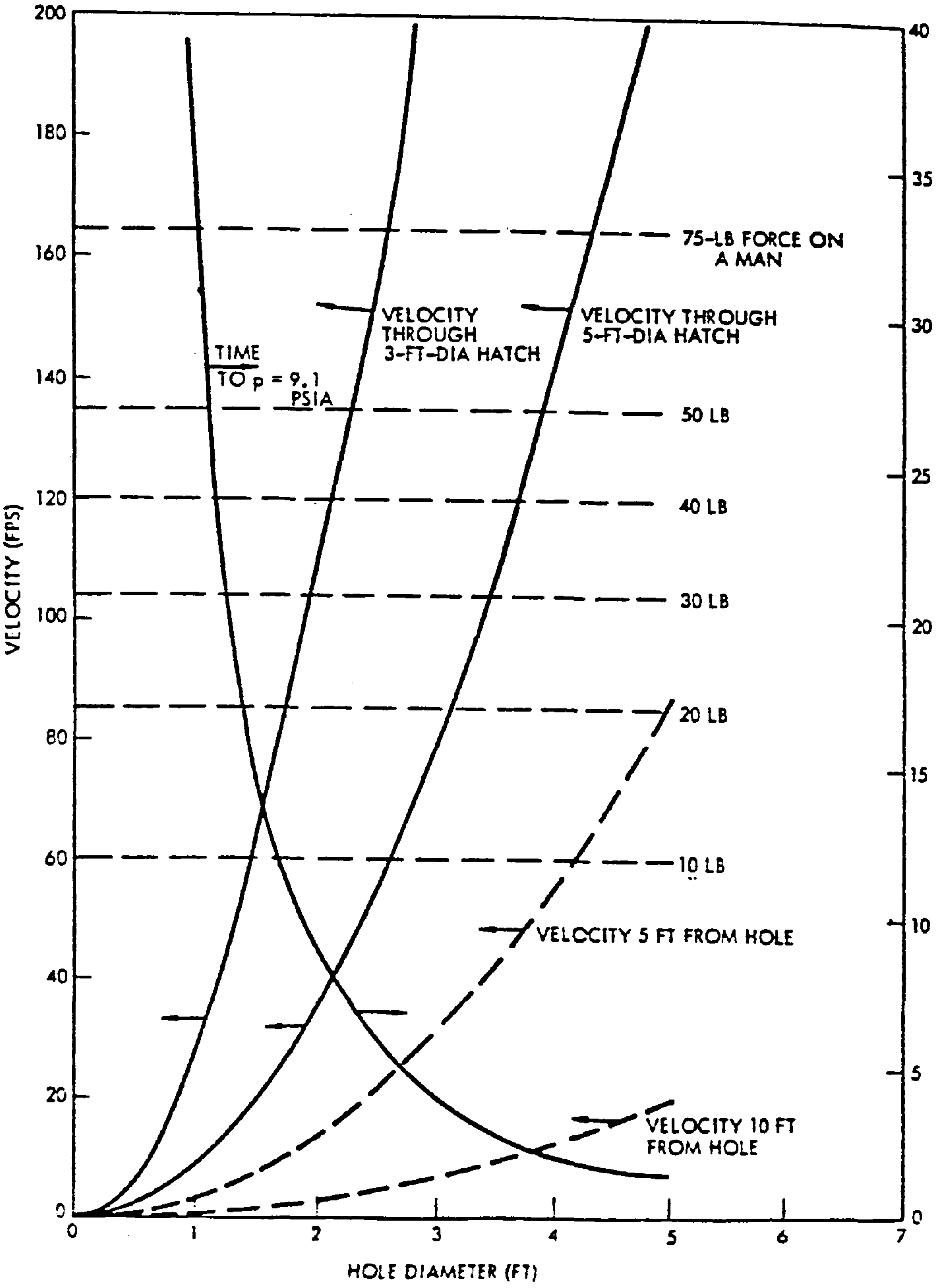


Figure 6-5 Air Velocities, Loads and Time Available Following Structural Leak

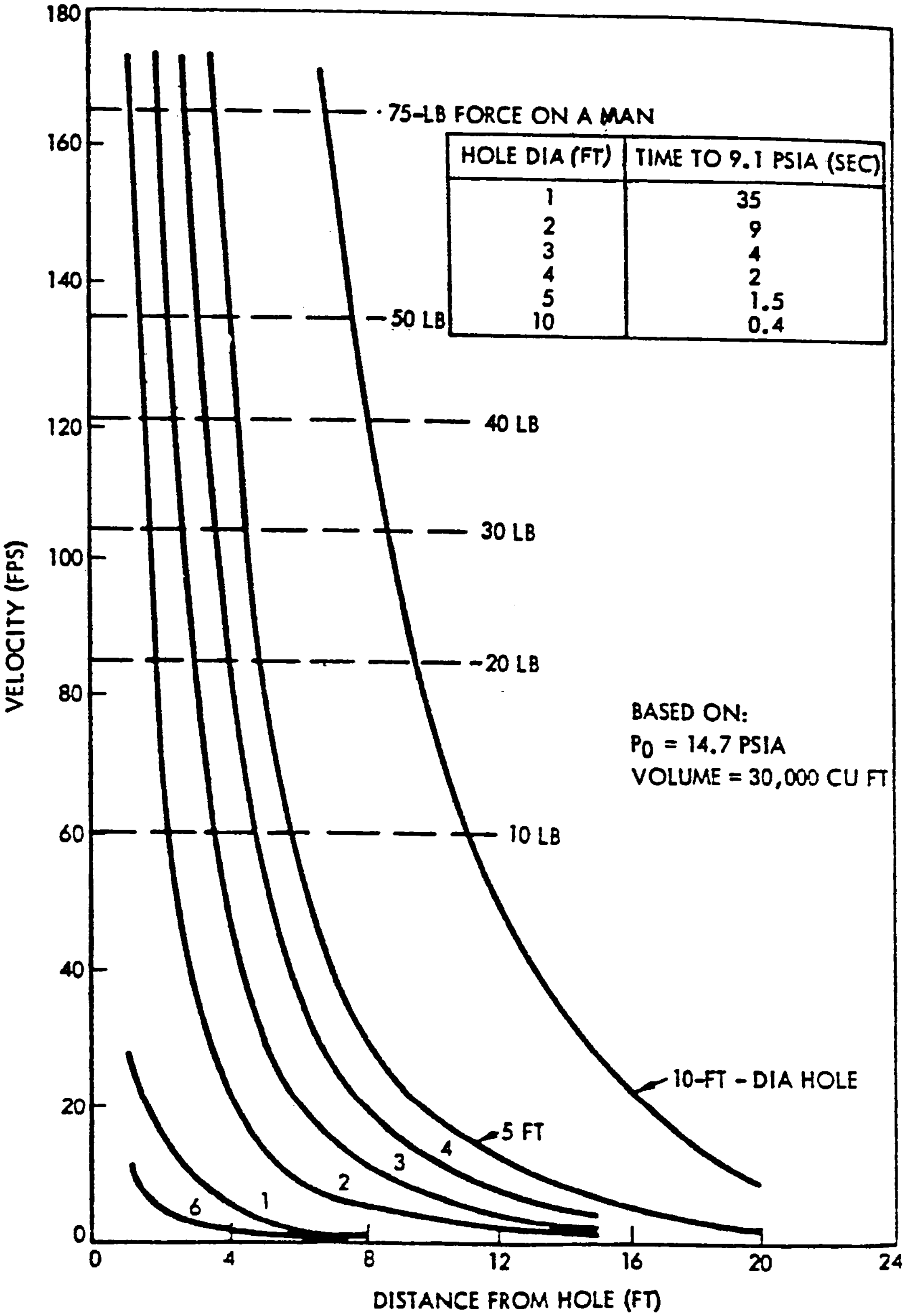


Figure 6-6 Air Velocities and Loads Following Structural Leak

Conclusions from the analyses are:

1. For the maximum assumed meteroid penetration of 2-inches diameter, 22 minutes is available for corrective action.
2. For holes of less than 1-foot diameter, there is adequate time available for corrective action; the wind velocities and loads are not a problem.
3. For holes above 2-foot diameter, there is practically no reaction time available, and wind velocities and loads are a problem (particularly in zero g).
4. Automatic closure of intervolume hatches should be considered for time-critical leakages (e.g., time less than 20 sec) as a means for saving personnel in the "good" volume when the pressure in that volume reaches the minimum acceptable level. This will be facilitated by the large loads on the hatches in such cases.

Consideration has been given to whether the hatches between the two volumes should normally be kept open or closed. Keeping hatches open is advantageous for situations in which relatively small holes occur. This maximizes the time available for corrective action.

Windblast Effects

Emergency conditions which subject crewmen to high airflow are encountered during situations such as explosive decompression or onboard explosions. These aerodynamic forces can cause injury and degrade the crewman's ability to perform necessary operational tasks. Dynamic pressures created by explosive decompression can force an unrestrained crewman overboard through an open door, hatch or large rupture in the cabin structure. Crewman injuries from head impact with structural objects, or from body impact by flying debris or loose equipment can result. Hypoxia, lung damage, decompression sickness and low temperature problems are encountered during decompression.

The injurius effects of decompression windblast depend upon a number of variables as follows:

1. Volume of cabin
2. Area of opening
3. Geometric shape (orifice flow coefficient)
4. Absolute pressure within the cabin
5. Absolute pressure of outside ambient atmosphere
6. Temperature of cabin atmosphere
7. Outflow other than leakage
8. Inflow from pressurization source
9. Ratio of cabin to ambient pressure (ratio will establish whether flow is greater or less than sonic)
10. Ratio of initial cabin pressure to final cabin pressure
11. Distance of crewman from opening
12. Position and physical attitude of crewman relative to direction of airflow
13. Weight and body size of crewman
14. Restraint system, if any
15. Type of clothing being worn (airflow - drag characteristics)

STRATEGY OPTIONS

Options for dealing with a Loss of Pressurization and related problems are discussed herein. Most of these involve design and operational requirements to prevent a loss of pressure, overpressure or explosion. Physiological response and protection required at reduced atmospheric pressure, and Life Support System design data are shown on Tables 6-2 and 6-3. Recommended decompression and recompression rates are given where operational delta pressure changes are encountered such as airlock operations, etc.

Multiple Volumes (021)

If an accident occurs which could result in decompressurization, atmospheric contamination, or loss of some critical function, the crew must be able to survive safely in a separate pressurized area until the affected volume is restored to a habitable condition or until they are rescued. As many as 21 days may be required to reach the station and this sets the minimum time for crew survival onboard the station. These considerations led to system safety criteria which required the station to be divided into separate pressure-isolatable volumes.

The suggested design (see Figure 6-7) solution consists of arranging the habitable modules into pressure-isolatable volumes of approximately equal capabilities. Each of the two volumes includes half of the core module, two station modules with crew support provisions, and provisions for attaching cargo modules and research application modules (RAMs). Each of the two volumes contains complete environmental control, thermal control and information subsystems, a control center, docking/berthing capability, and emergency supplies. Each volume can support the crew of six indenfinitely (subject to adequate consumables) independently of the other volume. Primary electrical power is supplied to both volumes from a common power module and is available to both volumes even if one has been evacuated.

One of the more credible reasons for evacuating one volume is that the atmosphere has become contaminated, possibly with smoke from a fire. The air circulation systems in the two volumes are, therefore, kept separate so that contaminants from one volume will not be introduced into the other volume. It was possible to design the station so that only the affected module could be isolated following an accident. However, this would require, for example, that each environmental control subsystem be able to supply other modules in the volume, and that many of the air ducts would have to be capable of operating in a vacuum (in the event of depressurization of that area). The valving system would also be considerably more complex. Because of these reasons, the simpler approach with each environmental control subsystem servicing its own volume could be adopted. This design allows for individual module isolation in many emergency situations. Loss of atmospheric and thermal control, however, would allow for only limited shirtsleeve operations in that volume.

Table 6-2

PHYSIOLOGICAL RESPONSE AND PROTECTION REQUIRED AT REDUCED ATMOSPHERIC PRESSURE

Altitude (feet)	Inspired $p^{O}2$ (mmHg)	Physiological Response	Protection Implications
Sea Level	160	Normal functioning	
5,000	130	Deficient night vision	Maximum altitude for normal night vision without supplemental oxygen
8,000	120	Undetectable hypoxia	Supplemental oxygen advised for routine flights
10,000	100	Subjective symptoms of hypoxia in some people	Maximum altitude without routine use of oxygen
18,000	75	Appreciable hypoxic handicap	Maximum for emergency without use of supplemental oxygen
20,000	70	Hypoxia represents an increasingly severe handicap above 20,000 feet	Cabin pressurization recommended
23,000	65		
25,000	60	Time of consciousness without oxygen, < 120 sec	
28,000	50	Time of consciousness without oxygen, < 70 sec	Pressurization required to prevent decompression sickness
30,000	45	Time of consciousness without oxygen, < 60 sec	Begin supplementing demand oxygen with positive pressure
35,000	37	Time of consciousness without oxygen, < 50 sec	Maximum for routine use of demand oxygen system
40,000	30	Time of consciousness without oxygen, < 30 sec	
42,000	25	Time of consciousness without oxygen, < 30 sec	Maximum for routine use of pressure breathing. Special pressure protection required above this altitude
43,000	23	Time of consciousness without oxygen, < 30 sec	Maximum for short-term emergency use of demand oxygen
50,000	20	Time of consciousness without oxygen, < 30 sec	Maximum for short-term use of pressure breathing

Table 6-3

LIFE SUPPORT SYSTEM DESIGN DATA

Condition	Optimum Value	Normal Limits		Extreme Limits	
		Minimum	Maximum	Minimum	Maximum
Oxygen (p^{O}2) in inspired air	160mm Hg	110mm Hg	160mm Hg	90mm Hg	760mm Hg
Metabolic Oxygen Consumption	0.1 lb/hr	0.075 lb/hr	0.2 lb/hr	0.050 lb/hr	0.5 lb/hr
CO_2 in inspired air	0.3mm Hg	0	8mm Hg	0	23mm Hg
Nitrogen in inspired air	596mm Hg	0	596mm Hg	0	619mm Hg
Respiratory flow rates					
Tidal volume	0.75 liter	0.25 liter	1.0 liter	0.25 liter	3.75 liter
Minute volume	10 L/min	8 L/min	30 L/min	5 L/min	100 L/min
Peak flow rates	35 L/min	20 L/min	90 L/min	20 L/min	200 L/min
Breathing resistance at Peak flow rates	0	0	25mm H_2O @ 50 L/min	0	100mm H_2O @ 200 L/min
Cabin pressure	760mm Hg	565mm Hg no added O_2	760mm Hg	446mm Hg no added O_2 190mm Hg with added O_2	760mm Hg
Decompression rate	1.0 psi/min	1 psi/min	5 psi/min	5 psi/min	1.0 psi/min
Recompression rate	4.0 psi/min	1 psi/min	4 psi/min	4 psi/min	0.5 psi/sec
Ozone contamination	0.1 ppm	0.10 ppm	0.30 ppm	1.0 ppm	10.0 ppm 0.5 hr/max.
Carbon Dioxide contamination	0.005%	0.01%	0.05%	0.05%	0.10% 1 hr. max.
Inspired air temperature	75°F	-0°F	+150°F	-60°F	390°F
Relative humidity of inspired air	40-60%	20%	80%	0%	90%

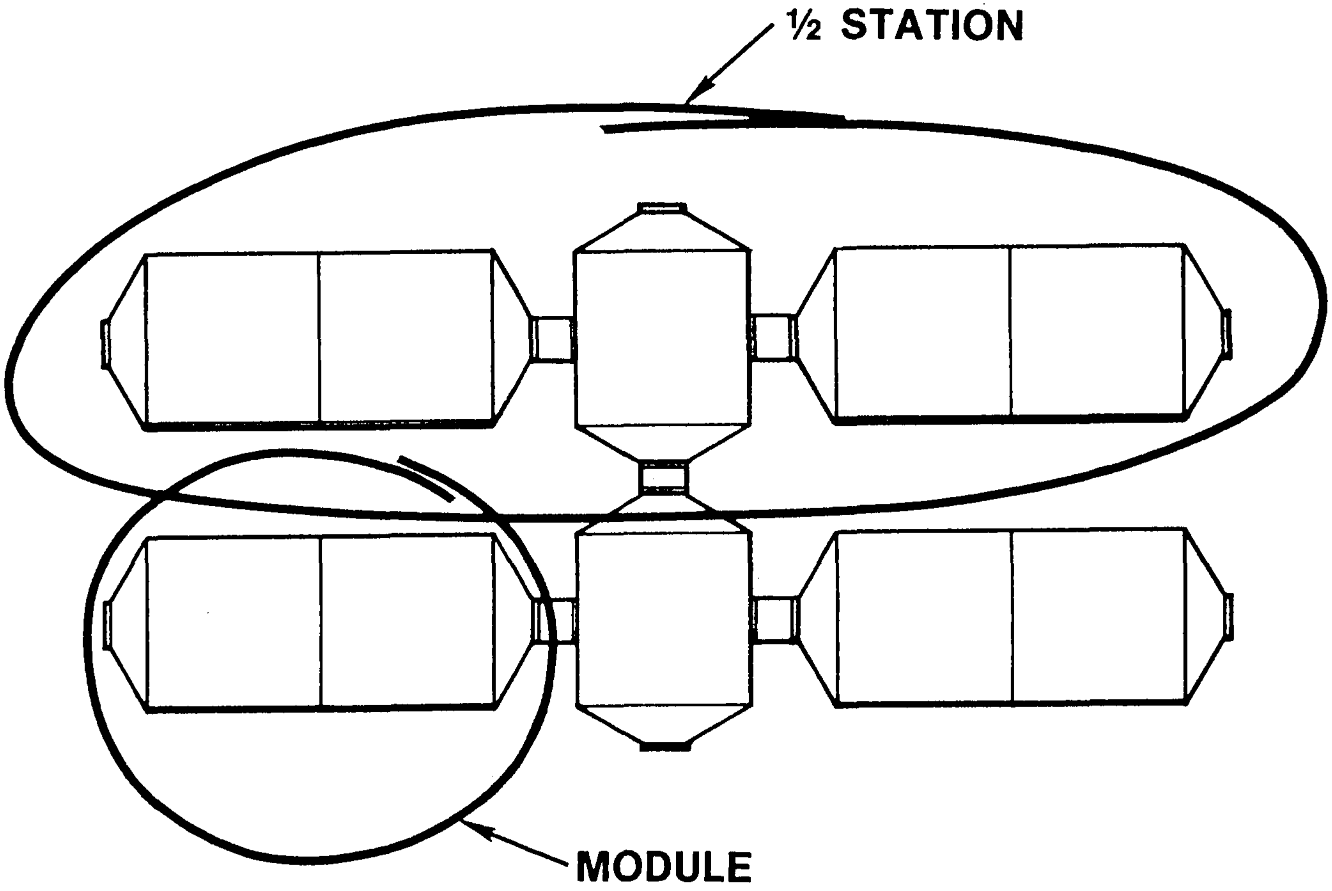


Figure 6-7 Typical Configuration

Pressure Vessel Criteria

A recognized hazard on any space station configuration is the storage of various fluids in pressurized tanks for long periods. Since it was not possible to eliminate this hazard, steps were taken to minimize its potential effects and to make provisions in case of an accident.

Three main concerns arose with stored fluids. First, leakage of certain gases such as hydrogen, methane, hydrazine could result in fire, explosion, or toxic effects; second, a large leakage rate inside a pressurized volume could cause overpressurization, leading to structural failure of the station; and third, a catastrophic rupture could cause damage to equipment, structural failure, and loss of life. A number of obvious precautions have been taken in the space station design. Every attempt has been made to locate hazardous and toxic fluid storage tanks and high-pressure tanks outside of pressurized and habitable volumes. Gases such as hydrazine have been avoided whenever possible because of their high toxicity. And, finally, for those tanks which must be placed inside the pressurized volume, every attempt was made to reduce the explosive potential of individual tanks and locate them so that an explosion of one tank would not propagate to adjacent ones.

The gases which are necessary on the station depend on the selection of atmospheric control, power, and reaction control systems. In all of the space station designs considered, large quantities of oxygen, hydrogen, and nitrogen have been required. Various means have been considered for preventing shrapnel from causing additional damage. These included use of chain link armor, blast shields, the use of blowout plugs oriented towards a safe direction, and the use of nonshattering tank material such as filament-wound fiberglass.

The explosive content of a stored gas, usually expressed in terms of TNT equivalent, depends primarily on the total energy content which can be released, and is approximately equal to the total enthalpy of the stored fluid. For a gas, this is proportional to the mass of the gas, the specific heat at constant pressure, and absolute temperature. The pressure at which a given mass of gas is stored relates to the TNT equivalent as shown in Figure 6-8. Since an explosion of a low-pressure tank could be as catastrophic as the explosion of the same mass of gas stored in a high-pressure tank, no attempt has been made to require storage tanks on board the station to be at low pressures for explosive reasons. However, damage assessment showed that an acceptable TNT equivalent for storage within the pressure volume could be approximately 0.025 pounds or 50 BTUs of energy (approximately the same as a hand grenade). While every attempt has been made to restrict on-board tanks to such a size, this became very difficult when the need for maintenance and replaceability of the tanks was considered. (021)

A potential solution consists of placing all of the high-pressure and hazardous gas storage tanks in a special module attached to the station externally. In this way, the hazardous gases are isolated away from the living and operating quarters. The outer hatch could be designed to accept the blast from any credible explosion. The atmospheric pressure in this module would normaly be kept low, but the module could be fully pressurized to allow crew access for maintenance, inspection, and resupply of individual tanks.

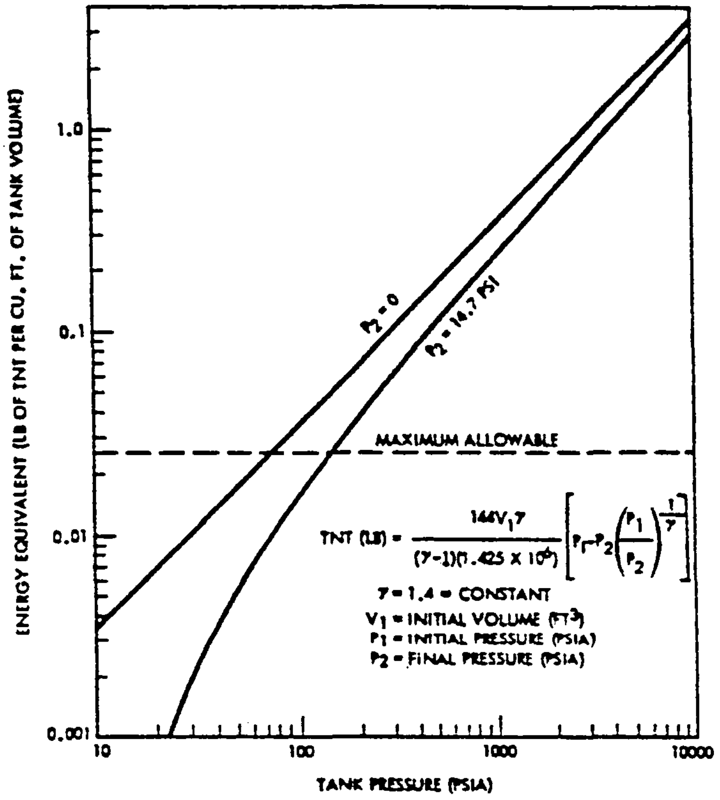


Figure 6-8 TNT Equivalent of Pressure Vessel

Flying Debris

In the event of explosive decompression, windblast forces can dislodge equipment and cause flying debris inside the cabin which can jeopardize a crewmans escape similar to that experienced in aircraft. This can be minimized by design such that air is not entrapped in enclosures, cabinets, drawers, wall surface insulation batting, and panel covers, etc. This is accomplished through the use of ventilation holes and fasteners which enable flexing or movement. Thus, air is allowed to escape, preventing a large delta pressure build-up across enclosure surfaces which enables them to stay intact.

Decompression Summary

The causitive factors, of the decompression threat, can be classified in two categories; the first is unplanned and the second is planned. The unplanned decompressions would in general be caused by a puncture from debris or materials, inadvertant crew action, or external leakage. The strategies for overcoming these problems include the capabilities to inspect and repair the vehicle inside as well as outside. Mandatory station survival electrical functions should be coldplated to assure the decompressed functional capability. Other hardware/electrical functions should be capable of being turned off.

The planned decompressions could be encountered to handle contingencies such as contamination, fire control and when necessary, maintenace. The station should be capable of handling three pressure volume changeouts. Also, cabin planned decompression discharges, as well as any gaseous or fluid discharge, should be designed to prevent any rotational or translation motions to the space station. This could be accommodated by having the exhaust terminate in a "tee" whereby the jet action would be split into two opposite/reaction, canceling forces.

For escape/rescue operation conditions where there is "time to react", four options are available; (1) EVA escape to an attached rescue vehicle, (2) move into a safe haven and then into an attached rescue vehicle, (3) move into an attached vehicle, and (4) use an IVA suit, then inspect, repair vehicle and egress to a safe area.

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7. RADIATION

DEFINITION

Radiation threats are associated with the exposure of the astronauts as well as equipment to ionizing radiation, ultraviolet or infrared light, lasers, and electromagnetic or radio frequency radiation. Ionizing radiation threats may be caused by leaking or inadequately shielded radioactive equipment such as RTG's, particle accelerators, liquid metal heat exchangers, etc. RF and electromagnetic radiation from RF generators can trigger ordnance devices or interfere with the operation of critical equipment. Allowable levels of each of these energies must be established, and design accommodation made to ensure that the space station astronauts and equipment are protected.

Radiation in space is a major issue to be addressed for manned space station accommodation. The subject includes many variables that effect and are affected by the space station planning objectives. At this time, these variables are discussed to the degree of their effectivity.

BACKGROUND

Radiation effects have been under study for almost a century. However, a need exists to correlate existing information with probable flight conditions as will be encountered in the space station. Basic and applied research data are source material. The subject of radiation is addressed by source:

Space Radiation - Solar

A solar flare, a bright eruption from the sun's chromosphere, may appear within minutes and fade within an hour. Flares cover a wide range of intensity and size and tend to occur between sunspots or over their penumbrae. Sunspots usually occur in pairs with a sunspot cycle average length of 11.1 years but varying from 7 to 17 years. Flares eject high energy protons which present a serious hazard to men in unshielded spacecraft. (403)

Occasional solar flares are associated with sun and solar activity. The data shown in Figure 7-1 shows the sunspot numbers during cycles 19 and 20, and plots of the proton fluences greater than 30 MeV. This is the total fluence of each individual particle event as a function of time. There is a rough correlation between the number of particles and the degree of solar activity. Generally there are anywhere from one to perhaps five particle events which might be called major events during any particular cycle. Some details of what happened during cycles 18, 19, and 20 can be found in Figure 7-2. Here are shown just the major events that occurred during these particular cycles. Notice that the largest events happened during the ascending or descending phase of the solar cycle. Major events are usually absent during solar maxima and minima. (402).

Galactic Space Radiation

Galactic space radiation is the result of explosions of supernovae. These cause a flux consisting of approximately 82%-85% protons, 12-14% alpha particles and 1-2% heavier nuclei. This flux will increase and decrease inversely as the solar activity changes since the screening effect of the interplanetary magnetic field lessens with the solar activity. The flux density of galactic space radiation particles in the energy range of 100-1000 MeV/nucleon increases 3-5 times when solar activity changes from maximum to minimum. The flux density of galactic particles, with energies of over 1000 MeV/nucleon, is not as much effected by solar activity. Over an 11-year period, the change in flux density was about 20%. Density of the total geomagnetic solar radiation flux is decreased by 10 times at average orbit inclination angles due to the geomagnetic field.

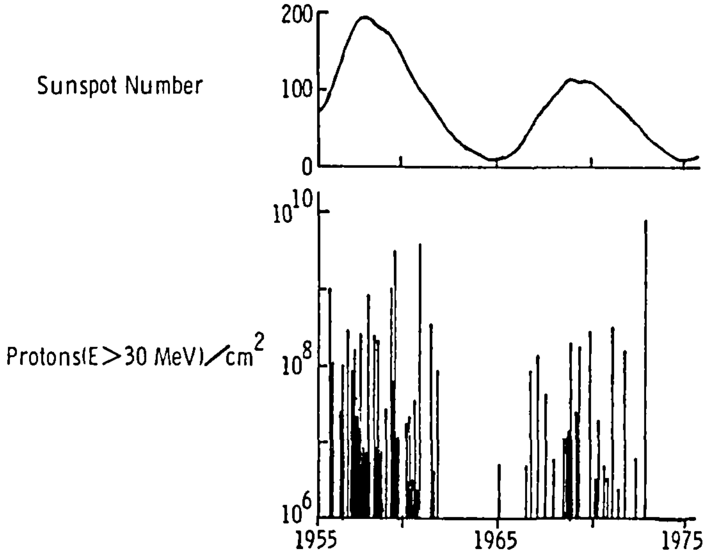


Figure 7-1 Solar Activity and Flare Proton Fluence

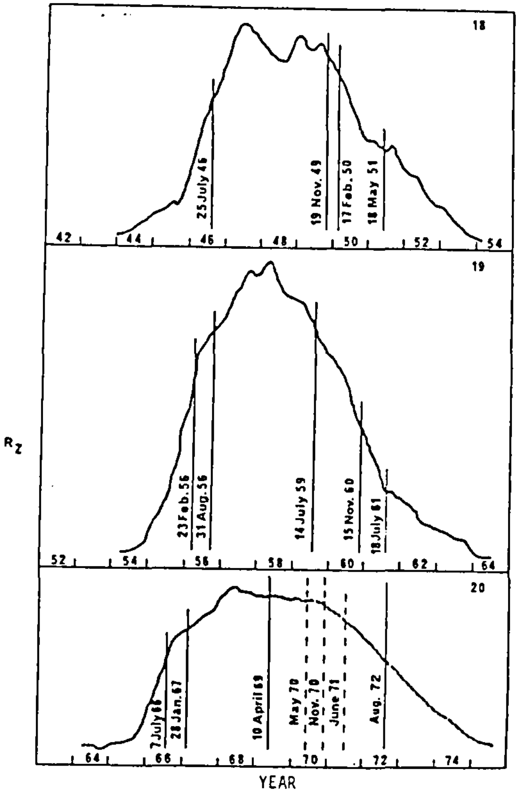


Figure 7-2 Major Solar Particle Events of the Last Three Solar Cycles

The Geomagnetic Field

The earth is enclosed by a geomagnetic field, the magnetosphere. This traps magnetic particles and is surrounded by the solar winds. At a specific distance from the earth, the geomagnetic field energy density equals the energy of the solar wind. At this point, the magnetic lines of force break down. It is the boundary between domination by the magnetic field and the solar wind.

The inner boundary of the transition region, the magnetopause, occurs at about ten earth radii on the sunlit side of the earth and forms an elongated teardrop with a long tail pointed away from the sun. The outer boundary is approximately 14 earth radii. See Figure 7-3.

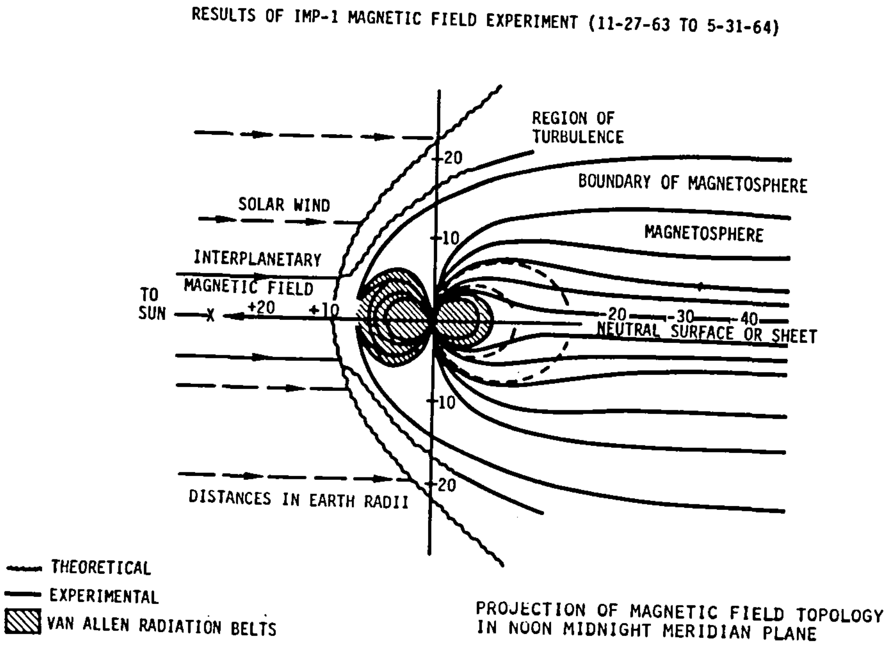
A method of depicting the distribution of magnetically trapped particles about the earth is by using the B-L coordinate system. The magnetic field strength at some specified point in space is the B coordinate and L is the magnetic shell parameter identifying the shell upon which the guiding center of the trapped particle is adiabatically confined as it drifts around the earth.

The penetration of charged particles to the vicinity of the earth is altered by the magnetic field.

In the vicinity of the earth, galactic space radiation (GSR), even in polar orbits, does not exceed 7m rem, in contrast to estimates of 50-100 rem per year GSR dose equivalent in interstellar space depending on solar activity.

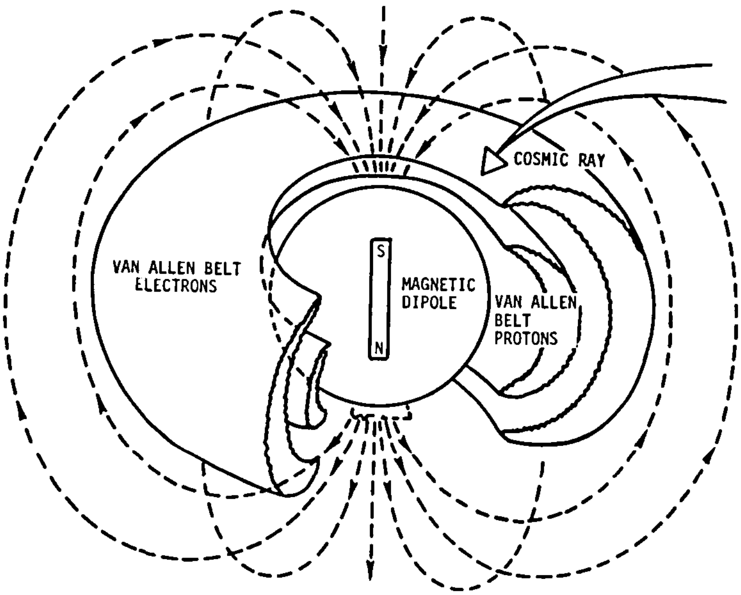
The direction of travel of a charged particle (ion) is changed by the magnetic field. The cosmic ray in the upper right of Figure 7-4 thus is deflected downward. Such deflections of cosmic rays produce the "latitude effect": cosmic rays are more intense at high latitudes (north and south) than near the Equator.

Deflections of slower moving ions - the protons and electrons in the solar wind - are larger, and the Earth's magnetic field has "captured" many of them in the Van Allen belt (named after physicist James Van Allen of the University of Iowa, who discovered it from measurements on the Explorer 1 satellite in 1958). The cutaway view of Figure 7-4 shows the doughnut-shapped regions where protons and electrons are oscillating north and south along the magnetic lines of force (dashed lines). These charged particles spiral around the lines of force at speeds of several kilometers per second and are reflected back where the lines of force get close together near the magnetic poles. There are no sharp boundaries to the regions where protons and electrons are oscillating, but the whole Van Allen belt is between 320 and 32,400 kilometers altitude and extends all around the Earth. The peak intensity of protons occurs at about 3000 kilometers altitude, where the protons have energies of more than 10 megaelectronvolts and a flux of more than 10,000/cm^2 sec. Because of the intensity of this radiation in the Van Allen belt, this region of space is by far the most hazardous to living organisms (and to sensitive instruments) in spacecraft. The NASA Pioneer 10 mission found the similar radiation belt of Jupiter to be several thousand times more intense. (159)



RECENT SATELLITE VERSION OF THE MAGNETOSPHERE
BASED ON RESULTS OF IMP-1 MAGNETIC FIELD. . .
(NOVEMBER 27, 1963 TO MAY 31, 1964) (364)

Figure 7-3



SCHEMATIC CONFIGURATION OF THE VAN ALLEN BELT (159)

Figure 7-4

The Earth's magnetic field is not as simple as the diagram in Figure 7-4 would suggest. Its outer regions are affected by the solar wind, and the "magnetosphere" - the region of the upper atmosphere that is dominated by the Earth's magnetic field - has a "shock front" facing into the wind (more or less toward the Sun) and a "tail" stretching down-sun. More important for Earth satellites such as Apollo-Soyuz, the magnetic dipole moment of the Earth's magnetic field is not at the Earth's center, causing the Van Allen belt to bulge downward towards the Earth's surface over the Atlantic Ocean just east of Brazil in a region called the South Atlantic Anomaly. This irregularity in the magnetic field produces a region of very intense radiation in the lower part of the Van Allen belt (about 1000 times more intense than in nearby space). NASA scientists have learned that some instruments on spacecraft give erroneous readings while they are in the South Atlantic Anomaly. NASA's Skylab, at a 444-kilometer altitude, went through it regularly. Apollo-Soyuz was below it at an altitude of 222 kilometers, where the radiation dose was almost 10 times less than the Skylab altitude. (159)

RADIATION SHIELDING

Shielding from radiation is a major consideration in space station design. As space occupancy time periods increase, the need for shielding becomes more pertinent. The incidence of solar flares is a major consideration. Also, EVA, which places an astronaut in a vulnerable position, requires serious consideration. Thus is well summarized by Dr. Delbert Philpott, NASA Research Scientist, Biomedical Research Div., who has written the following: (353)

Review of the literature and conversation with various people in the field of radiation points to the advisability of incuding radiation protection within the environmental "storm" shelter, even though projected radiation levels at a 28° inclination orbit should be acceptable for a 3 month tour. However, since a "storm" shelter is needed for other safety reasons (fire, noxious gases, etc.), building the walls out of radiation absorbing material would be advisable for the following reasons:

1. A large solar flare, which cannot be ruled out, could exceed exposure limits at a 28° inclination and 200 to 300 nautical mile altitude.

2. The decreased radiation affordable by use of a shelter could help offset any increased dose absorption which would be expected during the longer EVA periods.

3. Future higher inclination and geosynchronous orbits will necessitate radiation protection. Experience can be gained with shielding materials under actual flight conditions which would be especially useful for penetrating cosmic ray (HZE) particles. It is expected that the shielding would be kept to a minimum to reduce the weight penalty.

4. The shelter area would be very useful for a control area during radiation experiments and for the exclusion of radiation from other experiments as required.

5. While the present radiation limits are the same for male and female astronauts (35rem to bone/qtr; 75/yr), the earth recommended levels are lower (3rem/qtr, 5r/yr; fertile females 0.5rem/9 months). The lower level for females is based on their susceptibility to mutagenesis in the offspring. It appears that there will be more and younger females traveling in space. Also the N C R P is planning to reassess astronaut standards. Therefore, it is likely that the limits are lowered and the necessity for a radiation shelter would be increased.

6. Information useful for future polar and geosynchronous orbits would be obtained.

In support of a safe radiation haven, additional ground based studies are needed including:

1. Experiments to establish the efficiency of shielding and susceptibility of humans during space flight.

2. Experiments to evaluate the most efficient shielding material per unit mass. Living tissue should be used in such studies to confirm/correct the detected and estimated doses.

3. Experiments to determine the biological response to cosmic radiation especially the low dose long term effects.

In summary, As Dr. Tobias of U.C. Berkeley has pointed out, the time is coming when the astronaut population will need to be considered as part of the general population and not a small and separate group with separate standards of radiation exposure levels. Considering the need for a "storm" shelter, inclusion of radiation protection seems prudent and advisable. (353)

J. W. Haffner, RI, (290) has analyzed shielding based on a space station effective wall shielding. The results of this analysis are summarized in the charts which also reflect the effects of altitude.

The Van Allen belt radiation effects on the orbit altitude selection depend upon the shielding effectiveness of the Space Station and the amount of EVA required, and the shielding effectiveness of the EVA suit.

The tissue dose rates as a function of altitude and aluminum shield thickness are shown in Figures 7-5 and 7-6. These dose rates are based on the AP8 and the AE6HI Van Allen belt models (at 28.5° the solar flare particles are excluded by the geomagnetic field). At lower altitudes (300 NMi), the bulk of the daily dose is acquired over the South Atlantic anomaly; at higher altitudes, the dose rate is less dependent upon the latitude and longitude. In calculating the rem (instead of the rad) dose rates, use was made of the relationship

$$\text{rem} = \text{rad} \times \text{RBE}$$

where RBE = relative biological effectiveness (also sometimes called the quality factor). The RBE is a function of the LET (linear energy transfer) or

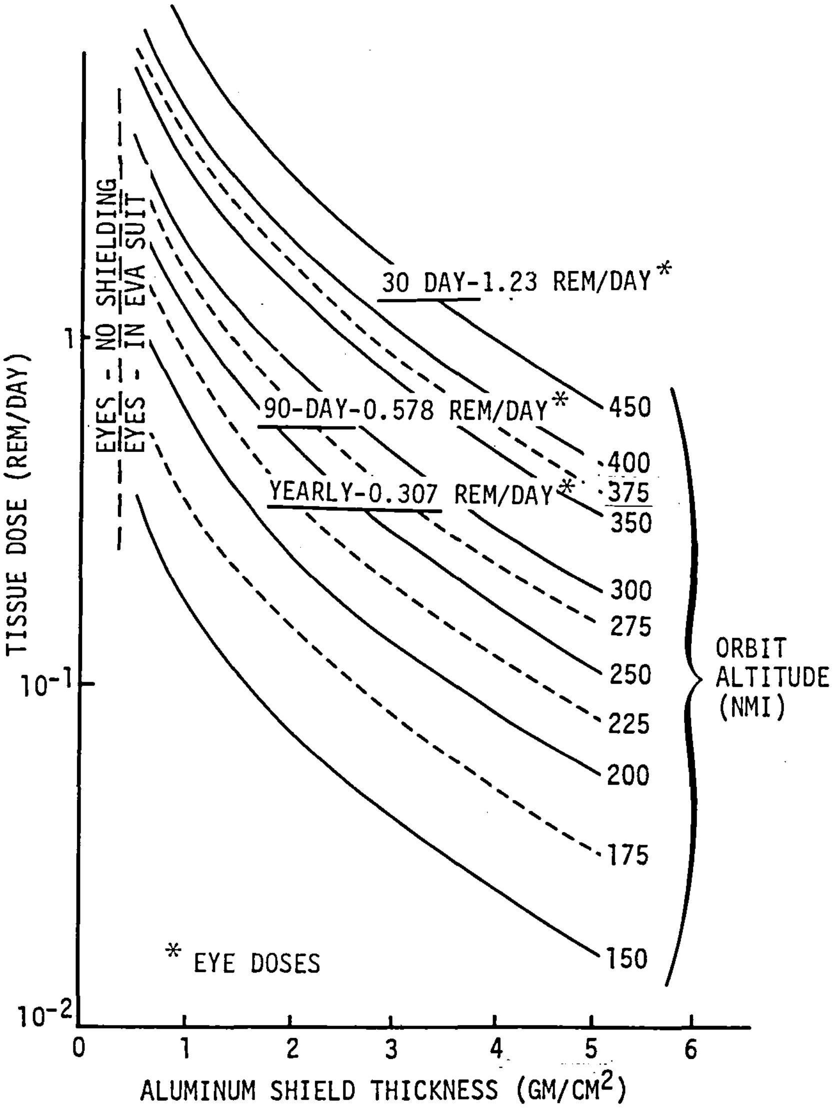


Figure 7-5 Tissue Dose vs. Shielding for Various Circular Earth Orbit Altitudes

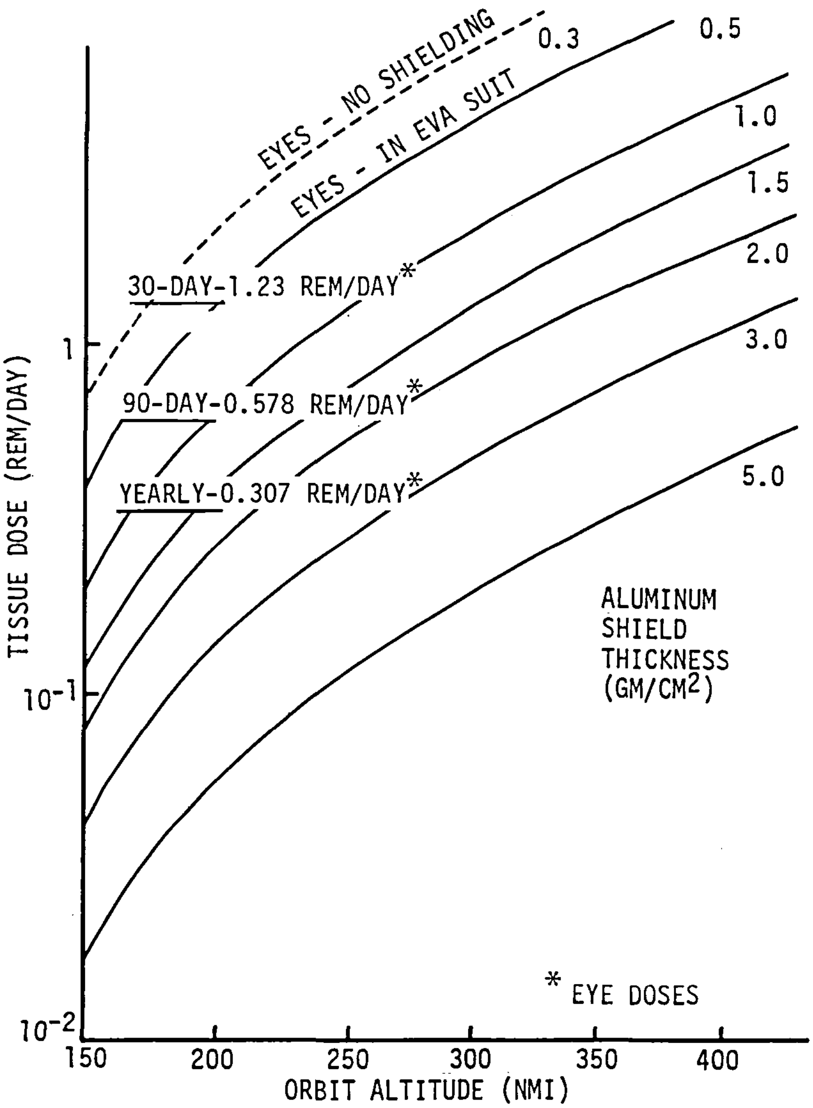


Figure 7-6 Tissue Dose vs. Circular Orbit Altitude for Various Sheild Thicknesses

dE/dx of the ionizing nuclear radiation. For this study, the RBE-LET relationship of Rossi was used to obtain the RBE for protons behind various thickness of shielding (the RBE for electrons of all energies is unity). The RBE as a function of shield thickness for the Van Allen belts in the 150-450 NMi altitude is listed in Table 7-1.

Table 7-1

RELATIVE BIOLOGICAL EFFECTIVENESS AS A FUNCTION OF ALUMINUM SHIELD THICKNESS IN THE LOWER VAN ALLEN BELTS

Shield Thickness (gm/cm^2)	Proton Cutoff Energy (Mev)	RBE for Penetrating Proton
0.5	18.5	1.8
1.0	28.0	1.55
1.5	34.5	1.45
2.0	40.5	1.35
2.5	46.5	1.3
3.0	51.0	1.25
4.0	60.0	1.2
5.0	67.6	1.15

The four critical organs of the human body, are the skin, the blood forming organs (bone marrow), eyes, and reproductive organs. The effective depth (within the body) and the recommended dose limits for each critical organ are listed in Table 7-2. Table 7-3 incorporates Space Station RFP dose rate. Included in Figures 7-5 and 7-6 are the recommended eye dose rates which correspond to the 30-day, quarterly, and yearly dose limits of Table 7-2.

The shielding required to preclude exceeding the 30-day, quarterly, and yearly eye dose limits of Table 7-2 are shown as a function of altitude for a 28.5° inclination in Figure 7.7. The data in the figure, which excludes allowances for radiation exposure occurring during EVA, indicates that for a 275 NMi orbit, approximately 1, 2, and 3 gm/cm^2 of shielding are required for the 30-day, quarterly, and yearly dose rate constraints respectively. An allowance of 0.3 gm/cm^2 was allowed for self-shielding of the eye.

Although no calculations of the effect of EVA on radiation dose are presented herein, such calculations must be made to determine the degree of radiation protection required both in the station and during the EVA, and possible limits to time in EVA must be identified.

TABLE 7-2 SPACE SCIENCE BOARD RADIOLOGICAL ADVISORY PANEL SUGGESTED AVERAGE RADIATION DOSE RATE (154)

Constraint	Bone Marrow 5 cm depth	Skin .1 mm	Lens .3 mm	Testes 3 cm
Avgd. over yr.	0.2 rem/day	0.6 rem/day	0.3 rem/day	0.1 rem/day
30 day	25 rem	75 rem	37 rem	13 rem
Quarterly[a]	35 rem	105 rem	52 rem	18 rem
Yearly	75 rem	225 rem	112 rem	38 rem
Career	400 rem	1200 rem	600 rem	200 rem

a - Note: May be allowed for 2 consecutive quarters, followed by 6 months of restriction from further exposure, to maintain yearly limit.

TABLE 7-3 IONIZING RADIATION EXPOSURE LIMITS FROM SPACE STATION RFP (388)

Constraints in REM	Bone (5 cm)	Skin (0.1 mm)	Eye (3 mm)
1 Yr. Avg. Daily Rate	0.2	0.5	0.3
30 Day Max.	25.0	75.0	37.0
Quarterly Max.	30.0	80.0	40.0
Yearly Limit	60.0	170.0	85.0
Career Limit	200.0	600.0	300.0

REM - Radiation absorbed dose in RAD's times a quality factor(q) to account for the different relative biological effectiveness (RBE) of different radiations. For planning purposes, q = 1.2

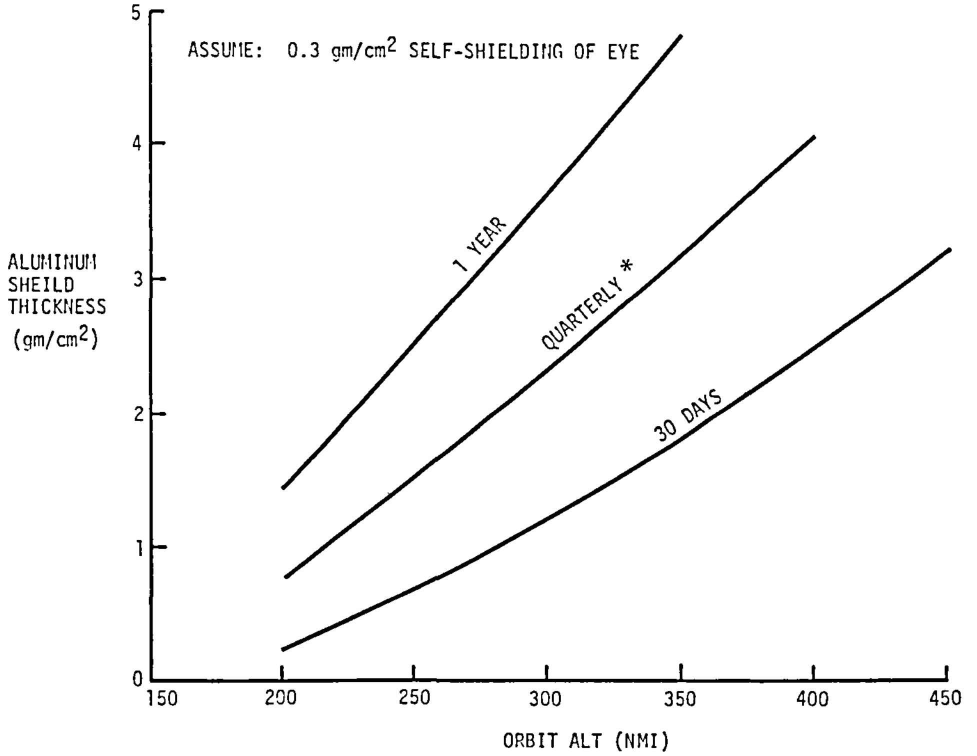
It should also be mentioned that no allowance has been made for the radiation dose the personnel might receive on their trips to and from the Space Station via the Space Shuttle. Since the duration of these trips is expected to be short (1 day) and the radiation protection provided by the Shuttle (1.5 gm/cm^2) is probably comparable to that of the Space Station, the effect of neglecting the dose received during transit will be small. Once a timeline has been established for the transits, the doses received during this operation can be explicitly included.

SHIELDING APPROACHES

Current knowledge of radiation sources, radiation effects, shielding and other protective measures should be applied to the Space Station program in order to assure optimum personnel safety. Pertinent points will be addressed, representing suggested design and planning factors. As discussed previously, vehicle wall and framing designs should be determined with consideration of the shielding potential. This could lead to new concepts as well as refinement of these existing. The use of mass, i.e., g/cm^2 aluminum has been common and is well accepted.

Aluminum Shielding

Wilson and Cucinotta (389) of NASA developed a series of curves based on computer compilation of available data. This has been condensed into those of Figure 7-8. It will be noted that the lowest altitude (200 km) experiences the least radiation. At the other extreme, 600 km, the 0° orbit experiences a minimal of radiation, the 30° orbit the worst, and the 60° orbit slightly less than the 30°. At the 400 km altitude, the 0° orbit experiences the least radiation. In general, the lower the altitude, the less the radiation. However, orbit is a major modifying factor.



*MAY BE ALLOWED FOR 2 CONSECUTIVE QUARTERS FOLLOWED BY 6 MONTH RESTRICTION FROM EXPOSURE TO MAINTAIN YEARLY LIMIT

Figure 7-7 Shielding Required As A Function of Altitude, No EVA (28.5 degree orbit, based on dose limit for eye lens)

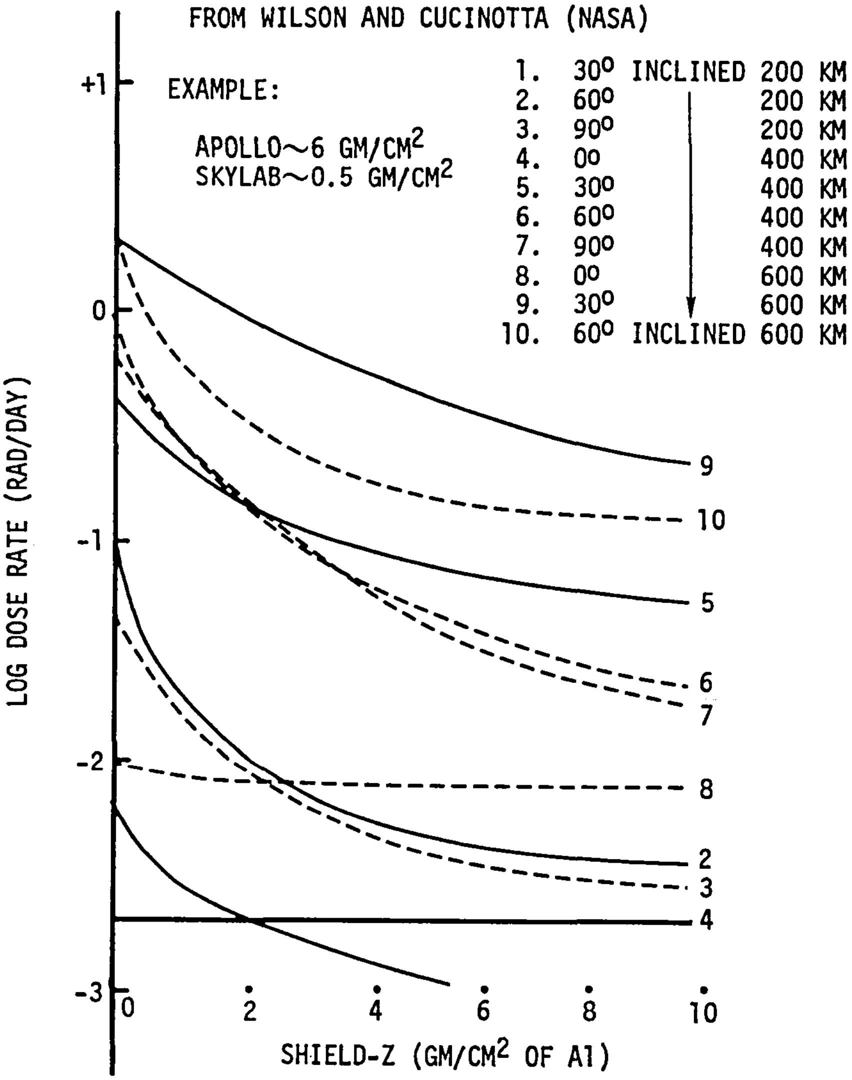

FROM WILSON AND CUCINOTTA (NASA)
EXAMPLE:
APOLLO~6 GM/CM2
SKYLAB~0.5 GM/CM2
1. 30° INCLINED 200 KM
2. 60° 200 KM
3. 90° 200 KM
4. 0° 400 KM
5. 30° 400 KM
6. 60° 400 KM
7. 90° 400 KM
8. 0° 600 KM
9. 30° 600 KM
10. 60° INCLINED 600 KM
LOG DOSE RATE (RAD/DAY)
+1
0
-1
-2
-3
SHIELD-Z (GM/CM2 OF Al)
0
2
4
6
8
10
9
10
5
6
7
8
2
3
4

Figure 7-8

The shielding frequently used is 6 gm/cm^2 al. The curves show this as having a major shielding effect.

These curves are excellent for comparisons and trends. Additional information would be desirable for quantitative evaluation of shielding under the myriad of space radiation conditions. Much research in that area will develop a data bank necessary for the construction of optimal space station protective and structural walls, frames and flight structures.

Water Shielding

During a recent radiation conference at JSC on this subject (November 16-18, 1983), J. Loftra (400) suggested the use of 6 inches of water in the walls for protection. He thinks magnetic shielding would interfere with communications and not help to shield against HZEs. He believes there will be 3 stations in orbit by 1990. There are plans for a Polar Orbit flight with 8 people and a 28° orbit flight with 12-28 people, and these flights would be 90 days/missions. A 10-year lifetime for use of the crews is planned. GEO would have 30-day duty with 4-5 people and would be mainly military. He thinks some restrictions may need to apply to females for EVAs. Average mission time would be 90-days and 6-hours for EVA men. Age range now is 26 to 54 years. Shuttle has 14 psi (21% oxygen) but 10 psi would be better (30% oxygen). This may reduce the effect of radiation on the body. These factors should be taken into consideration.

The positioning of space station equipment surrounding personnel areas is a practical and economical consideration. This should be a basic approach, and with supplemental steps, such as the water shield concept, will be evaluated.

Atmosphere Shielding

During the recent JSC conference, J. Conklin noted that some drugs help by reversing capillary permeability. Vitamin E and selenium help survival in mice. Monoclonal antibodies can be used to kill off gram negative bacteria that kill people after radiation. Benedryl has been found to affect histamine producton in the blood and may play a role in radiaton protection.

These factors should be evaluated with consideration of variables and practicality for application.

Extra Vehicular Shielding

The space station operation will require considerable EVA for experiments and maintenance. Shielding of personnel will be critical. Current shielding methods may not be satisfactory for the long term occupant. Space suit shielding is limited by the requirement for mobility and comfort. The space suit occupant cannot be impeded by unwieldy shielding.

Space shields must be considered. These will follow various concepts currently under development and will assure adequate shielding for normal radiation. Solar flare occurrence will require immediate retreat to sheltered areas, as shielding from these will necessarily be substantial.

Section 6, Volume I addresses EVA hardsuit's capabilities to provide radiation protection.

Shield From Space Station Sources

The space station will actually develop radiation by reactors. This radiation source will be predictable and controllable. Current state-of-the-art methods and materials will be used for this purpose. The handling of materials will follow proven procedures currently in use, with consideration for the space environment.

RADIATION EFFECTS

The effects of radiation are of extreme importance. Space station personnel will undergo exposure to all sources of radiation for extended periods. Although knowledge has been gained during space flights, much remains to be learned. The following discusses various aspects of the radiation hazard and effects as result of research and tests in actual flight.

Buecker and Facius, of the DFVLR Institute of Flight Medicine (357) have provided the following analysis:

The following topics are considered pertinent for a realistic assessment of the risk to man when exposed to ionizing radiation under space flight conditions: 1) prediction and measurement of the spectra of the physical traits of cosmic radiation as a function of orbital parameters and the mass shielding of the spacecraft; 2) synergistic or antagonistic modification of radiation effects by dynamic flight conditions and by the space environment; 3) production of biological damage becoming manifest only long after exposure, especially to the heavy ions; and 4) demonstration of possibly specific radiobiological mechanisms for the densely ionizing heavy-ion component of the cosmic radiation. Some recent work referrring to these topics will be presented and discussed with emphasis on the high LET component of the cosmic radiation.

Prediction of Relevant Physical Parameters

Before turning to the problem of ascertaining the spectra of some physical parameters, one must decide which of them are more relevant with respect to biological effects. Allowing for the accuracy of biological data, the measurement of energy spectra may be considered sufficient to predict the doses and thereby the biological risk with acceptable reliability. Unfortunately, the substantial contribution of solar flares to this ionizing component is still unpredictable. Where our radiobiological knowledge might be judged as adequate, at least for the practical problem of radiation protection, the unknown physical aspects of solar flares prevent any deterministic a priori risk estimate for longer term space missions. Instead, we are left with the necessity of estimating probabilities for lower and upper exposure limits.

By contrast, an almost opposite situation prevails with respect to the heavy ions of cosmic radiation. The mechanisms of the biological interactions of these ions are not yet understood. We only know that specific reaction channels must exist, and we have some speculative arguments considering acoustic shock waves as the physical part of this mechanism. With this restriction in mind, we want to mention the report of Kovalev and Markelov (355) on measurements of LET spectra in the Cosmos 782 and the Prognoz-4 missions, covering the near-earth region and the region outside the earth's magnetosphere respectively. Until improved understanding of the radiobiological mechanisms arises, the quantitative establishment of all possible physical aspects of this radiation field remains an important task. The authors did not present their originally measured LET spectra. Instead, they converted the LET spectra to a density distribution of absorbed dose over LET in tissue, in order to estimate an average radiobiological quality factor representative of cosmic particle radiation. The quality factor Q (LET), by which the physical dose is converted from Gray (1 Gy = 100 rad) into rems, the quantity relevant for radiation protection, depends on the LET of a given radiation. Q is unity for loosely ionizing radiation such as x-rays. By convoluting their derived distribution of dose over LET with an empirical function Q (LET), they calculated an average quality factor of 1.5 for the near-earth region and 5.5 for the region outside the magnetosphere. Presumably, they thereby accepted the commonly made assumption that Q reaches a saturation value of about 10 above an LET value of 1 to 2 GeV g^{-1} cm^2. Their result is discordant with quality factors estimated for the cosmic heavy ions from biological space flight experiments, which range from above 100 to above 1000 (356, 357, 358, 359, 360) and also from biological ground experiments with heavy ions typical for the cosmic radiation. (361, 362) The crucial difficulty apparently rests with the use of absorbed dose as the quantity of reference.

The modification of the primary fluences by fragmentation of the galactic heavy ions when penetrating mass shieldings has been treated previously by Heinrich (357). Recently, he extended these fragmentation calculations to the determination of the depth-dose relation for various heavy ions and energies when penetrating water as an approximation to biological tissue (363). Comparison with experimental results demonstrates that the prediction of the energy spectra of primary and secondary particles is possible with satisfactory accuracy, given the primary fluences and a specific mass configuration. The applicability of dose - which these spectra were converted to - as a predictor for the biological effects of cosmic heavy ions remains questionable.

Another important aspect for the prediction of particle fluences for the galactic heavy ions, especially for near-earth orbits, was treated by Heinrich and Spill. They calculated the modification of the energy spectrum of primary galactic heavy ions by the geomagnetic shielding as a function of the orbital parameters of a space mission. Although these calculations were performed only for vertical incidence, i.e., parallel to the earth-centered radius vector to the orbit, they are already quite involved. They demonstrate quantitatively the influence of the inclination of an orbit on the resulting energy spectrum and the thereby implied radiation exposure. Notwithstanding the computational difficulties of such a calculation, they should be part of the a priori risk assessment for longer term space missions, along with the above mentioned propagation of heavy ions through any shielding matter. Concluding this section, we again emphasize that a priori risk assessment remains conjectural due to either the unpredictable solar flare contribution, to the low LET radiation or to the unknown reaction mechanisms of heavy ions.

Biological Impact

Related information is by J. E. Pickering, (154), USAF School of Aerospace Medicine and provides the recommendations by the Space Sciences Board Radiological Panel as follows:

Recommendations of multiple review groups have reflected upon different organ/system sensitivities with both acute and latent results as concerns. For example, the Space Sciences Board Radiobiological Advisory Panel has on several occasions suggested average daily, 30-day, quarterly, yearly, and career doses to the bone marrow, skin, lens of the eye, and the testes. Table 7-2 relates these data.

The graph, Figure 7-9 is intended to place in perspective (1) the environmental and (2) occupational exposures, (3) a one-time "peace-time" emergency exposure, and (4) the recommended wartime "mission completion" dose for nuclear crews, while at the same time focus attention on the depth dose area (shaded area) representing current recommended career dose limits for space operations, as reflected in the above advisory panel recommendations.

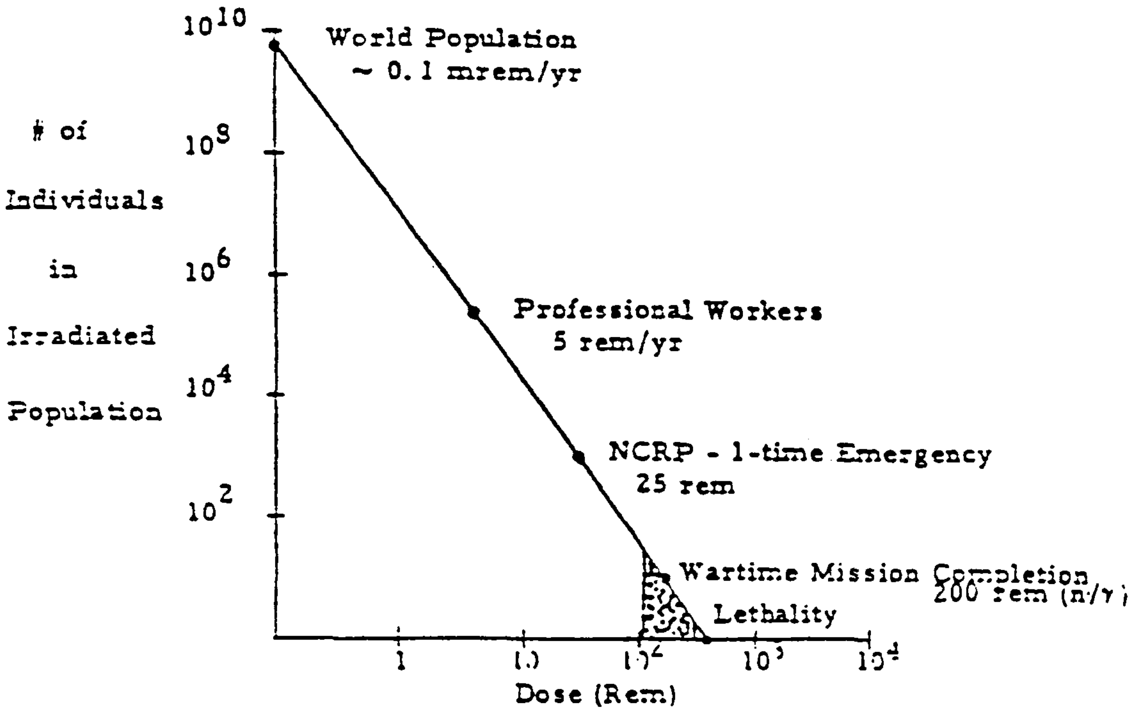


Figure 7-9 Population vs. Expected Dose (154)

In the absence of nuclear debris and fission trapping, radiation exposures from galactic background, the South Atlantic anomaly, and solar flares (should one occur) may produce doses on the order of the following in a vehicle like the shuttle where shielding is assumed to be 2gm/cm^2 or less.

Low Earth Orbit		Polar	Equatorial
Galactic Background	p^+	20 mrem/day	10 mrem/day
So. Atlantic Anomaly	e^{-B-}	200 mrem/day	100 mrem/day
Solar Flare	p^+, HiZE	10-15 rem	Greater than 10-15 rem)
Stay Time 90 Days		19.8+(10-15)	10 rem
Total		32 rem*	

Likewise for transfer from low earth orbit to synchronous, a one-time dose of 5 rem could occur.

Orbital Transfer		
Galactic Background	p^+	10 mrem
So. Atlantic Anomaly	e^{-B-}	10 mrem
Inner Belt	p^+	
Outer Belt	e^-	3-5 rem
Total		4.2 rem*

*Note: These two doses equate to today's current occupational and one-time emergency doses.

Infrahuman primates exposed in 1964 to different energies of protons and electrons form the basis for the following inferences for delayed as well as acute effects. The energies and doses are as representative of space as accelerators were available at that time:

Radiation	Energy	Dose Range (REM)
X-ray	2 MeV	300-870
Protons	32 MeV	280-2800
Protons	138 MeV	210-1220
Protons	400 MeV	50-1200
Protons	55 MeV	25-1800
Protons	2.3 GeV	50-1100
Electrons	1.6 MeV	1000-1500
Electrons	2 MeV	900-1500
Solar Flares - Mixed Protons		120-1300

Initial experiments were designed to examine only the short term or acute effects of proton irradiation. However, as the lower dose animals survived the first 120-day postexposure period, they were maintained, and as this population of animals grew, so did the idea of a long term colony, now 15 years postexposure. One energy, 55 MeV is provided, since it is fairly representative of the area of space discussed above.

Protons of this energy penetrate the body tissues to a depth of about 2.5 cm, which not only irradiate the integumentary system, but also irradiate a considerable fraction of the bone marrow, gastrointestinal tract, and the central nervous system. The $LD_{50/30}$ is about 1150 rem. The results are outlined below. The notation $LD_{50/30}$ indicates that the exposure will be fatal to 50 percent of the subjects in 30 days.

There was a depression of leukocytes and platelets, but to a much lesser extent that that seen after x-ray irradiation. Diarrhea and gastrointestinal symptoms occurred with doses above 1500 rem.

Exposure doses of 1500 rem or greater produced severe skin ulceration within one month after exposure, and severe incapacitating edema, especially of the face, occurred two months after exposure. Exposures of 1000 rem also produced desquamation and some edema within the first few months after exposure.

An additional consideration is provided by A. P. Arga (357) with respect to dosages and effects. The author develops all usable doseages and defines effects for various exposures.

Permissible Radiation Doses (357)

One important consideration in recommending any permissible dose is the length of time over which the body is exposed. For example, a dose spread over a period of 40 years may not show any significant damage. If an individual is exposed to a large single dose of radiation over a short interval of time, it is called an acute exposure, while a steady small dose of radiation over a long time is called a chronic exposure. It is found that on the average a typical individual in the United States receives a total dose of 180 mrem/yr (1 mrem = 10^{-3} rem) resulting from (1) 100 mrem/yr from natural radioactivity and cosmic rays, (2) 75 mrem/yr from dental and medical x-rays, and (3) 5 mrem/yr from fallout from nuclear weapons testing.

It is true that any amount of radiation exposure is considered to be a health hazard. But there are situations where certain exposures cannot be avoided (for useful medical and industrial applications). Under such circumstances the exposure should be kept to a minimum. For this purpose, at present, the maximum permissible amount of radiation dose to which an individual may be exposed (without any ill effects) is set at 500 mrem per year. It is assumed that such exposures are uniformly distributed over the whole year. It is also recommended that those persons under the age of 18 should have zero exposure. This is because at a young age, the body cells are growing and are very sensitive to radiation damage.

One may wonder at this stage what are the clinical symptoms of radiation sickness. For low long-term exposures (chronic exposures), there are basically no clinical symptons, but in many cases cancer has been found. But high short-term exposures (acute exposures) do have clinical symptoms, as summarized in Table 7-4.

TABLE 7-4 CLINICAL SYMPTOMS OF RADIATION SICKNESS

Time After Exposure	Lethal Dose (650r)	Medium Lethal Dose (400r)	Sublethal Dose (250-100r)
First week	Nausea, vomiting within 2 h Diarrhea Inflamation of mouth and throat	Nausea, Vomiting after 2 h	Possible nausea, vomiting
Second week	Fever Rapid loss in weight Death	Loss of hair Loss of appetite General discomfort	
Third week		Fever Severe reddening of mouth and throat	Loss of hair Loss of appetite General discomfort Sore throat Pallor Bleeding Diarrhea
Fourth week		Pallor Bleeding Diarrhea Rapid loss in weight Death 50% chance	Recovery likely

STRATEGY OPTIONS

1. Select altitude/elevation to avoid South Atlantic anomaly and higher radiation belts.

2. Synergistically develop a barrier systems analysis/trade study that optimizes module external walls for at least pressurization, meteroid/debris protection, shrapnel and radiation protection.

3. Consider supplemental use of lead partial clothing elements (ponchos, shorts, goggles, etc.)

4. Develop realistic allowable dose tables for EVA, flight quarter year and whole life.

5. Develop realistic allowable dose tables for in-station astronaut for flight, quarter, year and whole life.

6. Develop better mdels for dose estimation.

8. METEOROID PENETRATION

THREAT DEFINITION

A large quantity of space debris hurtles past the earth at speeds ranging from 7,000 to 45,000 miles per hour. Ten thousand tons of meteoritic material reach the earth daily. Most of the space debris consists of tiny particles which are prevented by the earth's atmosphere from reaching the ground. A satellite or space station has no such protection, and a meteoroid the size of a pinhead can penetrate 2 millimeters of aluminum.

A meteorite is a piece of space debris large enough to penetrate the earth's atmosphere and land on the earth. On rare occasions very large meteorites land. The largest one discovered to date weighs more than 50 tons. Very large ones are not found because they explode on impact, causing some of the largest explosions known to man before the atom bomb. There are craters giving evidence of meteorites weighing more than 200,000 tons.

Meteors are the shooting stars and fireballs seen in the night sky, usually not large enough to reach the earth's surface. Their size ranges from 0.1 millimeter to several meters in diameter. Meteoroid refers to all such bodies moving through space, and hence the term includes both meteors and meteorites before they reach the earth's atmosphere. The term micrometeorite refers to tiny dust particles below about 0.1 millimeters in diameter. (349)

A fallout of space debris studies will have to be a probability of strike and an assumed size of meteoroid. The potential impact of this threat has not been specifically defined at this time. However, basic assumptions should consider potential meteoroid penetration of the primary structure. Physical damage should be confined to one compartment and is assumed to consist of finely divided molten high-speed shrapnel (from spallation of the inner wall).

Penetration of the pressure wall of the primary structure by a meteroid will be a relatively rare event; however, the potential consequences of such an event must be considered.

The spacecraft structure is designed for no penetration by a meteroid defined by a certain probability of occurrence in a particular environment for the mission duration. Figure 8-1 shows the probability of no impact for a typical modular space station configuration during a 10-year mission. There is better than 0.999 probability of no impact by a meteoroid larger than 1 gm mass and 15 mm (0.6 inch) diameter, and this size meteoroid has been selected for defining the maximum credible meteoroid penetration in the credible accidents. Such a meteoroid would produce approximately 50 BTU's of energy inside the compartment it penetrated. This energy would be released in the form of heat, shock waves, and kinetic and thermal energy of finely divided molten high-speed shrapnel from spallation of the inner wall. This event was compared in magnitude to an explosion of a hand grenade (0.025 lb/TNT equivalent) and may be expected to injure personnel in the area, damage equipment, and start local fires. It also will result in a hole of approximately 2 inches in diameter in the pressure wall, and will cause depressurization of the module/vehicle. (021)

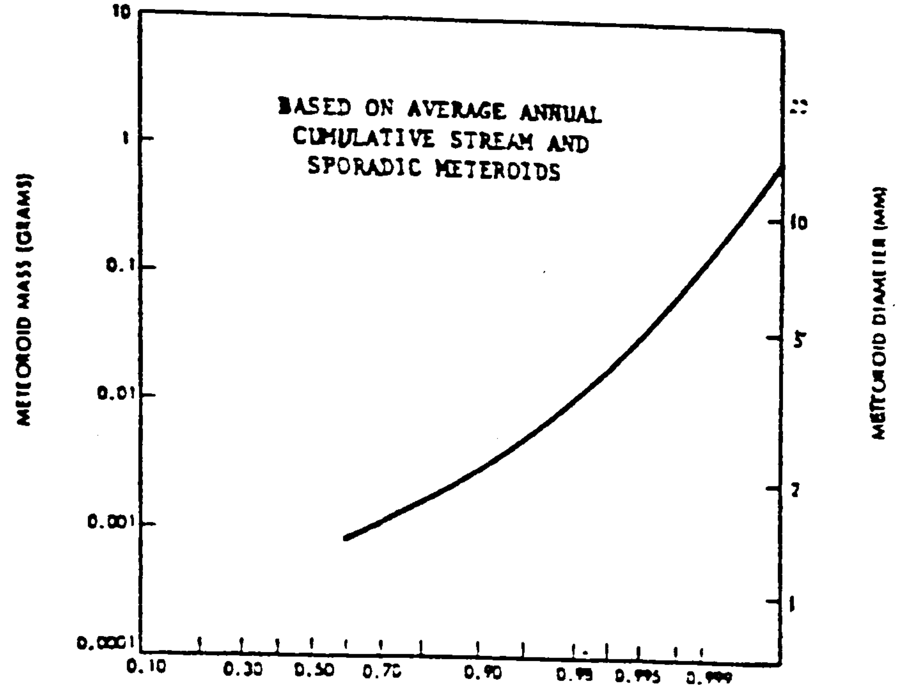


Figure 8-1 Probability of No. Meteoroid Impact (021)

The depressurization effect from a penetration will depend on its size as well as the volume being depressurized. The pressure will decay exponentially with time and the crew will be able to function until a pressure of approximately 9.1 psia is reached. At this point, the partial pressure of oxygen will be 1.9 psia, and below this hypoxia may result in unacceptable levels of crew performance, with degraded visual performance. At a pressure of approximately 6.0 psia, loss of consciousness may result after a variable period, depending on individual susceptibility. Decompression sickness (bends) may occur if the pressure drops below 7.3 psia. Although the onset and course of this decompression sequence is unpredictable for any one individual, symptoms rarely appear during the first few minutes of exposure to the low pressure. (021)

Figure 8-2 shows the decompression times to 9.1 psia for the maximum design case of a 2-inch penetration. If a single module were isolated, approximately five minutes of crew reaction time would be available for locating and making a temporary seal or for evacuating and sealing off the module. If several modules were open to each other, so that all of them share in the decompression, considerable more reaction time would be available. Operating the space station with the hatches open between modules, therefore, maximized the reaction time in the event of a leak, as well as allowing quicker access between the modules. (021)

The 2-inch penetration represents a very severe case which would typically be encountered once in 10,000 years of space activity. As seen from Figure 8sdmeteoroids with a more realistic probability of occurrence are considerably less massive and of smaller diameter. Although the size of penetration will not vary much, the energy released does decrease very rapidly with the size of the meteoroid. Meteoroids which are just beyond the structural capability of the primary structure will probably cause very small penetrations and the problem probably will be in detecting and locating them rather than in coping with damage. (021)

DISCUSSION

The solid objects encompassed by the term "meteoroids" range in size from microns to kilometers and in mass range from $\leq 10^{-12}$g to $\geq 10^{+16}$g. Those less than 1 gram are often called "micrometeoroids." If objects of more than approximately 10^{-6}g mass reach Earth's atmosphere they are heated to incandescence, producing the visible effect called a "meteor." If the initial mass and composition permits some of the original meteoroid to reach Earth's surface unvaporized, the object is called a "meteorite".

Meteoroids are thought to derive primarily from comets and asteroids with perihelia near or inside Earth's orbit. The original objects were supposedly broken down into a distribution of smaller bodies by collisions. Meteoroids recently formed still tend to be concentrated near the orbital path of their parent body. These "stream meteoroids" produce the well known meteor showers which occur at certain dates and from particular directions (Table 8-1).

TABLE 8-1. MAJOR METEOROID STREAMS (164)

Name	Period of Activity	Date of Activity	F_{max} Maximum	Geocentric Velocity (km/sec)
Quadrantids	January 2 to 4	January 3	8.0	42
Lyrids	April 19 to 22	April 21	0.85	48
η-Aquarids	May 1 to 8	May 4 to 6	2.2	64
O-Cetids	May 14 to 23	May 14 to 23	2.0	37
Arietids	May 29 to June 19	June 6	4.5	38
-Perseids	June 1 to 16	June 6	3.0	29
β-Taurids	June 24 to July 5	June 28	2.0	31
δ-Aquarids	July 26 to August 5	July 8	1.5	40
ζPerseids	July 15 to August 18	August 10 to 14	5.0	60
Orionids	October 15 to 25	October 20 to 23	1.2	66
Arietids, southern	October through November	November 5	1.1	28
Taurids, northern	October 26 to November 22	November 10	0.4	29
Taurids, night	November		1.0	37
Taurids, southern	October 26 to November 22	November 5	0.9	28
Leonids, southern	November 15 to 20	November 16 to 17	0.9	72
Bielids	November 12 to 16	November 14	0.4	16
Geminids	November 25 to December 17	December 12 to 13	4.0	35
Ursids	December 20 to 24	December 22	2.5	37

F_{max} is the ratio of average maximum cumulative stream to average sporadic flux for a mass of 1 g and a velocity of 20 km/sec.

Meteoroids may be classified by composition: stony, iron, and, perhaps, icy. From their composition the type of parent body can be inferred.

Meteoroids are attracted by the Earth's gravity field so that the flux from allowed directions in near-Earth orbit is increased by approximately 1.7 over the interplanetary value. The Earth also shields certain arrival directions.

The total mass infall to Earth is estimated to be approximately 10^{10}g/year. Figure 8-3 shows the distribution of number with mass, where N ($\geq$ m) is the number flux with mass > m. The flux is low and, therefore, difficult to measure. Evidence includes: spherules on the sea floor and the polar icecaps, impacts detected with special sensors on satellites, meteor trails in the atmosphere observed visually and by radar, lunar crater counts and zodiacal light.

The fluxes of Figure 8-3 are probably uncertain by a factor of 10. The units may be converted to particles/m^2 sec by division by 3.155 x 10^{13} = antilog 13.499. (To convert to interplanetary intensity, particles/m^2 sec ster, multiply by 2 to correct for Earth shielding, divide by 2 to correct for gravitational focusing, and divide by π). The data are of the form N ($\geq$ m) = const/m^{α}, with α, the slope, slowly changing. There is some evidence that the flux in Earth-lunar space is greater than the general level along the Earth's orbit by a factor between 1 and 2. The interplanetary flux is higher in the asteroid belt than at 1 AU. (164)

The simplified form N ($\geq$ m) = coust/m^{α} expresses the curvature of the particle flux data as linear segments for specific mass ranges averaging out the approximate curvature of the represented scattered data.

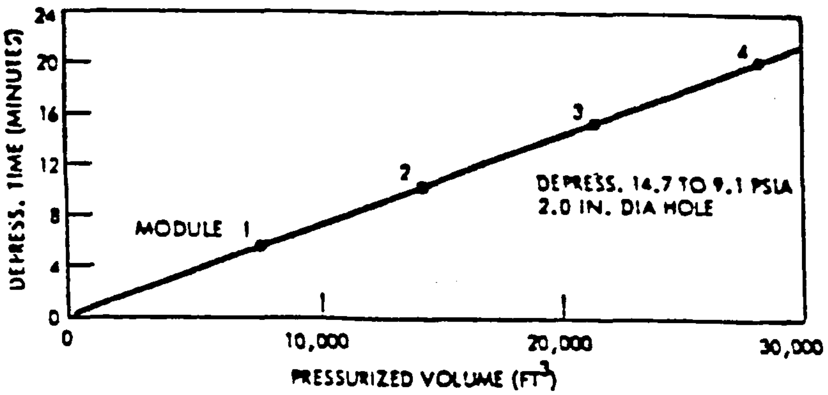


Figure 8-2 Effect of Number of Modules in Isolatable Volume on Depressurization Time

Figure 8-4 shows a recent compilation of data for near-Earth space derived by various means, over a more restricted mass range than Figure 8-3. (The fluxes shown in Figures 8-3 and 8-4 are 1-year averages.) The flux for m $< 10^{-12}$g is rather uncertain. There have been other recent estimates of micrometeoroid flux a factor of 10 higher than those shown in Figure 8-3. This appears to represent a real uncertainty. (164)

The main parameters affecting the meteoroid shield are mission duration, vehicle surface area and probability of puncture. Combining a mathematical model of the likely meteoroid environment, of hypervelocity penetration and a puncture criterion with basic probability theory, one finds that the shielding thickness required for icy meteoroids of cometary origin is up to an order of magnitude lower than that required for stony meteoroids assumed to be of asteroidal origin. Shield thickness and weight is therefore determined by asteroidal meteoroids in the first and secondarily by mission time. Thus, for flights to Mars, and for long capture times, in the case of conjunction missions, the required meteoroid shielding is likely to be heavier than for the space station. The tenative effect of heliocentric distance on the meteoroid shield weight is shown in Figure 8-5 based on 99 percent probability of zero puncture. (078)

Meteoroid Hazard for the Shuttle Orbiter

The debris may be meteoroids passing near the Earth or man-made objects generated during space operations.

The Orbiter will nominally operate in a circular orbit with an altitude of approximately 300 km. Because it is so much larger than the objects comprising the debris population, the Orbiter's mean cross-sectional area can be used to define the collision cross section. The cross-sectional area nose-on is approxiately 50 m^2, while the area in the plane of the wings is approximately 500 m^2. A mean cross-sectional area of 250 m^2 was used in performing the collision calculations. The assumed independence of debris size and the use of a mean cross-sectional area for collision cross section serve to introduce some uncertainty into the calculations.

The large values for the times between collisions contained in Table 9-3, Section 9, indicate that man-made debris of size 4 cm and larger will not present a significant hazard to the Shuttle Orbiter. In fact, the times are large compared to times for collisions involving the Orbiter with a meteoroid of sufficient mass to severly damage a TPS tile, as shown in Table 8-2. These times are based on the meteoroid population model of Cour-Palais. (365) The sensitivity of the LEO environment to man-made debris deposition is clearly illustrated by comparing the meteoroid population particle densities with fragment producing operations, such as antisatellite tests, which might occur in orbit. At any time there are about 100 kg of meteoroid material of mass greater than 0.01 g in the volume of space up to 4000 km altitude. Therefore a single incident which explosively fragmented 100 kg of material into the same mass distribution as displayed by the meteoroids would, if these fragments were dispersed uniformly up to 4000 km altitude, match the meteoroid debris levels. (282)

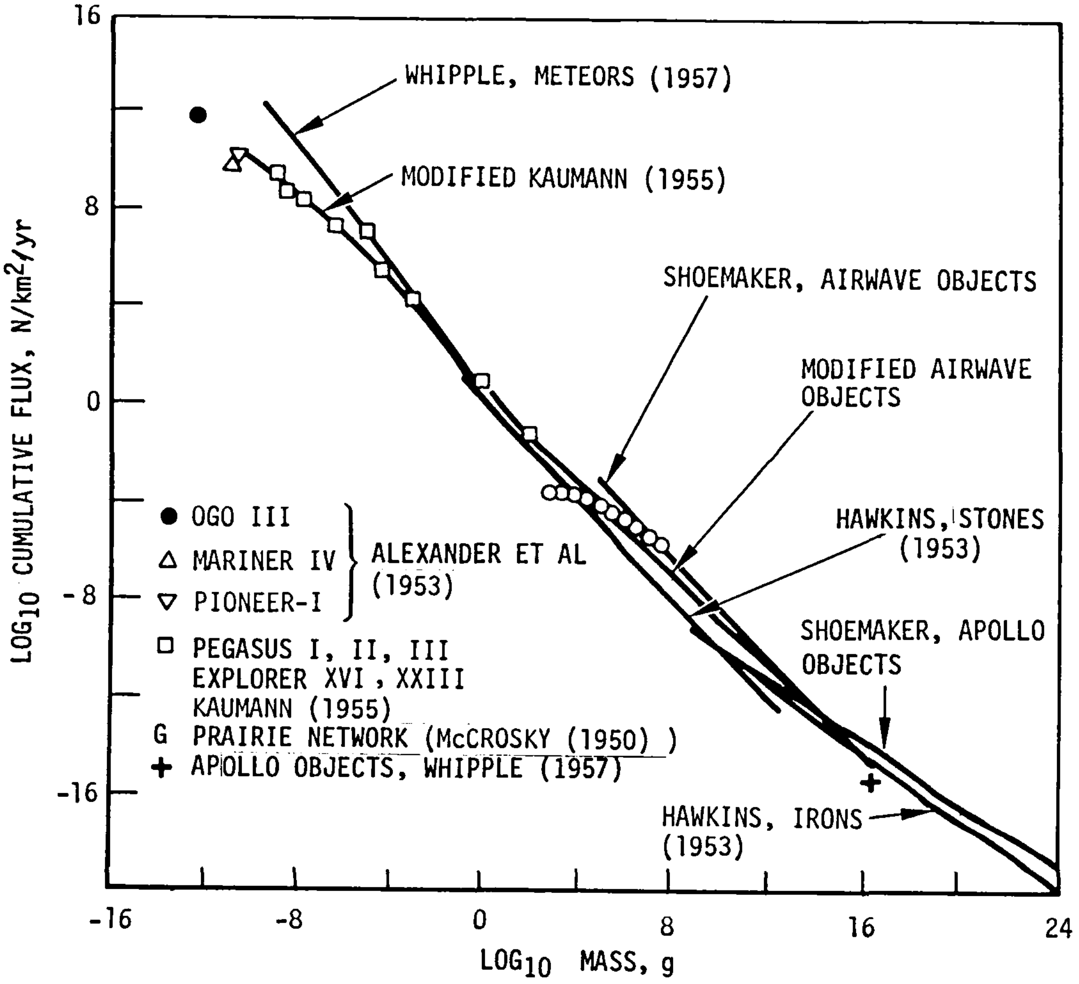


Figure 8-3 Terrestrial Mass-Influx Rates of Meteoroids - N is the Flux of Particles with Mass Greater than M

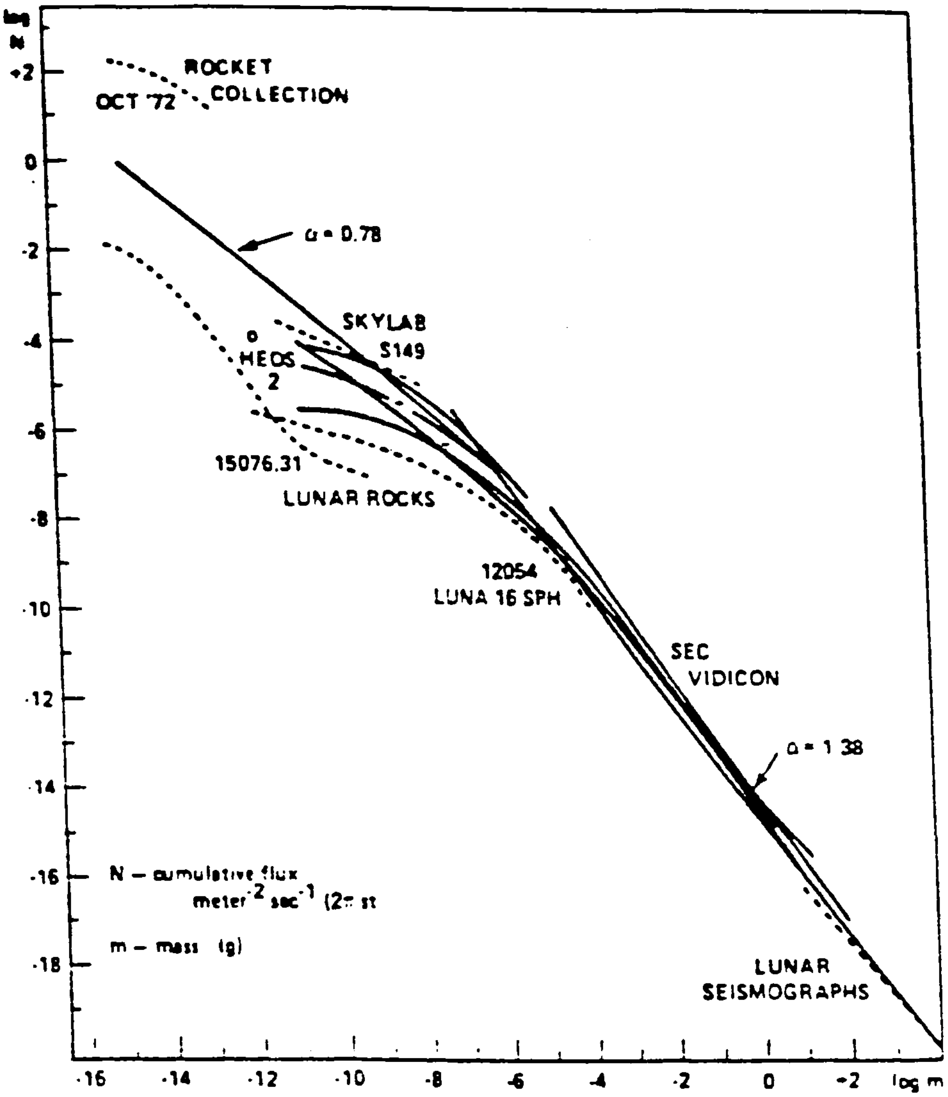


Figure 8-4 Cumulative Particle Fluxes from Various Data Sources (164)

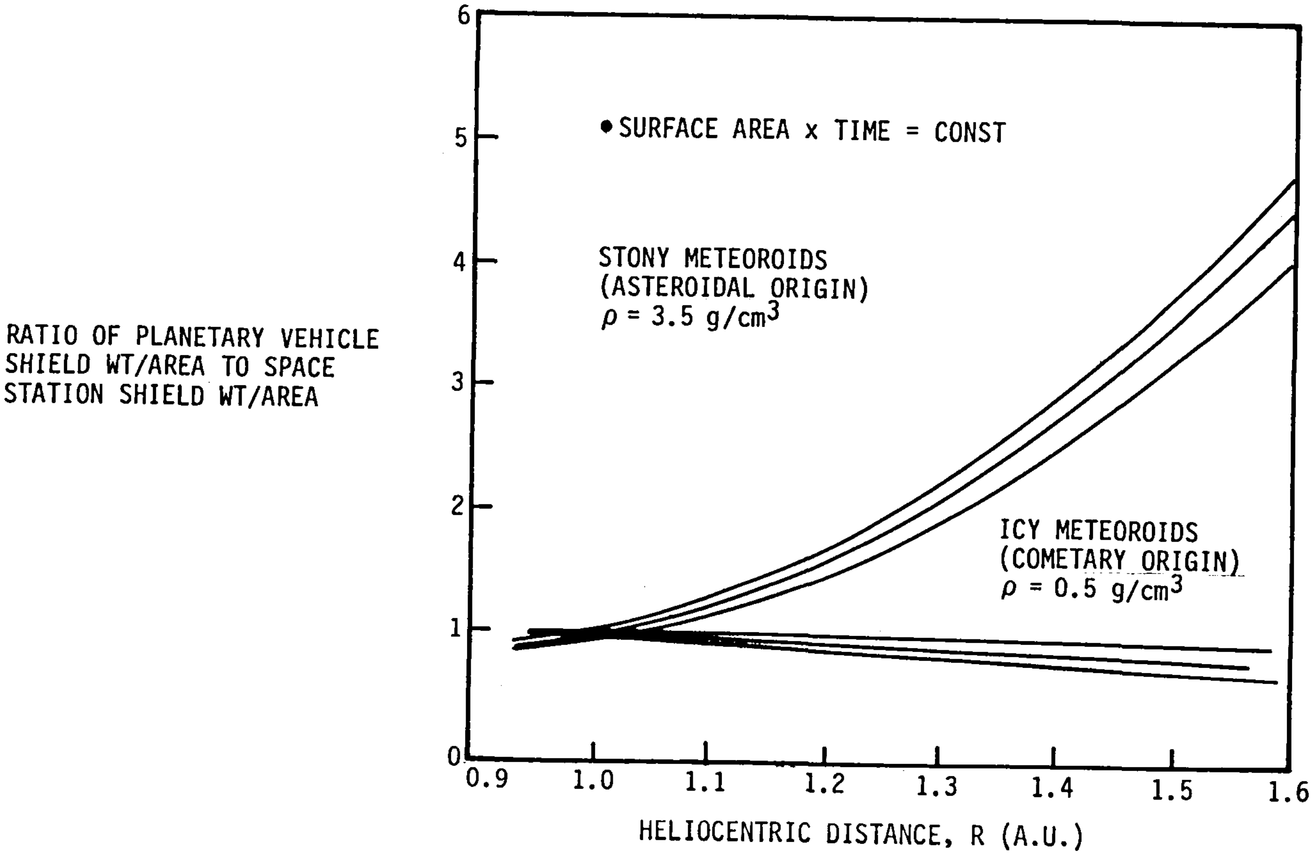


Figure 8-5 Meteoroid Shield Requirement (078)

TABLE 8-2 - TIME BETWEEN COLLISIONS BETWEEN THE SHUTTLE AND A METEOROID OF MASS GREATER THAN A GIVEN MINIMUM MASS (282)

Minimum meteoroid mass, g	Time between collisions, yr
10	350,000
1	25,000
0.1	1,800
0.01	130

Recorded Incidents

Post flight inspection of STS-8, Orbiter OV-099, August/September 1983, revealed that the forward windows (W-3 and W-4) had unacceptable visibility due to heavy haze/glare which resulted from abrasion. Normal hand polishing/cleaning techniques were not able to remove this haze/micropitting and the windows were replaced. This is the first flight where micropitting/hazing was noted. The cause of this micropitting/hazing is believed to be abrasion during entry and is under investigation.

A micrometeorite or man-made space debris struck and damaged a window on the Soviet Salyut 7 space station July 27,1983 causing a loud crack heard by the two-man cosmonaut crew. The Soviets characterized the impact as "an unpleasant surprise," although the 0.15-in.-dia. crater formed on the window did not threaten the pressure integrity of the pane.

A shuttle orbiter Challenger window suffered similar damage during shuttle Mission 7, forcing the damaged glass pane to be replaced. Micrometeoroids or space debris large enough to cause such damage are considered rare.

Soviet scientists believe the material that struck the Salyut was a micrometeorite because "experts have established that our planet is now passing through a meteoroid shower. The surprise incident with the micrometeorite attack amazingly coincided with preparations for a preplanned training exercise called 'urgent escape from the station,'" the Soviets said.

Minimum Salyut crew escape time, to survive an emergency such as a pressurization failure, is considered 15 min., the Soviets said. This would at least allow the crew to dive into the Soyuz transport and shut the hatch. The basic Salyut/Soyuz emergency return schedule is based on a 90-min. period that also includes some basic station mothballing activity, the Soviets said.

A micrometeorite or man-made space debris struck and damaged the shuttle orbiter Challenger's windshield in orbit during Mission 7 in June 1983. The small impact crater in the outer pane was measured optically at 0.0178 in depth, with a crater width of 0.0892 in. The overall damaged area was 0.2 in. wide including the crater and flaws in the glass emanating from the impact point. The outer thermal pane from OV-099 right hand middle windshield (Window No. 5) was removed from the vehicle after the STS-7 mission for inspection and analysis.

The window was replaced not because of any concern over pressure integrity caused by the impact, but rather the possibility the damage could expand to dangerous levels when subjected to aerodynamic and heating loads during a later launch or re-entry.

Each orbiter window comprises three panes with the outer pane composed of 5/8 in. thick silica glass. The impact damaged the outer pane, which is designed for thermal protection. The two underlying panes provide both a primary and secondary cabin pressure integrity seal.

Impact with a micrometeorite large enough to cause the Mission 7 damage is considered a rare event as statistically the chance for such a strike approximates only every 270 days in space.

Some minor damage from smaller micrometeorites is expected on orbiter windows. A previous suspected meteorite impact crater was detected on orbiter Columbia's Window No. 3 thermal pane, but this OV-102 pane was not removed.

However, OV-102 Window No. 4 thermal pane was removed because of surface cracks (bruise check) attributed to low velocity impact by a large soft object or to a static load.

Analysis procedures for the two replaced window panes are being evaluated.

Other recorded incidents of damage by or collision with Space Debris are addressed in Section 9, entitled Debris. In some of these cases the question whether the incident was caused by meteoroids or by man-made space debris may never be answered.

Meteoroid Bumper Experiment on Explorer 46

In July 1981 NASA-Langley Research Center (LaRC) released technical paper 1879 summarizing the results obtained from the Meteoroid Bumper Experiment on Explorer 46 and the conclusion reached therefrom.

Introduction: The damage to a spacecraft from meteoroid impacts may be greatly reduced by placing a thin shield around the spacecraft at some distance from the hull. The shield, a meteor bumper, would vaporize meteoroids upon impact, thus dissipating their penetrating powers.

The validity of the bumper concept was demonstrated in a number of laboratory studies. Even at impact speeds too low to cause vaporization, a bumper was seen to fragment the projectile and disperse the fragments over a large area of the main wall, giving the double-wall structure a much greater resistance to penetration than a single wall of the same thickness. However, all the laboratory tests were conducted at impact speeds less than the average meteoroid impact speed.

Even though the effectiveness of double-wall structures against meteoroids had not been demonstrated in space, the promise of great weight savings seen in the extrapolation of laboratory data led designers to use bumpers on a number of spacecraft. The bumper used on Skylab was counted on heavily to reduce the probability of a meteoroid penetration from approximatley 0.05, which is unacceptable for a manned mission, to about 0.0001. Skylab survived; its hull was not penetrated during the manned mission or during the post-mission period. This flight experience, however, does not provide data on the effectiveness of that bumper. It does not even demonstrate that double-wall structures have a greater resistance to meteoroid penetration than a single wall because no penetrations were expected to occur, even without the bumper.

The survival of the pressurized photographic canisters on four of the five Lunar Orbiter spacecraft demonstrated that meteoroid bumpers are effective in reducing meteoroid penetration damage. The thermal blanket on that spacecraft acted as a bumper which protected the pressurized photographic canister. However, the small statistical sample (only five canisters were flown and only one canister was penetrated) resulted in only a poor definition of the effectiveness of the double wall, indicating that the double wall had the same penetration resistance as a single wall 10 to 840 percent thicker than the combined thickness of the two walls.

The first accurate measurement of the effectiveness of a bumper in reducing meteoroid penetrations was made on Explorer 46. Explorer 46 was an Earth-orbiting satellite dedicated to the study of meteoroids and meteoroid protection. Three meteoroid experiments were carried onboard the spacecraft. The meteoroid bumper experiment was the primary experiment. (284)

Description of Experiment: Each wing consisted of three flat panels in a configuration that looked like a cross when viewed from the end. Each panel contained eight pressurized cells formed by joining two 50-μm-thick sheets of 21-6-9 stainless steel by resistance welding. The pressurized cells were long, narrow cells running the length of the panel. In addition, there was a 25-μm-thick bumper of 21-6-9 stainless steel on each side of the panel. The 50-μm wall represented the hull or main wall of the double-wall structure being tested, while the 25-μm sheet was the bumper that essentially surrounded the main wall. The spacing between the walls was 13mm.

The essential data obtained from the bumper experiment were the times at which each cell was penetrated by a meteoroid. (284)

Explorer 46 was boosted into orbit on August 13, 1972, from the NASA Wallops Flight Center by a Scout D launch vehicle. The spacecraft achieved an orbit of 490 km by 815 km with an inclination of 38°. The attitude of the spacecraft was not known. The final interrogation of the experiment was made on January 29,1975. (284)

Conclusions: The meteoroid bumper experiment on Explorer 46 showed that a bumper is an effective device for reducing meteoroid penetrations. The double-wall structure reduced the penetration flux by a factor of 30 from that expected for a single wall of the same thickness, and it provided the same protection as a 514-μm-thick single wall, which means it provided a weight savings of a factor of 6.9.

Explorer 23, single wall, and Explorer 46, double wall experiment results are shown in Figure 8-6.

Hypervelocity impact tests in the laboratory implied that failure of the Explorer 46 double-wall structure occured when bumper fragments penetrated the main wall. Blast-loading failures of the main wall did not occur because a very large spacing was used between the bumper and the main wall.

Even greater effectiveness may have been achieved if the distribution of material between the bumper and the main wall in the Explorer 46 experiment could have been optimized by transferring some of the bumper material to the main wall. Engineering problems prevented the experiment from being optimized. The optimum distribution was calculated to be one in which the bumper contains about 0.1 to 0.2 of the available material. (284)

Design Application: The efficiency factor of 6.9 for the double-wall structure on Explorer 46 cannot be applied to all double-wall structures. The efficiency factor may vary significantly with the distribution of material between the bumper and main wall, the spacing between the walls, and the material of which the walls are made.

The real contribution of the Explorer 46 data set is that it provides a test point for models used to calculate meteoroid penetration flux. A good model can be applied to future spacecraft wall designs of various configurations. (284)

Penetration Tests

On the basis of the encouraging results obtained from the Meteoroid Bumper Experiment on Explorer 46 further penetration testing was performed on double wall optimization. The conclusions reached to-date based on these tests and data evaluation from the Explorer experiments are summarized in the following.

The Meteoroid Environment Model, NASA SP-8013, 1969 and the Meteoroid Damage Assessment, NASA SP-8042, 1970 formed the data base for this evaluation.

Meteoroid Environment Model: The NASA design criteria use the basic model of the near-Earth meteoroid environment found in reference (365) which defines the size distribution, velocity distribution, mass density, and abundance of meteoroids. The model formulates the average annual cumulative total flux ø, in impacts/m^2s, of meteoroids of mass m and greater, in kg, on a spacecraft.

This Meteoroid Environment Model, NASA SP-8013, 1969, is still valid since no new data obtained subsequently justified a corrective improvement of this model. (365)

NUMBER OF METEOROID HITS

$$N(m) = \phi(m) At$$

$N(m)$, number of meteoroids of mass m or greater
$\phi(m)$, flux of meteoroids of mass m or greater (in impacts/m^2s)
A, area of spacecraft component (m^2)
t, duration of mission (s)

PROBABILITY OF AT LEAST ONE HIT

$$P(m) = 1 - e^{-\phi(m)At}$$

Reference (365)

Meteoroid Damage Assessment: Spacecraft designers need a method of calculating the penetration flux for any double-wall structure, preferably a method that is based on a fundamental understanding of the meteoroid environment and hypervelocity impact phenomena. The method recommended in the NASA space vehicle design criteria for meteoroid damage assessment only satisfies that requirement in part. (366) It is based on a fundamental understanding of the meteoroid environment, but admits to a lack of understanding of hypervelocity impact phenomena in double-wall structures. (284)

The referenced meteoroid damage assessment, NASA SP-8042, 1970, only provides formulas for metal plates and recommends testing any other components.

SINGLE WALL PENETRATION EQUATION
(NASA SP-8042)

$$t = K_1 m^{0.352} \rho^{1/6} v^{0.875}$$

t = thickness of wall, cm
K_1 = constant characteristic of wall material and temperature
m = mass of projectile, g
ρ = density of projectile, g/cm^3
v = impact speed, km/s

Example of Applicability to Manned Space Station

The need for debris protection and the relevance of the populatin and size man-made debris and meteoroids is illustrated in Figure 8-7. The flux of meteoroids and predicted 1995 levels of man-made debris, plotted as a function of the effective diameter of those particles are taken from data presented by Donald H. Kessler of NASA's Johnson Space Center (JSC) at an Orbital Debris Workshop held at JSC during July of 1982. For the purpose of illustration, a 0.10 inch aluminum wall thickness is assumed for the space station. Assuming the meteoroid and debris particle densities and speeds noted in Figure 8-7, the equation for single wall penetration is solved for particle mass and thus particle diameter, using K_1=0.54 for aluminum. The meteoroid and debris particle diameters capable of penetrating the 0.10 aluminum wall are nearly the same as noted in Figure 8-7. At an altitude of 500 kilometers (270 nmi) the meteoroids of sufficient size to penetrate the wall is better than two orders of magnitude greater than that of debris particles.

Assuming an approximately 1800 square feet of space station modules cross section area, the number of penetrations per year and the probability of at least one penetration over a twenty year period have been calculated and noted in the figure. Such penetration frequencies and probabilities are clearly unacceptable for a manned space station, and indicate that a meteoroid and debris protection is a must for the space station.

Evaluation and Interpretation of Penetration Test Data

It is important to understand that the Explorer 46 experiment was not intended to establish the highest efficiency that a double-wall structure can have in reducing the weight of meteoroid protection. The distribution of material between the bumper and the main wall was not intentionally optimized. Efficiency factors greater than 6.9 probably can be attained. The discussion of optimum double-wall structures contained in this section is included to support the contention that the Explorer 46 double-wall structure was not optimum and that efficiency factors greater than 6.9 can be expected. (284)

The NASA design criteria do not provide a model for the penetration of double-wall structures. Instead, they recommend that the penetration resistance of a double-wall structure to meteoroid impacts be established by testing the structure in a hypervelocity impact laboratory at the highest speeds attainable and extrapolating the results to meteoroid impact velocities by assuming that meteoroids of equal kinetic energy have equal penetrating capabilities. It is recommended that glass (ρ = 2300 kg/m^3) or syntactic foam (ρ = 900 kg/m^3) be used as projectiles to simulate low-density cometary meteoroids. (284)

The following notes apply to the three zones (a), (b), and (c) shown on Figure 8-8. The scales of Figure 808 have been arbitrarily selected:

(a) As velocity increases, the particle mass required to puncture both walls decreases.

(b) As velocity increases further, the particle starts to disintegrate when it bursts through the first wall (bumper). Penetration (of the main wall) is caused by pieces of the particle and pieces of the first wall.

(c) As velocity increases further the blast created by the rupture of the first wall (bumper) dominates the failure mechanism of the second wall (main wall). The material in the second wall fails because of stress failure due to the blast. See also figures 8-9 and 8-10 depicting the effects in Zone (c)

The Double Wall Optimization, as shown schematically on Figure 8-11, can be summarized as follows:

s - Large enough to preclude blast loading failure mode
- No effect on penetration by fragments

t_B - Thick enough to break up projectiles
- Thin enough that bumper fragments won't penetrate main wall

t_W - Thick enough to preclude penetration by fragments from both projectile and bumper

Tradeoff studies based on the results of laboratory tests will have to consider all of the following parameters:

s, t_B, t_W, total system weight, probability of penetration, meteoroids, man-made debris, other factors (incl. radiation)

Other tradeoff studies have to weigh the advantages of a void space between bumper and main wall for meteroid penetration versus the advantages of a material filler for enhancing the radiation protection.

STRATEGY OPTIONS

Damage containment for meteoroid impact becomes largely a tradeoff among structural weight, probability of occurrence of impact, and the acceptable damage. Since these tradeoffs are outside the scope of this report, only parametric considerations can be addressed. (028)

Damage Containment and Control Techniques

Certain time-critical hazardous situations may remain, even though every effort has been made in the mission planning, design and operational aspect to minimize or eliminate their causes. Some of these situations are meteoroid penetration and/or damage caused by meteoroid hits, resulting in potential decompression, fire, explosion and major damage to the Space Station modules, systems and/or subsystems. These situations, which can be catastrophic, may not allow time for the crew to take deliberate corrective action. Therefore, the emphasis must be on designing the Space Station to limit and contain the damage. Surviving crew members must be provided with the means and the margin of time to escape to a designated safe area within the Space Station from which they may evaluate the situation and make rational unhurried decisions. (028)

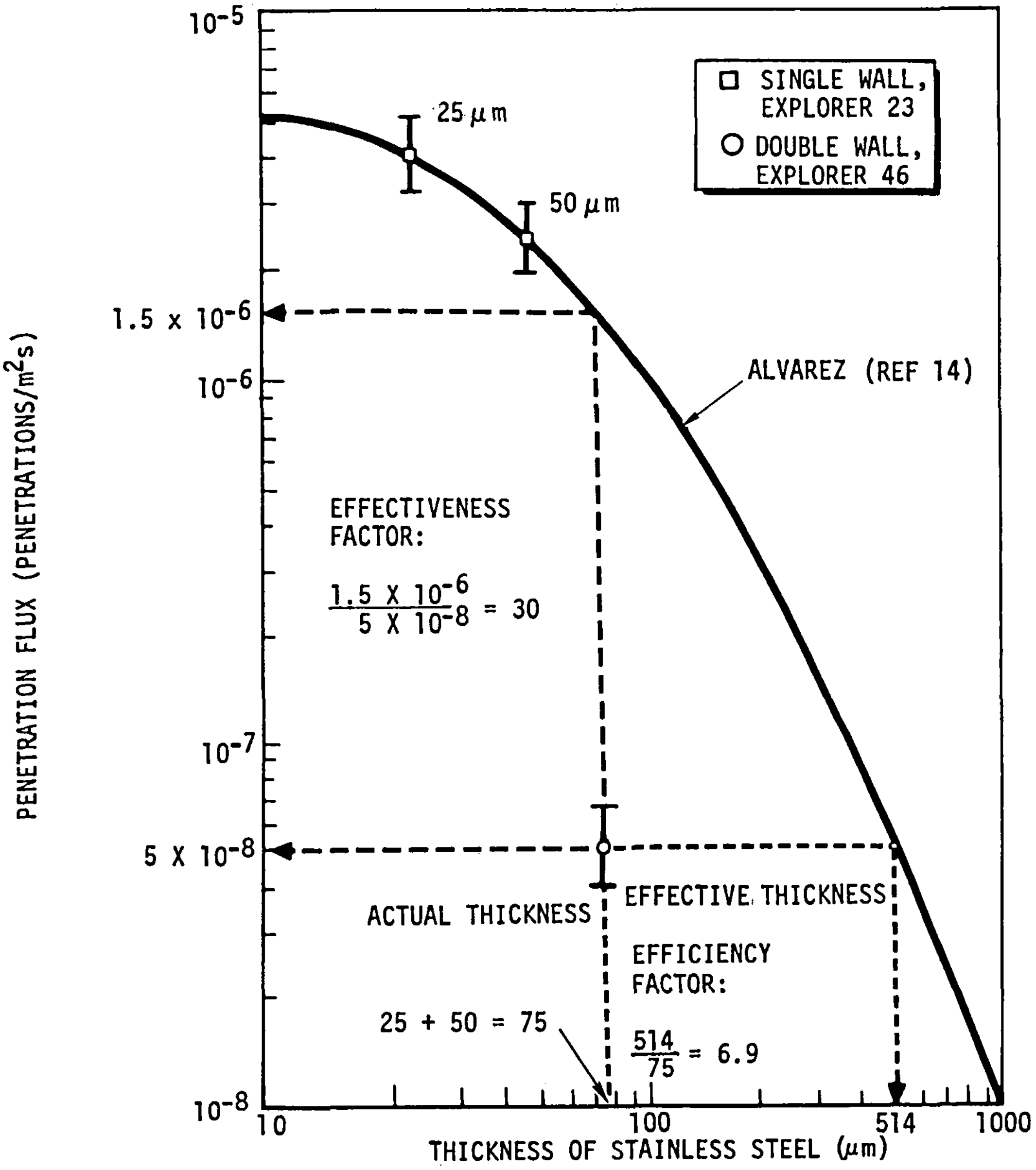
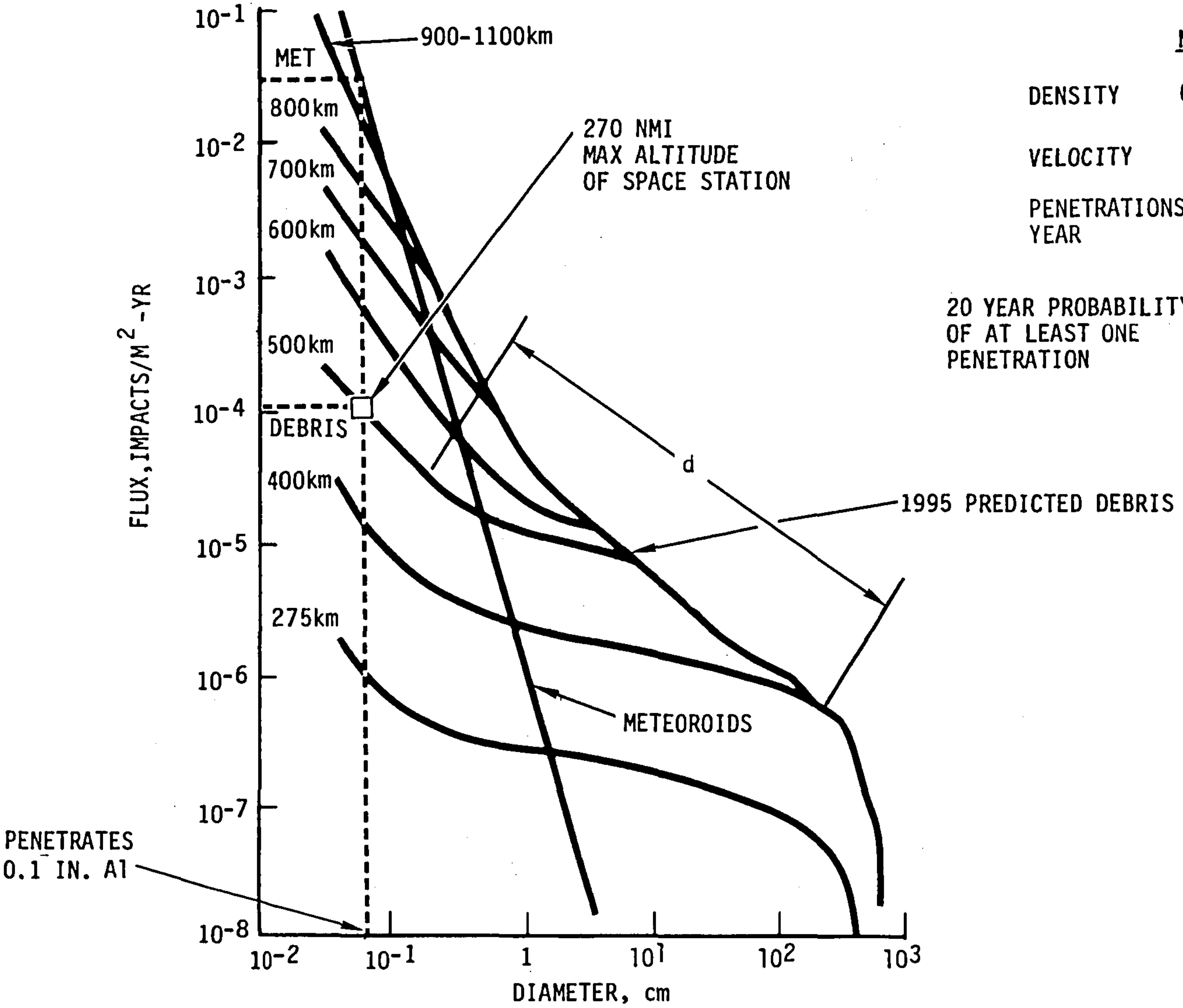


Figure 8-6 Penetration Flux for Single Stainless-Steel Walls and Explorer 46 Double Wall Stainless-Steel Structure, with 90-percent Confidence Limits (281)



	METEOROID	DEBRIS
DENSITY	0.5 g/cm^3	2.8 g/cm^2
VELOCITY	20 km/s	8 km/s
PENETRATIONS/ YEAR	2	0.02
20 YEAR PROBABILITY OF AT LEAST ONE PENETRATION	1.00	0.33

Figure 8-7 Predicted 1995 Cumulative Space Debris Flux Variation with Altitude

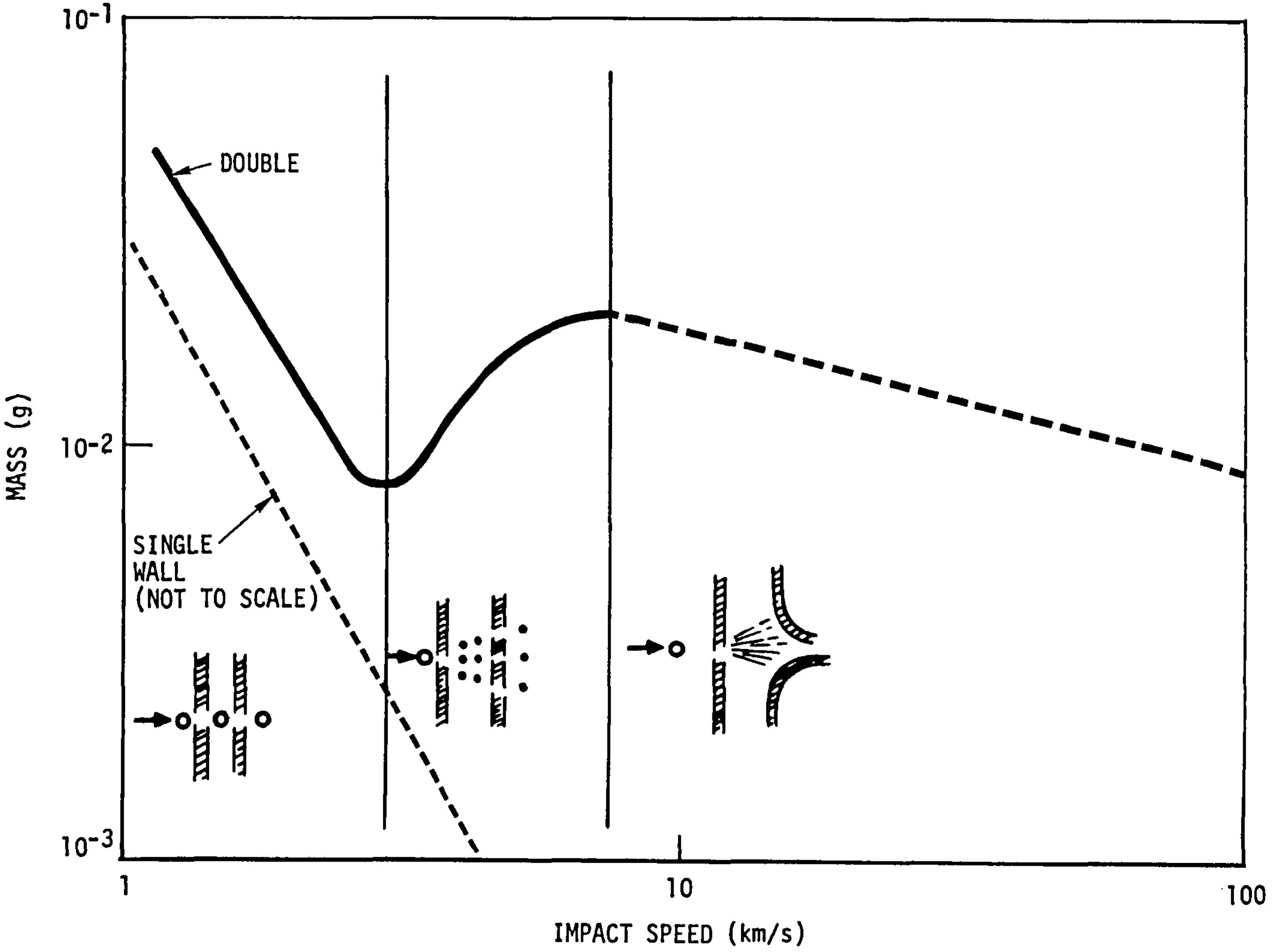


Figure 8-8 Effects of Impact Speed and Particle Mass on Double Wall Structure (281)

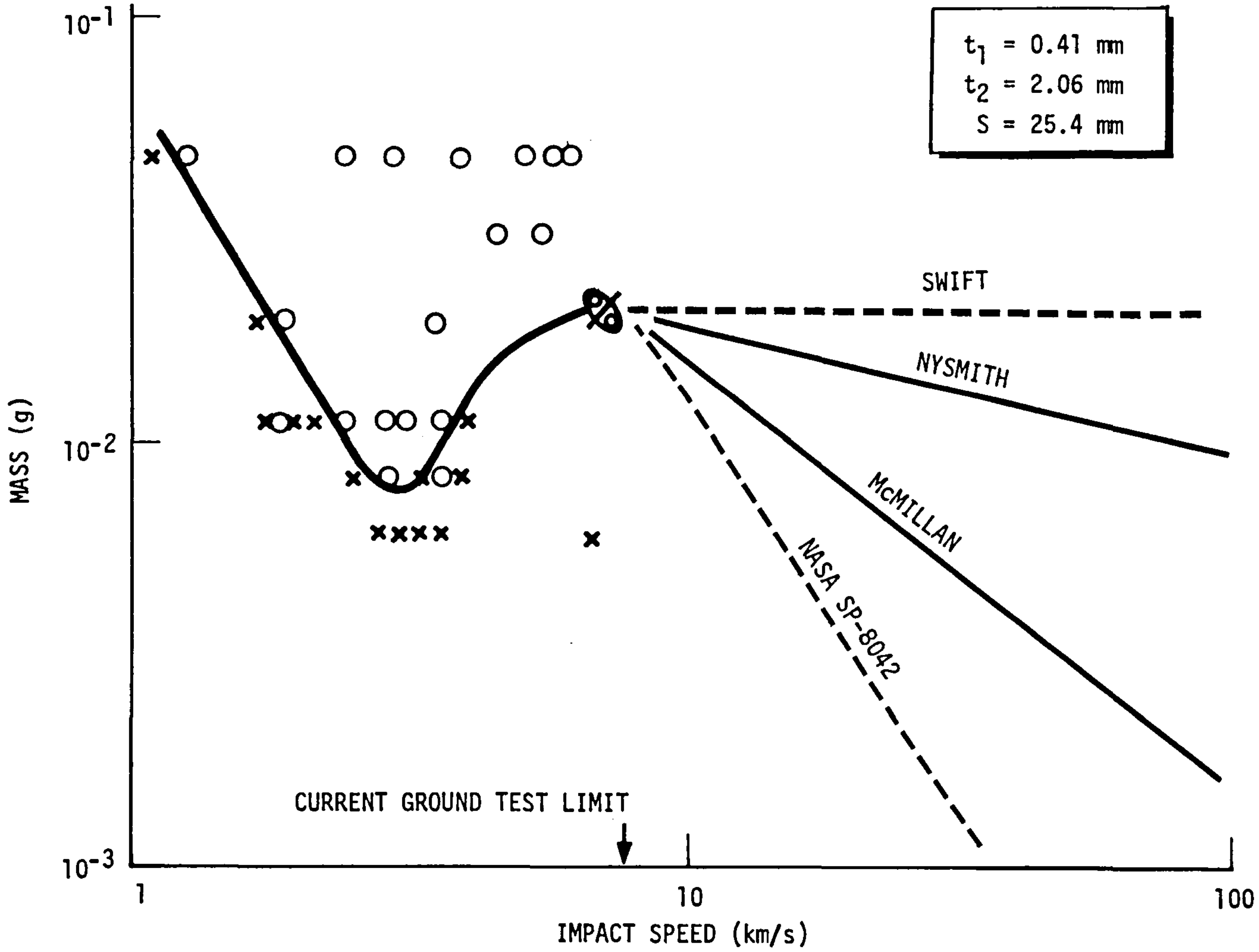


Figure 8-9 Aluminum Double Wall Structure (281)

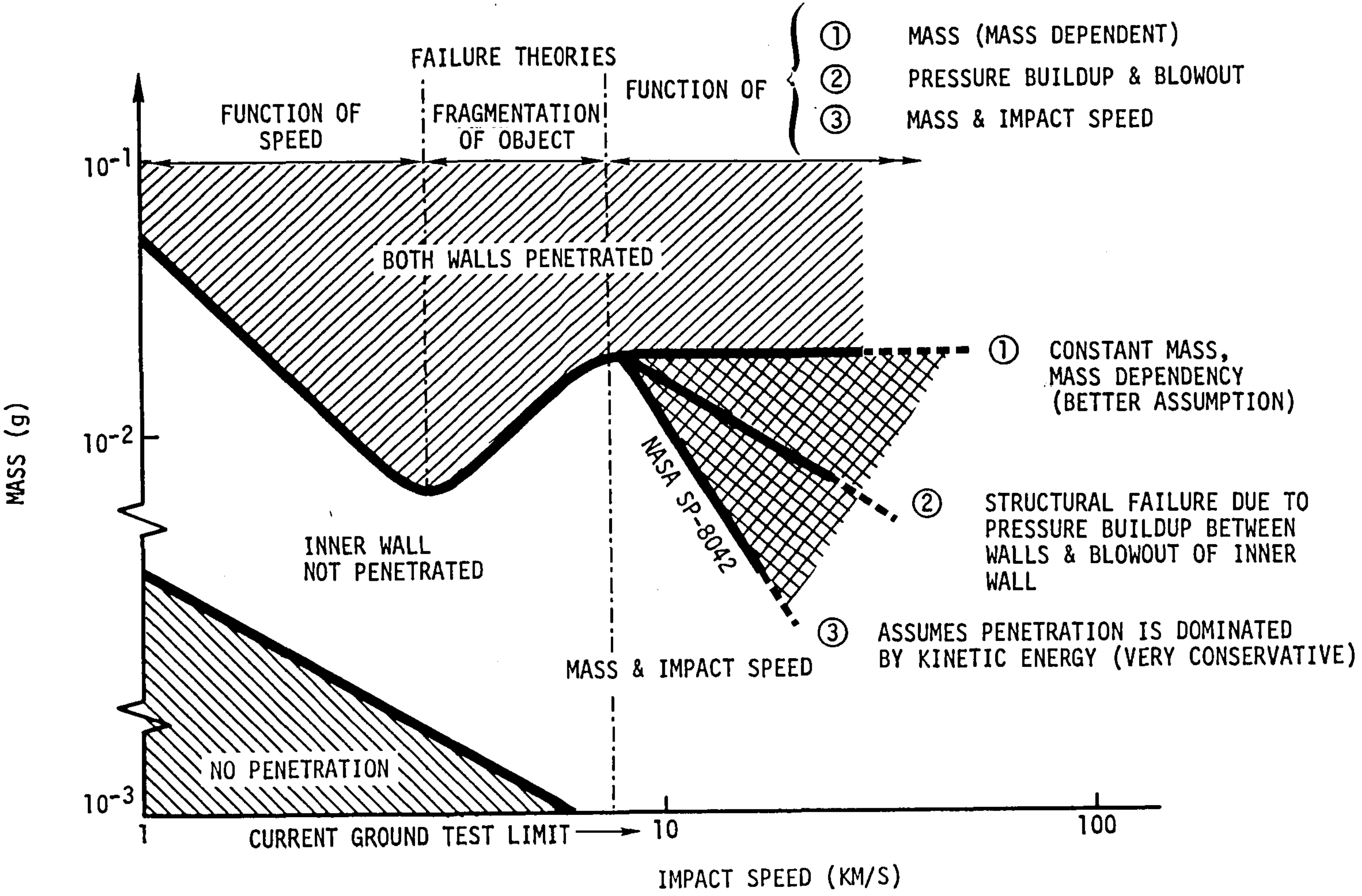


Figure 8-10 Effects of Impact Speed and Particle Mass on Double Wall Structures

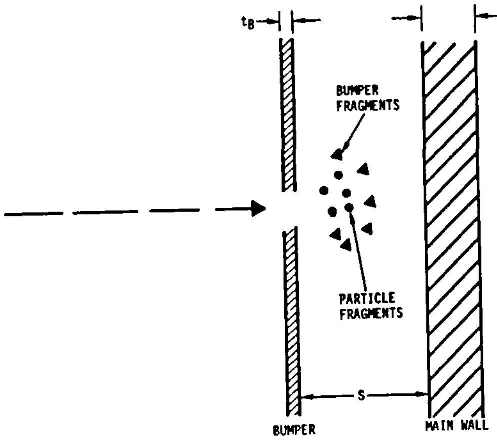


Figure 8-11 Double Wall Optimization (281)

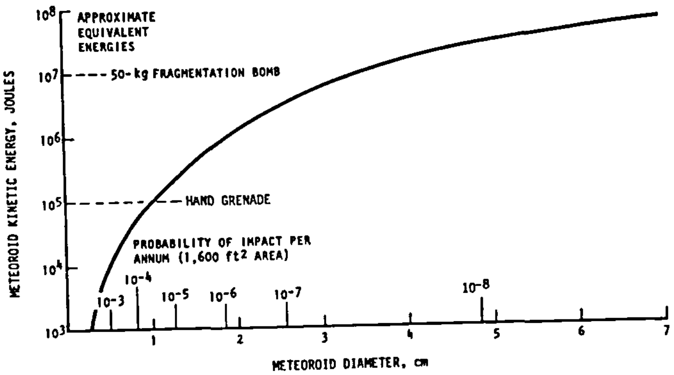


Figure 8-12 Energy and Probability of Impact of Meteoroids of Various Diameters

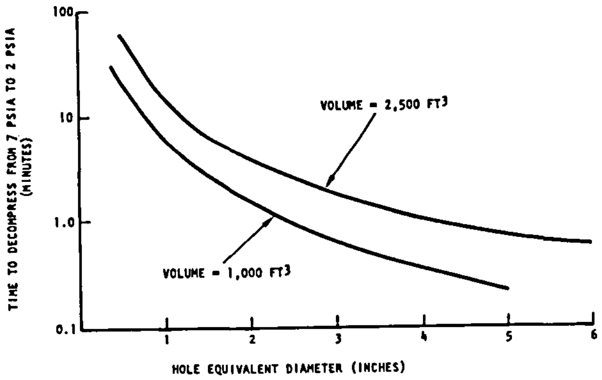


Figure 8-13 Time to Decompress from 7psia to 2psia

This safe area, or Safe Haven, may consist of certain designated modules or an isolatable part of the Space Station, which provides the required redundancy in critical systems, i.e., station attitude control, power, communications, life support systems, etc. In addition, redundancy of IVA/EVA equipment and repair tools and kits must be available in this safe area(s) to perform the required damage repairs or if the damage is too extensive, to facilitate the survival of the crew for 21 days and subsequent rescue by the Shuttle Orbiter.

Hazard Description

As stated earlier the main damage from meteoroids arises from the secondary material thrown out by the impact. Particles that do not penetrate cause spallation of the interior wall. Penetrating meteoroids 1 centimeter in diameter will perforate the hull with the same effect as a hand grenade, spewing approximately 5 cubic centimeters of molten particles into the pressurized area at velocities of 2000 fps or more. Resultant damage to electronic equipment would be irreparable, fluid lines would break, and crewmen would be injured. However, as shown in Figure 8-12, the probability of impact by this size meteoroid is very remote. The main damage control technique should be aimed at reducing the damage by meteoroids by using shields and confining potential damage to one compartment. Current structural concepts utilize minimum-gauge material in the external meteoroid protection bumper. The use of double walls (e.g., in the form of honeycomb material) in intercompartment walls and floors may be advantageous in reducing the probability of penetration of a second wall, however the particles large enough to pose a threat to these would practically destroy the module/compartment they penetrate. (028)

Time-critical decompression will result as a by-product of severe meteoroid impact or other structural damage to the spacecraft hull, as discussed in the beginning of this Section in reference to Figure 8-2, as well as in Section 6, Loss of Pressurization. As shown in Figure 8-13, a compartment of 2500 cubic feet will take approximately 4 minutes to decompress from 7 psia to a critical level with a 2-inch diameter hole, the time period when bends could be a problem. Damage containment techniques call for alternative habitable compartments within easy access of all unsuited crewmen, which can be quickly occupied and isolated by pressure-tight hatches. These hatches may normally be left open, and full controls of critical electrical and mechanical operations in designated areas must be provided for in each of the Safe Haven areas.

Collision with man-made space debris (parts of spacecraft or boosters and fragments from rocket and missile explosions still in orbit) will be discussed in Section 9.

Strategies

Strategies to minimize the hazards to the Space Station posed by meteoroids must address basic parameters, such as;

- Mission Planning
  - Orbital Altitudes

- Configuration
  - Modules
  - Solar Arrays
  - Radiators

- Protective Design Considerations
  - Double wall concept (meteoroid bumper)
  - Shrouds around service and maintenance facilities
  - Provisions to minimize and isolate damage in case of meteoroid hit

- Crew Protection
  - Safe Haven concept
  - Module isolation
  - Escape routes within Space Station
  - Interior partitions, hatches, etc.
  - EVA suits, escape balls (for crew rescue contingency) oxygen masks/equipment

- Operational Procedures
  - Limitation on number of crew members in any one module
  - Safety provisions for IVA, EVA activities
  - Safety provisions for escape and rescue

- Maintenance and Repair Considerations
  - Accessibility to main pressure shell from the inside of modules to facilitate repair of meteoroid penetrations
  - Emergency repair kits, patches
  - Availability of ORU's (Orbital Replacement Units)

- Crew Training
  - Emergency situations
  - Repair of damages

- Systems Redundancy
  - To accommodate emergency situations
  - To facilitate damage repair while maintaining station integrity and operational mode

Numerous studies have been conducted based on meteoroid environment models and meteoroid damage assessments. The meteoroid bumper experiments on Explorer 46 furnished valuable data regarding meteoroid shielding and the evaluation of subsequent test data confirmed the advantages of meteoroid bumpers and double wall construction.

The strategy options regarding meteoroid penetration can be summarized as follows:

- Environmental shield shall provide protection for a probability of 0.9 of no micrometeoroid penetration of space station modules for ten years. (021)
- Implement design, operational and procedural features to minimize and isolate damages
- Provide a meteoroid bumper or protection system which will assure an acceptably low probability of meteoroid penetration over the life of the Space Station.

9. DEBRIS

THREAT DEFINITION

The occurrence of a collision between man-made objects in orbit will be a catastrophic event for the objects directly involved in the collision, and may create hazards to other spacecraft as well. The speed at which objects will collide will be on the order of the orbital speed--roughly 8 km/s for low-Earth orbit (LEO)--making it likely that the impact will produce a very large number of new debris particles, most of them too small to be seen with ground-based detectors, and leading to an enhancement of the probability that collisions with other spacecraft will occur. If one of the colliding objects is a functioning spacecraft, the resulting damage, even from the smaller, untrackable objects, might impair, if not terminate, its operational capability. Hence on-orbit collisions will adversely affect future space operations by causing an increased likelihood of additional collisions occurring and by presenting a failure mechanism for operating spacecraft which will have to be factored into the cost of operation. (282)

The major source of the nearly 5000 objects currently observed orbiting the Earth is from rocket explosions. These explosions have almost certainly produced an even larger unobserved population. If the current trend continues, collisions between orbiting fragments and other space objects could be frequent. By the year 2000, satellite fragmentation by hypervelocity collisions could become the major source of Earth-orbiting objects, resulting in a self-propagating debris belt. The flux within this belt could exceed the meteoroid flux, affecting future spacecraft design. (283)

In space, stray orbital objects can be dangerous. The enormous speeds of orbiting bodies make a collision with even the tiniest of them being potentially catastrophic. According to NASA astrophysicist Donald Kessler, at Houston's Johnson Space Center, the impact velocity between 2 orbiting objects in the vicinity of earth would average 22,000 miles per hour. If each weighted just 1 pound, their collision could release as much energy as the detonation of 20 pounds of TNT. (179)

NORAD radars can track objects as small as baseballs, but fragments smaller than garden peas can damage an artifical satellite. The number of potentially destructive objects is estimated at 15,000 or more.

The most likely region for space collisions is 460 nautical miles above the equator, which objects in earth orbit must cross twice on each trip around. (179)

Debris consists of spent spacecraft, spent rocket stages, separation devices, shrouds, clamps, etc. and products of deliberate or accidental explosions. Because of the number of particles they produce, the latter accounts for the majority of space debris. There are three main areas of concern: the tracked population of debris objects, the untracked population, and the future population.

The Tracked Population

At present, the North American Aerospace Defense Command (NORAD) in Colorado is tracking more than 5,000 objects in orbit. Most are larger than 10 cm in diameter. Over the last ten years this population has grown at a rate of 10 percent per year. The greatest concentration of objects is at altitudes between 500 and 1,100 km, the maximum being at 850 km. The probability of collision for the Shuttle Orbiter with one of these objects has been calculated as only 4 x 10^{-6} for a typical seven day flight. Large space stations and platforms of the future, however, will be in increasing danger from space debris unless its proliferation is halted.

The Untracked Population

These are mainly the smaller particles which are known to exist, especially those resulting from explosions. Terrestrial tests in which particle distributions from explosions have been studied show that it is reasonable to infer the presence of some 10,000 small particles for every low-intensity explosion and up to 10 million for high-intensity events.

The Future Population

If past trends continue, the number of tracked objects in space is predicted to increase by a factor of two to eight (depending on the rate of future explosions) within the next 20 years. In addition, there is the possibility of collisions between particles to produce additional fragments. (199)

Figure 9-1 illustrates the hazard levels presented by debris currently being tracked. On the horizontal axis is a measurement in sq. m. of the surface area exposed to possible collision (rising from small unmanned payloads on the left to the large space structures proposed for the 1990's on the right, with 10,000 sq. m. and more surface area). The vertical axis shows the expected time in years between collisions; the sloping lines are numbered to indicate the risks at different orbital altitudes. (199)

Figure 9-2 plots the observed object density vs. altitude. The peak density levels are from 600 to 1100 km altitude and again in the 1500 km altitude region. It should be noted, however, that the objects are assumed to be uniformly distributed in spherical shells without regard to inclination angle effects. (199)

D. J. Kessler of NASA, JSC addressed the projected environment and plotted the 1995 predicted debris in his AIAA paper 80-0855R (283), which is covered in the following under the heading "Discussion". Reference is specifically made to Figure 9-7 therein and the related discussion portion. Another figure was presented by D. J. Kessler at the JSC debris workshop in November 1983, which shows the 1995 predicted debris for different altitudes. This figure is covered in Section 8.0, under Figure 8-7 (281) together with a selected text portion.

This cluttering of space with debris raises issues of collision - hazard assessment, control techniques, and spacecraft survivability.

Collision Probability in Low and Geosynchronous Orbits

The probability of collision between a given spacecraft and another object in orbit is a complicated function of the orbital parameters, relative position and velocity, projected areas of the spacecraft and time. The complexity results primarily because of the time-varying encounter geometry caused by Earth's oblateness, air drag, and solar-lunar perturbations. An approximate expression for the probability of collision based on the assumption of uniform distribution of objects in a specified region of space takes this form: $p(col) = \rho A v \Delta t$ where ρ=density, A=target satellite projected area, v=target-satellite relative velocity, and Δt=time interval.

Applying this approach gives the following 1000-day-mission collision hazard for representative spacecraft of 10- and 50-m radius in low Earth orbit. The 1980 range of values represents the uncertainty in the density of the debris objects. The multiplying factor for the 1985 and 1995 periods reflects the greater numbers of objects expected. (138)

S/c size	1980 (4000 obj)	1985 (10,000 obj)	1995 (30,000 obj)
10-m radius	1.5×10^{-3} to 3×10^{-3}	2.5[a]	7.3[a]
50-m radius	4×10^{-2} to 8×10^{-2}	2.5[a]	7.3[a]

a - multiplying factor for 1980 results.

Table 9-1. 1000-Day Mission Collision Hazard (138)

The probability of collision by 1995 for a 50-m radius spacecraft in a 1000-day circular-orbit, low-altitude (500-1500-km) mission could be on the order of 50 percent. This would clearly be unacceptable. (138)

Figure 9-3 illustrates the current 1000-day geosynchronous-orbit probability of collision for a representative small spacecraft based on the sample of 133 tracked objects. The collision hazard is several orders of magnitude smaller than at low altitude primarily because of much lower encounter velocities (50 m/sec vs. 7 km/sec, typically). It may not be negligible, however, particularly for larger spacecraft with respect to small objects (e.g., explosion fragments of less than a square meter in cross section). The population of the latter, and hence the collision hazard, may be as much as an order of magnitude greater. (138)

Time Between Collisions (yrs) of Current Population of Tracked Objects vs. Collision Cross-Section (meters^2)

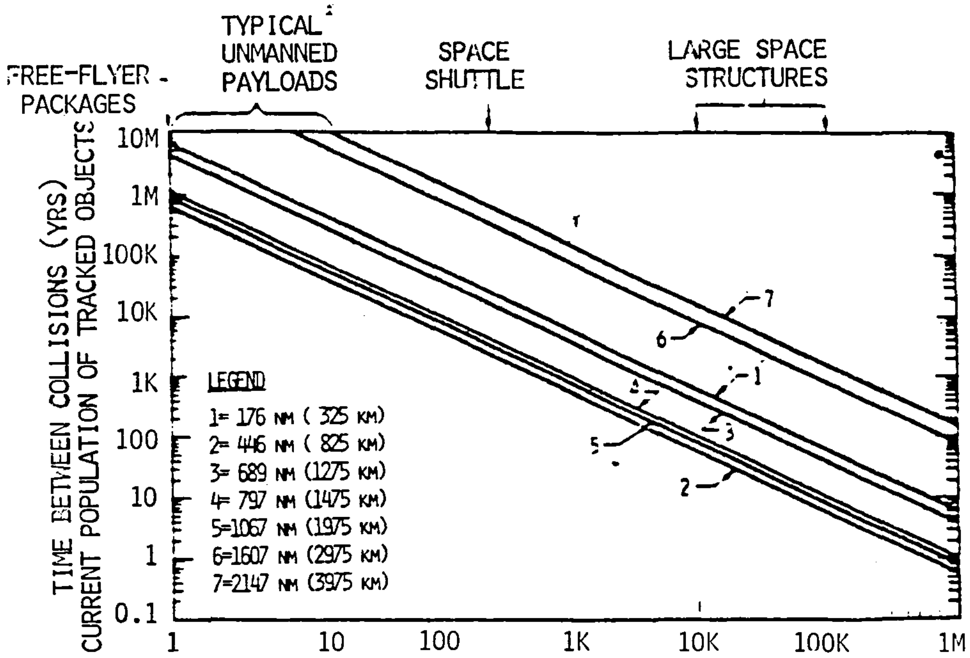
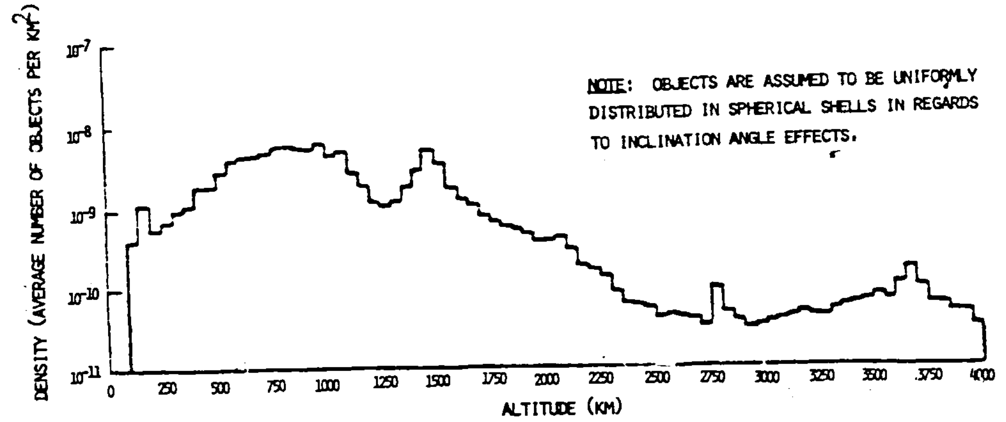


Figure 9-1 (199)

Observed Object Density vs. Altitude



NOTE: OBJECTS ARE ASSUMED TO BE UNIFORMLY DISTRIBUTED IN SPHERICAL SHELLS IN REGARDS TO INCLINATION ANGLE EFFECTS.

Figure 9-2 (199)

DISCUSSION

General

Numerous literature sources cover the aspects of Orbital Debris, its sources, density in relation to orbital altitude and inclination, and the associated hazards to space vehicles. Whereas different methods have been used to predict the orbital debris environment model, resulting in slightly varying data, graphs and tabular values, the general parameters are in agreement and the conclusions reached are basically the same.

In order to preserve the continuity in this discussion and agreement between the text and the incorporated figures and tables the following excerpts under the heading "DISCUSSION" were taken from the two source documents as follows:

- Source Document by D. J. Kessler, NASA JSC, Houston, Texas (283)
- Source Document by R. C. Reynolds, N. H. Fisher, and E. E. Rice, Battelle's Columbus Laboratories, Columbus, Ohio (282)

Source Document by D. J. Kessler, NASA Johnson Space Center, Houston, Texas (283)

AIAA 80-0855R, Sources of Orbital Debris and the Projected Environment for Future Spacecraft, by D. J. Kessler

Presented as Paper 80-0855 at the A.I.A.A. International Meeting a Technical Display "Global Technology 2000," Baltimore, Md., May 6-8, 1980; submitted July 10, 1980; revision received Oct, 24, 1980. This paper is declared a work of the U.S. Government and therefore is in the public domain.

Reprinted from JOURNAL OF SPACECRAFT AND ROCKETS Volume 18, Number 4, July-August 1981, Page 357. This paper is declared a work of the U.S. Government and therefore is in the public domain. (283)

Background

The hazards from orbital debris were first examined in 1966 for the Apollo program, and in 1970 for Skylab and possible future programs. (381) The probabilities at that time were sufficiently low enough that no action was taken, although the larger collision probabilities for structures 100 m in diameter did produce some concern. Later, Brooks et.al. (382) demonstrated that the observed population was increasing in number, and that an even larger number of untracked objects should be expected from the explosions that have occurred in space. In 1978, Kessler and Cour-Palais (383) predicted that within the next 10 to 20 years, the space object population could become "self-regenerative" through fragments generated by collisions between satellite fragments and old payloads and rocket motors. At that time, the orbiting debris population would constitute a larger hazard than the natural meteoroid hazard for certain types of missions.

In order to minimize this hazard, it is important to understand orbital debris and its self-regenerative quality, with the goal of either protecting against or controlling the future environment. This discussion will update the environment as it is known today, identify its sources, and present data predicting a current untracked population. A future environment will be predicted. The damage to future spacecraft from the environment and the sensitivity of the environment to controls are identified as areas of future work. (283)

Observed Population

As of December 31, 1979, 11,665 objects had been offically "launched" into space. (384) Of these, 4549 were still in orbit. Another 170 objects had been detected by NORAD but were still awaiting official status. (385) The probability of a particular spacecraft colliding with any of these 4719 orbiting objects is a function of that spacecraft's orbital position and velocity. However, for most types of orbits, the probability is mainly (within a factor of 2) a function of spacecraft altitude--the major exception being for spacecraft in orbits of inclinations between 100 and 130 deg where the probability can be several times the average for that altitude. (382) Average probabilities were calculated from a 4 percent random sample of satellites in the October 78 catalogue. (387) A 4 percent sample was chosen because it was small enough to both allow for the necessary computer requirements and the identification of sources of each object, yet large enough, at most altitudes, to be statistically significant. However, the number of objects at altitudes less than 450 km was sufficiently low enough that the sample was gradually increased with decreasing altitudes. All objects below 200 km were used. The resulting flux on 1-m^2 cross-sectional area is shown in Figure 9-4. The average collision velocity was found to be 10 km/s. Note that a hypothetical space station having a 100-m diameter and 500-km altitude would experience a collision rate of about 0.005/yr. Allowing for population growth and an orbital lifetime of 10 years, the probability of collision would approach 0.1. Thus, for structures of this size and larger and altitudes between 400 km and 2000 km, collision probabilities with the observed population are high. Smaller structures at lower altitudes have significantly less of a collision probability with the observed population. (283)

Sources of the Observed Population

The source of each satellite used in the 4 percent random sample was researched using the TRW Space Log (390) and the Satellite Situation Report (391). The result of this research is shown in Table 9-2. Note that 95 percent of the tracked population is nonfunctioning and hence orbital debris. The largest single source of this debris is from explosion, with most coming from 11 accidental U.S. explosions. Some of these rockets were presumably dead in space for as long as 3 years before exploding. An engineering problem obviously existed within some of these rockets, which allows the proper functioning of the rocket, but causes the spent stage to become a "time bomb" in space. Once such problems are identified, engineering fixes would do more than any other single action toward limiting the observed population. Since 1972, the only U.S. explosions have come from the Delta rockets. Steps have recently been taken to stop these explosions.

The relatively small number of observed fragments generated by the eight USSR antisatellite tests may be misleading. High-intensity explosions produce a very large number of small, unobservable fragments (392). Thus, their contribution to the total debris picture could be much larger.

Since all explosions produce a certain number of small fragments, one would expect an orbiting population too small to be detected by ground radar. Recent test results and analysis indicate that this population may be larger than the observed population. (283)

Collision Probability in 1000 Days

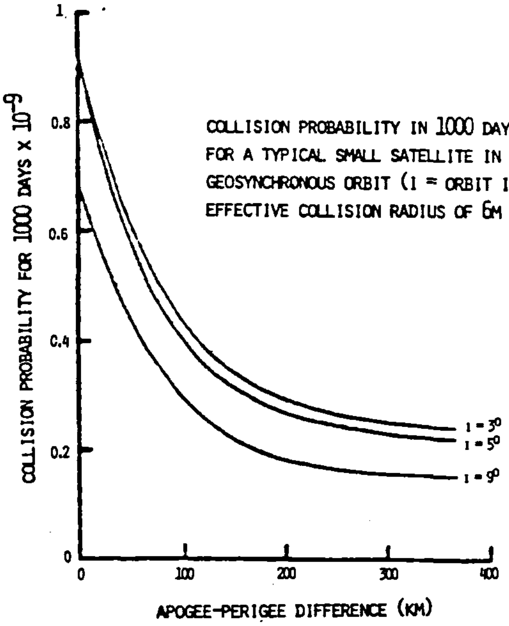


Figure 9-3 (138)

Observed Debris Flux as a Cross-Sectional Area (138)

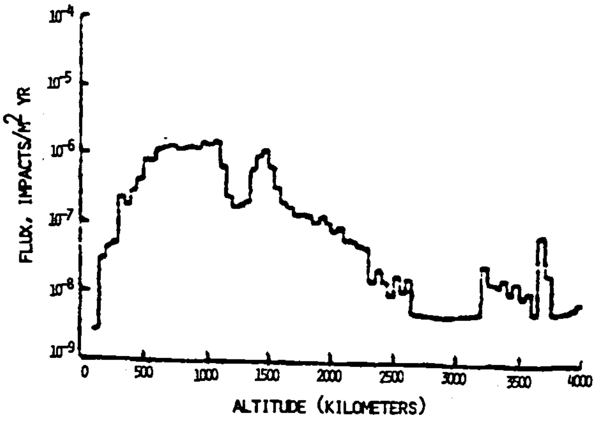


Figure 9-4 (283)

Unobserved Population

In general, NORAD's operational system does not track objects smaller than about 10cm at 1000 km, or 4 cm at 400 km. During a special test conducted by NORAD in 1978, this sensitivity was increased slightly. The results of the test revealed an unobserved population that was between 7 percent and 14 percent of the observed population, However, a much larger percentage of previously unobserved objects was found below 400 km. Most of these objects had sizes smaller than 4 cm. Due to atmospheric drag, orbital lifetimes for objects this low and small are very short--some as short as a few hours. The obvious source of these objects is from higher altitudes where they were too small to be observed either by this test or the operational system. A similar test in 1976 produced similar results. (393) Thus, a sufficient reservoir of small, untrackable objects at a higher altitude must exist to produce a continuous flow of objects "raining down" through lower altitudes because of atmospheric drag. The size of this reservoir could be determined from the turnover rate at lower altitudes, if the altitude of the reservoir were known. For example, the time an object in circular orbit spends at various altitudes as it descends is inversely proportional to the atmospheric density at that altitude. Thus a reservoir about 450 km would require the population at 450 km to be a factor of 2 larger than the population at 400 km. A reservoir above 600 km requires a population at 600 km that is 40 times the population at 400 km. Of course, the reservoir is actually distributed in altitude and a more complex approach is required to obtain the unobserved population number. Such an approach requires developing a time-dependent model that describes the explosion fragments. The model is then refined by testing it against the NORAD test and other observations. Such a model is currently being developed.

A quicker, though less accurate, technique to determine part of the unobserved population is to examine the size distribution as a function of altitude. If the source size distribution is independent of altitude, then the normalized distributions observed at each altitude should be identical, except for the effects of atmospheric drag at lower altitudes. Drag changes the shape of the size distribution, with smaller objects removed more rapidly.

As noted in Table 9-2 the primary source of fragments is the low-intensity explosions of U.S. rockets, primarily the 2nd stage of the Delta. If these explosions were simulated on the ground, they would provide significant insight into the actual distribution of orbiting debris. However, the only similar data available are from the low-intensity ground explosion of an Atlas missile, which produced 1337 fragments. (392) These data were tested for consistency to represent the source size distribution. (283)

The size distribution of fragments from the Atlas missile test was compared with the orbiting size distribution of fragments. Between 600 and 700 km, the two distributions (normalized to the number of larger objects in each sample) were very much alike for sizes larger than 20 cm. Below this size, the number of objects produced from the Atlas explosion begins to exceed the number of objects observed. Between 1000 and 1100 km, the two normalized distributions were alike for sizes larger than 40 cm, again with the Atlas data exceeding the number of smaller objects observed. If atmospheric drag were responsible for removing a significant number of observed objects at these altitudes, then the minimum size in which the Atlas data fit the observed fragment population should decrease with altitude. The observed increase in the minimum size is consistent with the loss in ability of the NORAD radars to detect objects at higher altitudes.

TABLE 9-2 SOURCES OF IN-ORBIT POPULATION TRACKED BY NORAD

SPACE OBJECT	PERCENTAGE OF TRACKED POPULATION IN ORBIT %	NOTES
Operational Payloads	5	Distributions are roughly equally divided between USSR and U.S.
Nonoperational payloads	12	
Mission related (rocket bodies, shrouds, etc.)	18	
Explosion fragments	54	6 Delta Stages 20% 3 Agenas 12% U.S. 42% 2 Other 10% 8 USSR satellite tests 12%
To be determined origin	11	While a certain fraction of these may prove to be nonexistens, most are probably explosion fragments. Many will reenter before they become part of the official catalogue. Some are in geosynchronous orbit, possible refound objects whose orbits are no longer maintained.

In the altitude range between 300 and 450 km, objects as small as 4 cm are detected; however, the size distribution is controlled by atmospheric drag. The rate in which objects drag through this region is inversely proportional to the particle diameter, assuming a constant mass density. Thus, the Atlas size distribution was weighted by the fragment diameter, normalized, and compared to the normalized size distribution of fragments in this altitude range. The two distributions were very much alike, implying that most of the 4-cm fragments may be detected at this altitude.

Thus, to assume that the Atlas missile data represent the source size distribution of fragments in space to 4 cm is consistent with the observations. Figure 9-5 compares the observed debris flux in the 600-1100 km region with the corrected debris flux using the Atlas missile data. Note that the orbital debris flux is already much greater than the flux of comparable size meteoroids. Note also that the corrected flux to 4 cm is about a factor of 3 larger than the observed flux. Since the NORAD radars apparently cannot consistently detect objects smaller than 4 cm at any altitude, any attempt to estimate their number becomes highly uncertain. The Atlas data above indicates that a significant number of these particles exist; however, other sources, such as high-intensity explosions or collisional fragmentation could produce a much larger number.

From this analysis, it is obvious that the flux shown in Figure 9-4 results from smaller objects at lower altitudes, while these same size fragments go undetected at higher altitudes. The number of these fragments was estimated by assuming that the Atlas missile data represent the true size distribution of fragments to 4 cm. The ratio of the 4-cm flux to the observed flux was then determined for various altitude bands by using the techniques previously discussed and illustrated in Figure 9-5. This ratio was then plotted as a function of altitude, curve-fitted to remove statistical fluctuations, then multiplied by the fluxes given in Figure 9-4. The results are shown in Figure 9-6. Note that the unobserved population increases over the observed population with increasing altitudes, becoming a factor of 10 above the observed population at 3000 km. (283)

Projected Environment

Whereas the current major source of orbital debris is from explosion fragments, the future major source will probably be fragmentation through collisions. Using the corrected distribution shown in Figure 9-6 and the associated distributions of size, velocity, and latitude dependence, the probability that any two objects will collide was calculated in an identical manner as the 1976 observed population. (396) The probability obtained was 0.06/yr, or 1 collision every 17 years. This compares to 0.013/yr obtained in 1976, with the increases resulting from adding the unobserved population (factor of 3) and the 1978 increases in number and area (factor of 1.5). Within the next 20 years, if current trends continue, the number of objects in space will easily double, possibly quadruple. Since the probability that any two objects will collide is proportional to the square of the number of objects, the collision frequency by 1998 would be between 0.24/yr and 1/yr.

This new potential source of fragments is important because of the larger number of fragments that are generated in typical hypervelocity collisions. Based on the current "corrected to 4 cm" population, a typical collision would involve a fragment between 4 and 40 cm in diameter colliding at 10 km/s with a payload or rocket body of approximately 3-4 m in diameter, Observed Flux Corrected to 4cm Limiting Size

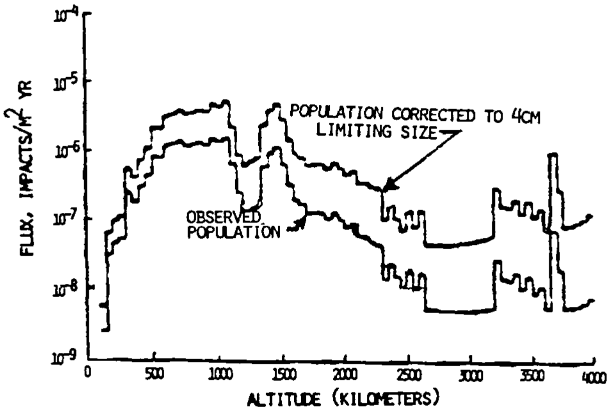


Figure 9-6 (283)

Cumulative flux in 1995 between 600 & 1100 km Altitude

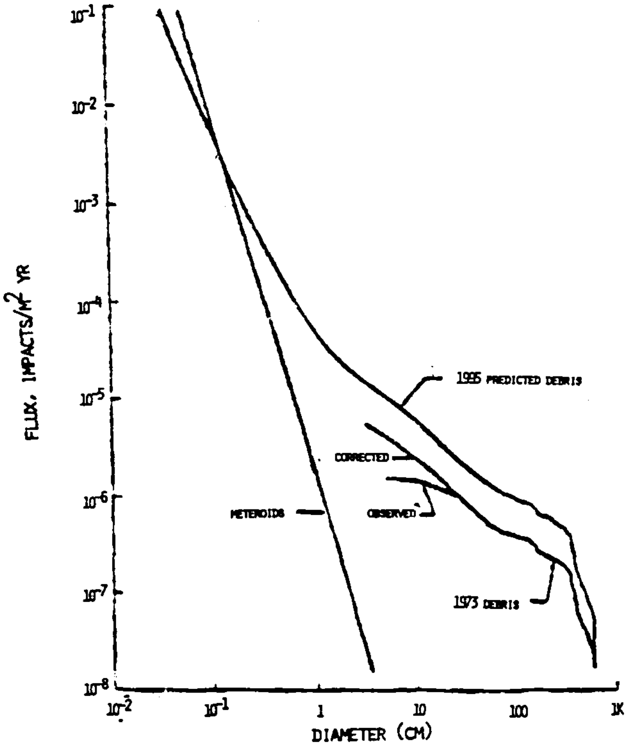


Figure 9-7 (2S3)

producing an average of 300 kg of ejected mass. Such a collision would produce 1.4 x 10^4 particles larger than 1 cm and 3.5 x 10^6 particles larger than 1 mm^3. Figure 9-7 predicts a future debris flux where the current population is increased by a factor of 2.5, and 3 collisions have occured. If the past trend of the satellite population increasing at the rate of between 300 and 500 objects per year (396) continues, this could be representative of approximately the year 1995. Note that collision products would dominate the projected environment for sizes smaller than 4 cm, causing the flux from orbital debris to exceed the meteoroid flux over most sizes of interest for both manned and unmanned activities in the 600 to 1100-km region of space. (283)

Conclusions

If current trends continue, the orbital debris population will become self-regenerative through collisions. The resulting environmental hazard of other spacecraft may exceed the hazard from the natural meteoroid environment, depending on the type of spacecraft and its position in space. Although the hazard may be reduced by the addition of shielding to some spacecraft, control of the environment may be necessary for others. Control techniques are known, although their necessity and relative effectiveness are not well understood. (283)

Source Document by Robert C. Reynolds, Norman H. Fisher, and Eric E. Rice, Battelle's Columbus Laboratories, Columbus, Ohio (282)

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Man-Made Debris in Low Earth Orbit - A Threat to Future Space Operations.

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This paper represents a refined method, a more sophisiticated approach to the calculations of Space Debris hazard levels. The following excerpts, figures and tables are quoted from the above reference. (282)

Man-made debris in orbit represents a potentially serious threat to satellites residing in low-Earth orbit, a threat which may become sufficiently large to serve as an operatonal constraint. Previous work has focused on presenting the hazard as a function of altitude. In this paper, a path integral formulation for calculating hazard levels is presented. This formulation enables specific spacecraft orbits and debris deposited in specific orbits to be considered in determining hazard levels. Two cases are presented: for the Space Shuttle in 160 nm (300 km) orbit and for spacecraft in sun-synchronous orbit. The previous work is found to be in good agreement with the path integral results. The sensitivity of the hazard to spacecraft orbital inclination is presented in tabular form. (282)

In this paper, a model is presented which can be used to calculate collision hazard levels based on a knowledge of the set of orbital parameters for a debris population. The model is similar to the model first presented by Kessler and Cour-Palais (383) and discussed further in a series of papers by Kessler. A conceptual difference from the Kessler model is the use of path integral formulation for calculating collision probabilities; a significant sophistication in this model involves the inclusion of the debris population velocity distribution function in the probability calculations. These features allow collision hazard levels to be calculated for specific orbital planes and for debris deposited into specific orbital planes, the latter an important capability for analyzing the hazard increase introduced by a specific debris deposition event.

The discussion is divided into two parts. The first part is an assessment of the current hazard levels, with a discussion of the problems associated with controlling future hazard levels. The hazard model used in this part of the discussion employs the traditional approach of using particle density as a function of altitude. In the second part, a path integral formulation for calculating collision probabilities is introduced. This formulation takes into account the velocity distribution of the debris population as a function of position and is suitable for developing models for hazard minimization and for calculating the contribution to the hazard level introduced by the deposition of debris in specific orbits. A comparison of results of the two formulations verifies their essential compatability. (282)

Debris Hazard for the Shuttle Orbiter

The Orbiter will nominally operate in a circular orbit with an altitude of approximately 300 km. Because it is so much larger than the objects comprising the debris population, the Orbiter's mean cross-sectional area can be used to define the collision cross section. The cross-sectional area nose-on is approximately 50 m^2, while the area in the plane of the wings is approximately 500 m^2. A mean cross-sectional area of 250 m^2 was used in performing the collision calculations. As stated earlier, the assumed independence of debris size and the use of a mean cross-sectional area for collision cross section serve to introduce some uncertainty into the calculations.

Given the orbital altitude and collision cross section, the collision hazard as a function of orbit inclination can be computed. The results are presented in Table 9-3 in the form of time between collisions. The debris populations are 1) the objects contained in the October, 1976 Satellite Situation Report ("Present Population") 2) the October, 1976 population corrected for unobserved particles, using Kessler's correction factors (283) and 3) the October, 1976 population, corrected for unobserved particles and augmented by a 5 percent annual growth rate for 20 years. The corresponding quantities for the latitude-averaged debris values, assuming a relative speed of 7 km/s, are also shown.

The large values for the times between collisions contained in Table 9-3 indicate that man-made debris of size 4 cm and larger will not present a significant hazard to the Shuttle Orbiter. In fact, the times are large compared to times for collisions involving the Orbiter with a meteoroid of sufficient mass to severely damage a TPS tile, as shown in Table 9-4. These times are based on the meteoroid population model of Cour-Palais. (394) The sensitivity of the LEO environment to man-made debris deposition is clearly illustrated by comparing the meteoroid population particle densities with fragment producing operations, such as antisatellite tests, which migh occur on orbit. At any time there are about 100 kg of meteoroid material of mass greater than 0.01 g in the volume of space up to 4000 km altitude. Therefore, a single incident which explosively fragmented 100 kg of material into the same mass distribution as displayed by the meteoroids would, if these fragments were dispersed uniformly up to 4000 km altitude, match the meteoroid debris levels.

The problem of preferential deposition of debris into the Orbiter environment, as would occur if an explosion occurred on a stage still in the low-Earth parking orbit or if debris was routinely deposited during normal Shuttle operations, can also be examined using the path integral formulation.

TABLE 9-3 TIMES BETWEEN COLLISIONS (YRS) BETWEEN SHUTTLE ORBITER AND MAN-MADE DEBRIS (ALTITUDE 300 KM)

Shuttle Orbit inclination deg.	Present Population of tracked particles	Present population of tracked particles corrected for unobserved particles to size 4 cm	Corrected population with annual growth for 20 years
28.5[a]	2.7×10^4	1.4×10^4	4.6×10^3
56	2.0×10^4	1.0×10^4	3.3×10^3
82	1.6×10^4	8.0×10^3	2.7×10^3
90	1.5×10^4	7.5×10^3	2.5×10^3
98	1.4×10^4	7.0×10^3	2.3×10^3
Latitude averaged[b] debris properties	2.5×10^4	1.3×10^4	4.3×10^3

[a] Path integral formulation

[b] Results based on analysis equivalent to those used in Ref. 1

TABLE 9-4 TIME BETWEEN COLLISIONS (YRS) BETWEEN SHUTTLE AND A MEREOROID OF MASS GREATER THAN A GIVEN MINIMUM MASS (283)

Minimum meteoroid mass g	Times between collisions, yr.
10	350,000
1	25,000
0.1	1,800
0.01	130

Time between collisions between the Shuttle and a meteoroid of mass greater than a given minimum mass

One of the conslusions of Reynolds and Fischer (395) was that observations of fragments resulting from explosions of Delta second stages were consistent with the production of about 500 debris fragments. If such an explosion occurred at the Shuttle parking orbit altitude, the debris deposited from a 28.5-deg orbit would lead to a time between collisions of about 600 years. This result assumes the particles have relaxed to having a random distribution in right ascension of ascending node and in argument of perigee. While the motions are correlated, the hazard level is higher. The relaxation time for the transition of correlated to uncorrelated motion is on the order of a year. A model to calculate collision probabilities while correlated motion exists is being developed. This collision time is based upon a fixed increase in deris and does not consider debris decay. (282)

Debris Hazard as a Function of Altitude

The reduction to simple altitude dependence from distributions defined on the two-dimensional grid is quite simple.

The significance of debris densities is best appreciated by translating them into collision frequencies.

Since the data contributing to Figures 9-8 and 9-9 come only from objects being tracked by NORAD, a correction should be made for objects not being tracked, most of which are those too small to be seen by NORAD detectors. The minimum size of an object which is detectable by NORAD is 4 cm at lowest altitudes and increases with altitude. (283) Since this size is much larger than that required to cause extensive damage in collision with a spacecraft, there is a potential segment of the debris population which represents a hazard but which cannot be seen.

The contribution of unobserved debris to the collision hazard represents the major uncertainty in current collision hazard assessments. Kessler[5] has proposed a correction factor to account for this debris. If this correction is included, the times between collision shown in Figure 9-9 are reduced to those shown in Figure 9-10. Clearly, future programs will introduce systems/structures large enough to collide frequently with man-made debris, a conclusion which may indicate there will be severe constraints on the use of LEO space in the future.

The results shown in Figure 9-9 allow an estimation of the frequency of debris-debris collisions for the current tracked population. Accepting a mean collision cross section of 5 m^2 for these objects, the time between collisions as experienced by a given object will be about 200,000 years. The mean time between collisions involving any two objects will be this time divided by the number of objects in the population, which is about 5000. Therefore the expected rate of collisions between objects in LEO large enough to be tracked is about one collision every 50-100 years if the present population level is maintained. (282)

Debris Hazard for Sun-Synchronous Payloads

A greater debris hazard might be expected for sun-synchronous spacecraft than for the Shuttle because lifetime and stationkeeping requirements for such payloads favor placement at higher altitude, in the range of from 600 to 1200 km, where debris densities are largest. However, the increase in debris density, as shown in Figure 9-8 is compensated for by the characteristically smaller size of sun-synchronous spacecraft, as shown in Figure 9-9. The net effect is that the hazard level to sun-synchronous spacecraft, at least of the type presently in use, is nearly the same as for the Orbiter.

Because the sun-synchronous payloads must reside in retrograde orbits, the speed of the spacecraft relative to the debris should be larger than 7 km/s, the speed assumed in generating Figures 9-9 and 9-10. Table 9-5 presents a set of collision times for the October, 1976 population of tracked debris, smoothed over latitude and assuming V=7 km/s, and for the spacecraft in a sun-synchronous orbit using a path integral formulation with the same debris populations used to generate Table 9-3. A collision cross section of 5 m^2 was used.

The elevation of the hazard level from debris augmentation by explosion of a Delta second stage in sun-synchronous orbit is less pronounced for sun-synchronous spacecraft than it was for the Orbiter at 300 km because the debris density is already so much higher at the sun-synchronous orbit altitudes. If the explosion produced 500 particles, the time between collisions involving one of these particles and a sun-synchronous spacecraft would be about 50,000 years. (282)

Density of Tracked Debris Objects For the
October 1976 Debris Population

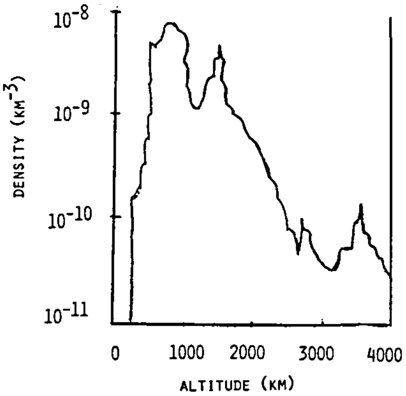

Figure 9-8 (282)

Expected Time Between Collisions
October 1976

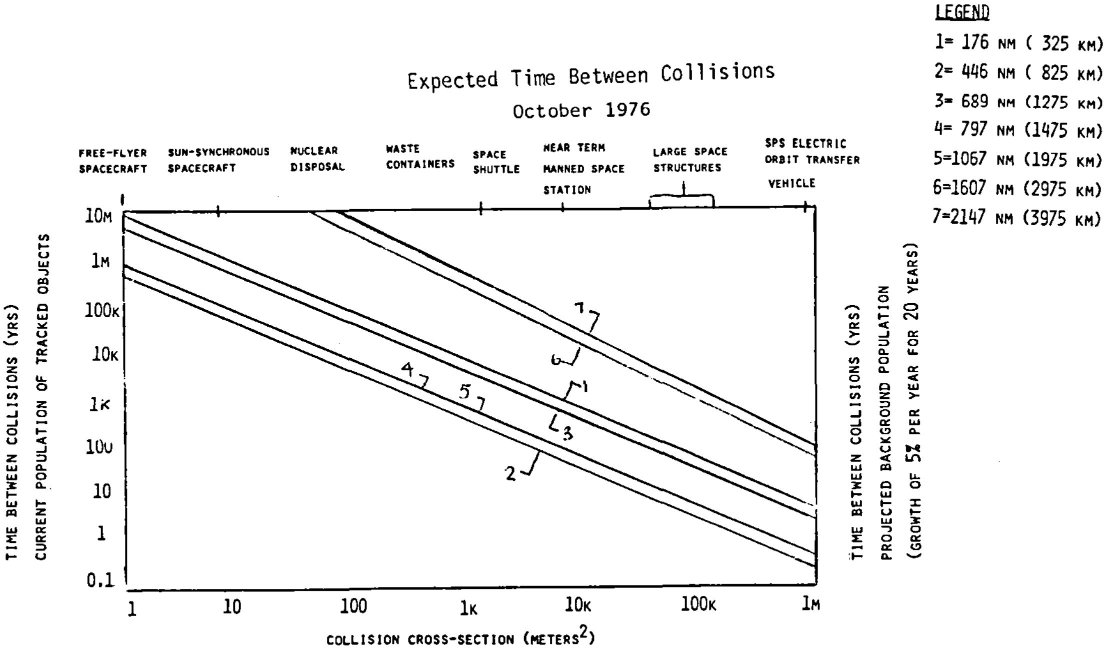

Figure 9-9 (282)

Conclusions

The problem of man-made debris on orbit has a varied character, depending on the size of the objects on orbit, on the operating altitude, and on the length of time it remains on orbit. The debris population will certainly be sufficiently large enough that collisions will occur on some of the larger structures being considered for use in future programs. The effect of such collisions on the operation of the spacecraft, the implications which the deposition of the resultant debris has on the evolution of the debris population, and its effect on space operations must be understood before such events begin to occur. If not, it is conceivable that a debris population will be created which will make the near-Earth environment unusable for any extensive space program. If this occurs there will be very little that can be done except to wait for atmospheric drag to clean out the lower-altitude regions.

The use of a path integral formalism for the calculation of collision hazard levels allows more information on the properties of the debris population to be used than can be accommodated with a latitude-averaged model. It is well suited to analyzing the effect of debris augmentation from a specific event. Collision times calculated with the path integral formalism are generally shorter (Table 9-3, indicating a collision is more likely to occur than is shown by an analysis using a smoothed population with relative velocity 7 km/s).

The hazard presented to spacecraft as large as the Space Shuttle it seen to be small, as long as they operate at low altitude. Much smaller spacecraft can operate with little danger even in the regions of maximum debris density, as can be seen for the sun-synchronous spacecraft. These conclusions would remain valid even if a significant (greater than a factor of 10) increase in the spatial densities of debris should occur.

However, for large structures in space, such a comfortable margin is not available. Large astronomical instruments, space stations, or large vehicles such as the SPS Electric Orbit Transfer Vehicle would have to be flown assuming a considerable risk that collision with man-made debris would occur. Increases in the population size in the future will only serve to make that risk greater. (282)

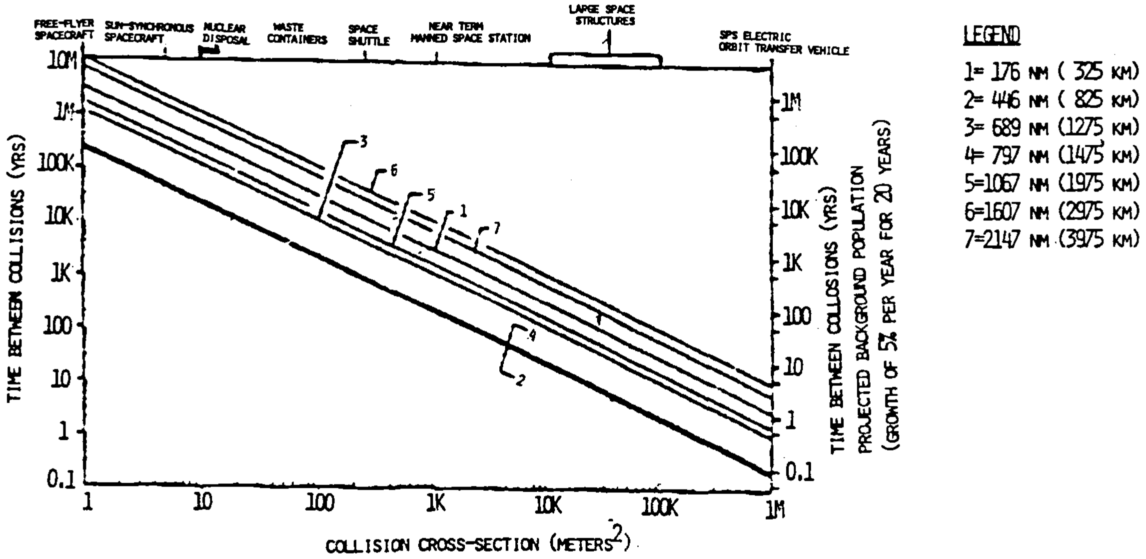

Figure 9-10 Expected Time Between Collisions of Fig. 9-9 Corrected to Size 4cm for Unobserved Objects (282)

Table 9-5 Time Between Collisions (yrs) Between Sun-Synchronous Payloads and Man-Made Debris (282)

Orbit altitude, cm	Correction factor for unobserved particles	Present population of tracked particles smoothed over latitude	Present population of tracked particles	Present population of tracked particles and factor for unobserved particles	Corrected population with the annual growth rate for 20 years
350	2.5	1.8x10^3	1.2x10^3	4.9x10^4	1.9x10^4
400	2.7	5.3x10^3	9.3x10^4	3.4x10^4	1.3x10^4
450	2.9	4.8x10^3	7.9x10^4	2.7x10^4	1.0x10^4
500	3.0	6.1x10^3	9.6x10^4	3.2x10^4	1.2x10^4
550	3.15	7.9x10^3	1.3x10^3	4.0x10^4	1.5x10^4
600	3.25	1.5x10^4	2.2x10^3	6.8x10^4	2.6x10^4
650	3.5	3.5x10^4	4.8x10^3	1.4x10^3	5.2x10^4

Time between collisions (C^{-1}) (in years) between sun-synchronous payloads and man-made debris (collision cross-section 5 M^2)

RECORDED INCIDENTS

Introduction

Objects in orbit in the vicinity of the Earth, which will be referred to as "debris," present a collision hazard to spacecraft conducting operations in orbit. The level of hazard to a given spacecraft depends on its size and time on orbit and on the number and size of debris objects in its operating environment.[1-3] The debris may be meteoroids passing near the Earth or man-made objects generated during space operations. The focus will be on man-made debris since it is this debris which presents the dominant and controllable collision hazard to operating spacecraft. It is imperative that those involved in the use of the near-Earth environment become concerned with this hazard, as the growth of this debris may in the near future begin to have a significant and adverse effect on space operations. Even now there is mounting evidence that orbiting spacecraft have experienced collisions. (397) It is certain that such events will occur with greater frequency in the future as the debris population grows and/or the space activity expands. (282)

Both the NASA and the military now have active investigations into the hazards of accumulating space debris. The potential threat to the space shuttle, large space platforms of the future, and smaller satellites now in orbit will only get worse. (139)

Nearly 5,000 orbiting objects, ranging in size from a few inches to complete spacecraft and rocket bodies, are catalogued and tracked by NORAD. More than half of those objects are debris from explosions. Others are protective clamshell shrouds ejected from payloads, pieces that have torn away from tumbling satellites, objects ejected deliberately, and unknown items suddenly "spawned" from other objects. A new report says that another 5,000 untracked, but still dangerous, objects are in orbit.

More than 70 explosions or "fragmentations" have occurred in space since 1960. Some were deliberate, including 19 Russian anti-satellite tests, but most weren't. Of these, 10 were derelict U.S. Delta rocket second stages, some exploding nearly three years after completing their missions. At least seven explosions of all types occurred in 1981 alone. (139)

On 2 July 1982, on the fifth day of its final test flight, STS-4, the Space Shuttle Orbiter Columbia OV-102, flew uncomfortably close to the burned out upper stage of a 1979 Soviet Intercosmos rocket. Flying above the north western coast of Australia (a region still smarting from the dramatic return of Skylab in its midst in 1979), Ken Mattingly and Henry Hartsfield passed within eight miles of the stage. It flew past them at almost 7,000 mph (11,200 kph) above and in front of the Orbiter. Mission Control said that there was no danger of collision, but that Columbia could have taken evasive action if necessary. The Flight Director commented "No way they could have seen that thing. You'd have to be looking at exactly the right place at exactly the right time and not blink".

The incident highlighted the growing hazard posed by man-made space debris. In the 25 years since Sputnik 1 was launched, this problem has not been considered to be too serious, but with the possibility of very large space structures in both low and geostationary orbits in the 1990's, it is now a problem that must be faced. In 1981, the American Institute of Aeronautics and Astronautics (AIAA) produced a "position paper" on Space Debris to encourage debate; a similar paper was also read at the International Astronautical Federation Congress that year. The AIAA concluded that "at the present time, the collision hazard is real but not severe." However, "the probability of collision will increase and eventually reach unacceptable levels, perhaps within a decade". (199)

On July 24, 1981 the Russian navigation satellite Cosmos 1275 was hit and destroyed by what was suspected to be a piece of metal space debris.

Cosmos 1275 was launched on June 4, 1981, had become operational, and was travelling in a near-polar orbit 600 miles high. Only 50 days later it disintegrated into more than 140 pieces of orbiting junk.

The Kessler Syndrome-a moving layer of space garbage whose flotsam can lead to disastrous collisions in orbit-had almost certainly claimed its most significant victim.

"It's speculation because no one could see it happen," according to a West Coast expert in the field, who also described the craft's probable shape. "But of possible collisions in the past, this one is the strongest candidate.

"We think it was a gravity-gradient satellite with no thrusters or fuel tanks on board. [A gravity-gradient spacecraft orients itself by responding to changes in gravity. The Russians have never released technical details on their navigation satellites.] Its mission was navigation, so it carried nothing that could explode. And it was working normally until something happened that broke it apart."

Another expert who analyzed the trajectory data agreed. "There is a good possibility that it was a collision, not a simple explosion," he said.

That event is just one in 1981 that is helping to feed a new and growing concern about debris in space. (139)

Collisions are increasingly probable. Two other Russian craft may have spawned pieces from collisions, but the evidence is circumstantial. A deflated U.S. communications reflector balloon named PAGEOS probably was fragmented by collision in July 1975, but, again, absolute evidence is lacking.

Near misses (objects passing within 30 miles of each other) are increasing. At least two satellites were put under special watch in 1981 when NORAD radar data predicted closest approach by debris to be less than 1,000 yards. At geosynchronous altitudes alone (22,000 miles) there were 120 near misses in the last six months of 1981. Two active communications satellites passed within six miles of each other in April 1980. (139)

The Delta rocket explosions already were being examined. Engineering work traced the probable cause to the common bulkhead between the hypergolic fuel and the oxidizer. A 15-pound-per-square-inch pressure difference could rupture the bulkhead.

In a typical mission, the Delta vent valves were closed after a payload was deployed. Floating in and out of sunlight would cause pressures to build up until the bulkhead blew, as one did on January 27, 1981, over Edith Range Land, Antarctica. That Delta had been in space nearly three years; others exploded in as little as a day. (139)

Once the problem was isolated, a software change was implemented to move the stage away from its payload, then fire the engine until it burns to depletion.

It seems to have worked. Recent Deltas have not blown. But some older stages still in orbit may yet contribute to the growing volume of debris.

Most of the Delta explosions come in the 900-mile-altitude range.

Another and heavier debris concentration is found about 500 miles up, according to Vladimir A. Chobotov, manager of the Space Hazards Office at the Aerospace Corporation. Much of that may be remnants of Soviet anti-satellite tests. Russian "hunter satellites" explode within about five miles of their targets, spraying large amounts of shrapnel into the area.

That belt is within the altitude limits of the space shuttle, though not for a typical mission. But debris does filter down into the shuttle's primary operating altitude range.

The hazard increases with the square of the radius of the spacecraft, and right now the problem is not severe.

It is calculated that a shuttle at 170 miles altitude will have 67 encounters (within a distance of 120 miles) with objects larger than one meter during a four-day mission. The probability of collision: a million to one.

But there are many more small objects raining down through this area, and the number of objects up there is growing every year. NASA's Kessler believes that collisions themselves, mostly between pieces of junk, will be the major source of debris within 10 years.

The most probable point for collisions is where orbits intersect, according to Kessler, and the impact velocities can be from zero to about 10 miles per second.

Thus, the polar regions, where large numbers of surveillance satellites in north-south orbits constantly cross, and the geostationary nodes used by communications satellites, could become danger zones. Many of the Delta fragments are in polar orbits.

Microscopic fragments of junk also orbit the Earth.Pits found in Apollo spacecraft windows and a Skylab window brought home for analysis showed traces of aluminum that could only have come from a manufactured item. The finding causes concern for future instruments, such as large telescopes whose optics could be degraded. (139)

Previous spacecraft windows have returned with microscopic pits, many of them caused by impact with aluminum oxide debris from solid rocket motor firings in space.

Space debris may be originated by dislodged thermal protection tiles during acsent, orbit or re-entry. After shuttle Mission 5 in November 1982, Kennedy Space Center inspection revealed unacceptable damage to a windshield window on the orbiter Columbia, OV-102.

Kennedy managers are not certain when the damage discovered after Mission 5 occurred, since a new window polishing technique used after the flight helped reveal the flaw. A thermal protection tile struck that area of the window during Mission 3 in March 1982, but it is unlikely tile alone could cause such damage.

Analysis suggests the window was more likely struck by a metal 6 X 6-in. tile carrier plate dislodged from the orbiter's nose during reentry on Mission 5. That window was removed, and the Kennedy technique used to install the tile carrier plate involved also was reviewed.

Reentry of decayed spacecraft poses unique hazards as heavy, solid spacecraft parts do not burn-up during reentry and impact the earth surface.

Various such incidents have occured:

On July 11, 1979 parts of the 77-ton U.S. Skylab Space Station fell over a wide part of the Australian coast, some into the Indian Ocean, some onto coastal land areas along a path 160 km wide and 4,000 km long.

Since 1957, 5,700 space objects have re-entered the atmosphere and burned up. Several hundred pieces of debris have hit the surface; none have resulted in personal injury or damage claims. The largest piece from the US space program, a Skylab rocket stage larger than the Lab, re-entered in January 1975 and fell into the Atlantic Ocean.

Of concern are satellites powered by radioactive materials that could one day fall back to Earth. Two types of radioactive power stations - one active and one passive - have been used either in the US or Soviet Union space programs. The active kind is similar to the reactor that powered Cosmos 954. As in most nuclear power stations on Earth, these reactors use uranium in a chain reaction which fissions atoms, producing energy and harmful gamma radiation.

The Soviet nuclear-powered satellite, Cosmos 954, disintegrated over the North-Western Territories of Canada on 24 January 1978.

The end of Cosmos 954 over northern Canada did not create any danger for the population of the area. Nor was there any danger to people during other emergency falls of satellites with nuclear power units on board.

This was the opinion of Academician Leonid Sedov in a Tass interview published on 4 February, 1978.

Academician Sedov emphasised that Cosmos 954's small nuclear reactor containing Uranium-235 was designed to ensure its destruction and burning up on entry into the dense layers of the atmosphere. It was not in any way explosive.

The origin of Cosmos 954's erratic behavior was not definitely known since it was beyond the range of Soviet tracking equipment. But on 6 January 1978, Cosmos 954 suffered a sudden depressurization causing the on board system to go out of operation and the satellite to begin its "uncontrollable descent."

It may be assumed, said Academician Sedov, that the satellite collided in flight with some other object of natural or artificial origin.

Only one US satellite with such a reactor on board has ever been launched; that occured in 1965 and the satellite has since been boosted to a very high orbit where it will remain for 4,000 years. According to US sources, all Soviet satellites using reactors also have been boosted to higher orbits - except when the apparent failure of the booster engine caused the re-entry of Cosmos 954.

The second class radioactive power station, and the one used operationally in the US space program, is a passive unit (not a reactor) called the radio-isotope thermal electric generator, or RTG. These units contain plutonium which decays naturally, giving off heat that is converted to electricity. During the Appollo program, astronauts on the Moon handled RTG's; using tongs, they removed the units from a compartment on the Lunar Module and inserted them into a central station that powered scientific instruments.

At present, the United States has eight satellites powered by RTG's in Earth orbit, six in deep space and five on the Moon. The eight are a NASA Nimbus weather satellite, five Navy navigational satellites and two communications satellites.

All of the RTG's are encased in graphite, designed to withstand the heat of re-entry and bring them to Earth intact should the satellites re-enter the atmosphere. None are expected to re-enter for years, well beyond the time when the plutonium, with a half-life of 88 years, is exhausted.

Three RTG's have, in fact, survived re-entry, in each case on aborted satellites or spacecraft. Two units powered a Nimbus satellite that fell into the Santa Barbara Channel off the West coast of the United States. The RTG's were recovered undamaged from the ocean. The third was on the aborted Apollo 13 Lunar Module that fell into the South Pacific.

Before the change in design which insures the RTG's would survive re-entry, the RTG's were designed to burn up in the atmosphere. In 1964, a satellite with an RTG did re-enter and burn up.

All the rest of the Orbiting US satellites are powered by solar energy.

But spacecraft sent to planets at great distances from the sun use RTG's for power. The two Pioneer spacecraft that flew by Jupiter in 1973 and 1974 respectively both have RTG's on board. One Pioneer is on a path that will take it out of the Solar System; the second flew by Saturn in 1979. The two Viking Landers on Mars are powered by RTG's as are the two Voyager spacecraft en route to Jupiter.

Norad's command center, under Cheyenne Mountain near Colorado Springs, constantly sorts the information, maintaining records of space debris that can be rapidly distinguished from missiles or other attack weapons.

With the increasing number of pieces to be tracked, and concerned with the ever growing risk of collision, other tracking systems are being studied to complement the existing system, such as radar, lidar (laser-radar) and passive optics. Each of these systems would consist of sensors aboard orbiting spacecraft, to monitor the amount and trajectories of particles from 0.1 to 10 cm. (139)

SOURCES OF SPACE DEBRIS

Discussion

The significance of the orbital debris problem depends primarily on the number and size of objects on orbit. When considering objects large enough to damage most spacecraft, man-made debris constitutes the dominant threat. In the past, man-made debris had two sources: routine space operations. which include the deposition of spent stages as well as hardware released during normal maneuvers, and on-orbit explosions, both intentional and accidental. More recently, there have been several unusual events involving debris generation which might be attributed to collisions rather than explosions. An additional debris source, which may be significant for optical devices, is particulate matter ejected in solid rocket motor exhaust.

The number of objects which are large enough to be tracked by NORAD detectors is about 4500 and consists of about 35 percent objects released during normal operations and 65 percent objects associated with on-orbit explosions. In addition to the tracked objects, there is a population of uncertain size consisting of objects too small to be seen with currently used detectors. (282)

The amount of debris in space is increasing. Although the number of spacecraft launched each year stays almost constant, the number of associated fragments, discarded rocket stages, non-functional components such as despin cables, release bolts, tie-down clamps and miscellaneous bits and pieces, is going up. Almost 75 percent of the objects in orbit can be classed as either debris, rocket stages or non-functioning spacecraft. These inhabit a wide range of orbits from a few hundred kilometers high to several thousand kilometers. Objects in the latter orbits have lifetimes between several months and hundreds of years. And each piece of the space debris poses a potential space hazard.

As an example of how space is being increasingly polluted by debris, let us take the case of Soviet navigation satellite Cosmos 1275. This spacecraft, for no apparent reason, suddenly disintegrated in space in July 1981. Nicholas Johnson suggested that, because Soviet navsats do no carry either internal propellant supplies or destruct packages, disintegration of this military operational payload, a mere seven weeks after launch, was caused by the impact of a piece of space debris, possibly travelling in exactly the opposite direction and at exactly the same altitude; by October 1982 some 180 individual fragments of Cosmos 1275 had been tracked by NORAD and these will inhabit this particular orbital slot for years to come and will themselves become a hazard to spacecraft orbiting in this region.

This case is not unique; earlier fragmentations have included Delta second stage rockets used to launch Landsats 1, 2 and 3; Soviet spacecraft involved in anti-satellite tests; Agena rocket stages and Soviet upper stage rockets. (265)

Disconnected Rocket Stages

When the spacecraft is separated into a similar elliptical transfer orbit, ground commands initiate spacecraft apogee injection rocket motor firing at an equator crossing-point near apogee; this pushes the payload into geostationary orbit. It is here that one source of geosynchronous debris originates.

The majority of U.S. communications satellites, existing and planned, use an apogee injection motor which is integral to the payload structure. After firing, this remains a part of the spacecraft and does not become a separate object.

But Soviet communications satellites behave differently. Their apogee motors are attached to the outside of the spacecraft structure. After firing, these are separated by a spring mechanism. Although the spacecraft is controlled from the ground and commanded to move around the geostationary orbit until the desired location is reached, the spent apogee motor is left to drift. Soviet apogee motors measure about two meters by two meters and are liquid -fueled. Any propellant remaining in the motor after firing is usually vented through the engine to provide further separation from the main spacecraft.

Most of these apogee motors, 23 to date, are currently tracked by NORAD sensors, so their orbits and positions are known. But, there are about a dozen of these separated motors which are not tracked; these are drifting in orbits that intersect the geostationary altitude at widely varying longitudes. The potential collision hazard from all these apogee motors is quite high. In 50 percent of cases, they present a potential source of trouble to other spacecraft.

The biggest (in terms of size) danger to geostationary satellites are Titan-30 transstages which enter geosynchronous orbits after injecting their payloads into geostationary orbits. The transstages are about six meter by about three meters and weigh over 1250-kg in orbit. Today, over 25 of these rocket stages are trackled in a variety of paths, most of which intersect the geostationary orbit. A good example of the inherent problems occurred in 1965, when a Titan transstage, in a 600-km orbit, exploded into 460 fragments. Even though these object are continuously monitored by NORAD, the dangers of a collision are always present.

Fortunately, at the present time, debris at geostationary altitudes is not as bad as nearer Earth, but a potential hazard does exist. This arises from defunct spacecraft, some small components, and some very large rocket stages drifting around the geosynchronous orbit and not under any control from Earth.

All four countries capable of placing spacecraft in geosynchronous orbit - the United States, the Soviet Union, European Space Agency and Japan-use similar techniques: the payload and attached rocket stages are placed in a low Earth parking orbit where, during the first revolution after launch, the upper rocket stage ignites to place the payload into a geostationary transfer orbit.

This procedure, especially during Soviet launches, leaves components in the low parking orbit. These components re-enter within a few days of launch and do not normally pose a hazard to other space traffic. Once in the highly elliptical transfer orbit, with an orbital apogee near the geosynchronous altitude, but inclined between 10° (for ESA-launched spacecraft) and 47° (for Soviet spacecraft) to Earth's equator, the launch vehicle stage is jettisoned. It remains in this orbit and so poses little hazard to geostationary spacecraft. (265)

Drifting Components

Another source of orbiting "debris" is components that are ejected or separated from the parent spacecraft after geostationary orbit has been achieved. Few of these are tracked, partly because they are usually very small objects. Some examples are the navigation spheres ejected from ATS-3; apogee motor nozzles from the weather satellites Goes-4 and Goes-5; the radiometer covers from European and Japanese geostationary weather satellites; an adapter from Indian spacecraft Apple-1 and possibly solar cell array panel release mechanisms from some Soviet geostationary spacecraft. These objects are usually too small to be detected by Earth-based sensors and because their precise location, orbital characteristics, and drift rates are unknown, they present a hazard of unknown proportions to geostationary spacecraft. (265)

Misplaced Satellites

Placing a spacecraft into a precise equatorial geostationary orbit is a complex operation. Occasionally things go wrong: spacecraft are placed in incorrect geosynchronous orbits and may or may not be controllable from Earth. The first and second Japanese Experimental Communications Satellites, for example, were both placed in incorrect orbits and are now drifting around Earth, with the former in a "subsynchronous" orbit below the geostationary altitude, and the latter in a "supersynchronous" orbit above this altitude in eastwards and westwards directions respectively. Both these spacecraft, and several early U.S. and Soviet satellites, no longer operating or under ground control, also pose a potentially serious hazard. (265)

Defunct Spacecraft

Finally, defunct spacecraft pose a serious hazard. Because of the gravitational attraction of the Sun and Moon (air drag is virtually non-existent: at 35,800 km) geostationary satellites are gradually pulled out of their 24 hour orbits. Regular thruster firings are needed to nudge them back into place. A defunct spacecraft, however, does not have this capability and eventually begins to drift. Although there are a large number of these satellites, none are tracked. These include early military geostationary spacecraft, the first Syncoms and old Intelsats, although the latter are usually pushed out of geostationary orbit when they expire. (265)

STRATEGY OPTIONS

Introduction

Three fundamental options exist for dealing with the debris environment: 1) accept the risk 2) add shielding to reduce the risk and 3) alter the environment. For certain types of missions, the risk is at an acceptable level. For example, the Space Shuttle has an average cross section of 250 m^2 and an operational altitude of about 300 km. At this altitude, the current collision probability for the Space Shuttle is about 1×10^{-4}/yr. This is less than the probability of an accidental death on Earth (5×10^{-4}/yr., of which half is from traffic accidents) (398). However, this acceptability will decrease with time, with larger structures, and with higher altitudes. The inherent structure will protect most spacecraft from impacts of 1mm and smaller. The addition of shielding may be a practical alternative to protecting against impacts between 1 mm and 1 cm. However, the amount of shielding required to protect against impacts larger than 1 cm becomes very large and may be totally impractical in terms of additional weight requirements. Thus, the aternative of controlling the environment may be essential to certain types of missions. (283)

The most effective control technique consists of eliminating objects from space before they become a source of fragments. Emphasis should be placed on designing rockets to eliminate explosions in space. The combination of explosion fragments (acting as projectiles) and nonfunctioning rocket bodies and payloads (acting as targets) produces an effective mix of objects that will eventually produce a self-regenerative fragmentation process through collisions. This process may also be minimized by reducing the number of targets. The eventual disposition of a rocket body or payload could be planned before it is placed into space. Techniques have been developed to cause geosynchronous transfer orbits to reenter simply by controlling the time of their launch. (399) With the Space Shuttle, it may prove beneficial to retrieve old payloads and rocket bodies. The designation of an area of space to become a "garbage dump" may be useful. However, these options should not be implemented without careful consideration of their effectiveness, alternatives, and other possible consequences. A program is being developed to understand the current and projected environment, and the most effective methods of control. This program will eventually lead to a space object management philosophy where remedial actions will be recommended. However, since the problems are international in scope, coordination with the international community will be required to implement any controls. (283)

Discussion

The discussion on Strategy Options has been adressed in the following in two separate subsections, i.e.:

- Safety Strategy Options.
- Space Environment Strategy Options.

Safety Strategy Options

Safety Strategy Options cover safety aspects and parameters to be considered and/or implemented during the design development, construction and operation of the Space Station, and associated space vehicles.

Three Basic Safety Strategy Options are discussed in the following. These are:

- Accept the Risk.
- Add Shielding to Reduce the Risk.
- Avoid the Risk by Evasive Maneuvers.

These strategy options are within the present state of technology, and implementation is realistically feasible.

These basic space station safety strategy options are illustrated on Figure 9-5, and can be summarized as follows:

- Design to smallest size debris trackable or accept risk.
- Plan to move station to avoid larger sized trackable debris.

DEBRIS TOO SMALL TO TRACK

TRACKABLE DEBRIS

- By Space Station - By NORAD

ACCEPT THE RISK

Debris Size

< 1 mm

1 Cm

4 Cm

> 4 cm

DESIGN SPACE STATION
TO WITHSTAND - ACCOMMODATE-SURVIVE HIT

Meteoroid Bumpers
Double Wall Concept
Protective Shrouds Around Maintenance/Servicing Facilities

Systems Redundancy
Safe Haven
Rescue

DESIGN AND PLAN SPACE STATION
TO MANEUVER OUT OF DEBRIS PATH

Space Station Tracking	NORAD Tracking
-Sophisticated Detection and Tracking Equipment	-Pre-Planned Orbit Changes/Evasive Maneuvers

- Propellant Reserve to Perform Maneuvers

Figure 9-5. Basic Space Station Safety Strategy Options

Accept the Risk.

The time between collision for objects the size of the Shuttle Orbiter will be very large, even in regions of greatest debris density. However, larger objects, such as the large astronomical mirrors or other large space structures, will certainly collide during their operational lifetime with man-made debris large enough to be tracked from the Earth if they operate at these altitudes. Collisions with such large objects will not only jeopardize the continued functioning of these spacecraft, they will also act as sources of additional man-made debris and contribute to an elevation of the collision hazard level. (282)

Impact protection may not be feasible in most cases because of the likelihood of very high approach velocities (of the order of 10 km per second) and the fact that protruberances such as solar arrays, radiators and antennae cannot easily be permanently shielded. (199)

Since the large relative speeds of objects in LEO make even very small objects a danger, sophisticated detection and avoidance systems would be required onboard all operating spacecraft if avoidance was to be attempted. Such systems would cost payload, both for the detection hardware and for the extra fuel, and are considerably beyond the current technology. (282)

Add Shielding to Reduce the Risk

Even with the current debris levels, there are some regions of space which would be very hazardous for some of the larger proposed spacecraft to use if they had no collision protection.

The alternative to avoidance would be to employ bumpers which could accommodate the impact without allowing it to damage the operating systems on the spacecraft. However, there are essential parts of a spacecraft, e.g., the solar panels, which are difficult to shield; moreover, the fact that much of the man-made debris is of large mass would require very massive or complex bumpers. (282)

Meteoroid bumpers and double-wall features have been extensively discussed in Section 8, Meteoroid Penetrations. Reference is hereby made to these pertinent discussions regarding the Explorer 46 Bumper Experiment and subsequent laboratory tests. Meteoroid bumpers/double-wall construction offer considerable weight savings for shielding against space debris.

Avoid the Risk by Evasive Maneuvers

The threat category of external debris includes objects in excess of meteoroids in size, usually referred to as space garbage. Nominally, space debris, as opposed to meteoroids, would have lower closure rates allowing the possible option of collision avoidance.

The possibility exists that enough debris from U.S. and foreign spacecraft may be in intersecting orbits with the space station to pose a significant hazard probability for a ten-year operation.

Means must be evaluated to detect, track, and predict the paths of such debris; and to provide means of evasion by providing adequate and timely delta-v capability at the station. (21)

The prerequisite to initiating evasive maneuvers is of course the detection and tracking of space debris. The concept of evasive maneuvers, therefore, can only apply to trackable debris and may be considered in two categories:

- Pre-planned evasive maneuvers to avoid collision with orbital debris tracked by NORAD, i.e. larger than 4 cm in size.
- Forced evasive maneuvers to avoid collision with orbital debris detected by on-board detection devices. This applies to debris sizes smaller than 4 cm in size, which cannot be tracked by NORAD.

A scenario for pre-planned collision avoidance is described in the following in general terms based on hypothetical parameters.

The method used to eliminate or considerably reduce the number of collisions in LEO involves a rescheduling of the orbit trim (drag makeup) maneuver of the Space Station. It is assumed in this scenario, that the orbital profile results in 15 revolutions around the Earth per day and that at the completion of the 15th revolution an orbit trim maneuver is performed and the gradual decay begins again.

Collision avoidance operations takes place in the following manner. At a given revolution (such as number 4) it is determined that on rev 5 the Space Station will be hit by an object(approaching perpendicular to the orbital track) if no corrective action is taken. At that time, however, an unscheduled orbit trim maneuver will be initiated which will increase the altitude of the station and as such results in lower orbital velocity, and on a relative position basis, puts the station at a new position for rev 5, which is approximately 7 kilometers downtrack from the original scheduled position of rev 5, and consequently should eliminate the possible collision. The key factor in this avoidance operation is a need for approximately 1 rev of warning time, thus requiring both on-orbit and ground tracking and predicting capability. (337)

Object coming into the Space Station along a more tangential path can also be avoided using a similar technique, but requiring a greater change in altitude and consequently more propellant. For example, a change of 6 kilometers in altitude requires TBD kilograms of propellant. Since the large change in altitude also results in excessively large changes in along track position, a deorbit maneuver is also required (TBD kilograms of propellant), thus bringing the station back to its nominal orbital position. (337)

Forced evasive maneuvers would require not only sophisticated, long-range detection devices on-board the Space Station, but also computerized debris path evaluation and automated reaction control systems, as the lead time for collision avoidance is limited by such factors as debis size, detection range and reaction time.

Evasive maneuvers may reduce the present probability of collision for specific satellites in certain circumstances, but they do not provide a practical long-term solution. In addition there will be the added weight burden on spacecraft of having to carry sophisticated detection equipment (to catch the untracked particles) and propellant to perform the maneuvres. (199)

Space Environment Strategy Options

Space Environment Strategy Options, however, cover considerations which require either international cooperation and observed policies or new technology development or both, such as:

- o Eliminate Fragmentation Sources.
- o Minimize Number of Targets.
- o Retrieve Space Debris.
- o Achieve Space Object Management Philosophy.

Implementation of the above by the U.S.A. alone may reduce the proliferation of space debris temporarily, but as more and more nations develop space technology and actively pursue space exploration, the solution to the debris problem and associated hazards for all participants can only be achieved by an International Space Environment Management Policy.

These basic space environment strategy options are summarized in Figure 9-11.

Eliminate Fragmentation Sources	. Accidental Explosions . Planned (Military) Explosions
Minimize Number of Targets	. Eliminate Detachment of Components . Facilitate Out-of-Orbit Maneuvers . Control Time of Launch
Retrieve Space Debris	. Space Shuttle (. Orbiting Garbage Truck) (. Dedicated Space Tug) (. Scavenger Rockets) (. Designated Area of Space as Garbage Dump)
Achieve Space Object Management Philosophy	. Education on the Critical Nature of the Problems . Explosion Prevention Policy . Debris Monitoring and Control . Collision Hazard Assessment . Measures to Limit the Likelihood of a Collision or Minimize Damage . Review of Space Vehicle Design Guidelines ∂ Operations . Evaluate the Best Orbits . International Space Environment Management Policy

FIGURE 9-11. SPACE ENVIRONMENT STRATEGY OPTIONS

Background

The evolution of the debris population under plausible conditions can be sketched. In this scenario, normal operations and on-orbit explosions, which might result from correctable design flaws, insensitive operational procedures, inadequate preventive design characteristics, or antisatellite operations, which represent controllable debris sources, would continue to contribute to the population of man-made objects in orbit. These objects, being generally large, would populate long-life orbits and increase the size of the population, characterized by N, its number of members. In consequence, the expected time between debris-debris collisions, which has a $1/N^2$ dependency, would decrease (as will be seen, this time is already unacceptably short, -50 yr. for the current population levels). With the advent of debris-debris collisions, an uncontrollable debris source, which for some events might produce many thousands of debris objects, would be introduced. If the removal time for the collision debris proved to be greater than the expected time before experiencing another collision, collisions could become the dominant debris source and would yield a rapidly escalating growth rate in the number of debris objects. (383, 396) The increasing number of debris objects would also decrease the time between collisions as experienced by a particular spacecraft since this time has a 1/N dependency. (282)

The rise in the number of debris objects would continue until debris removal by atmospheric drag balanced the debris being generated by collisions. This method of removing debris will become more effective as debris undergoes successive fragmentations, since the smaller particles will generally have a larger ballistic coefficient. However, the inefficiency of debris removal by atmospheric drag indicates that the debris population might become very large before this debris sink became effective.

While most of the orbital decay will occur during the period of maximum solar activity, many solar cycles will be required to remove massive objects deposited as low as 700 km.

Orbit decay by atmospheric drag will eventually cause the debris to re-enter the Earth's lower atmosphere, but this mechanism will take a very long time to remove all but the very smallest debris pieces or debris deposited in low-perigee-altitude orbits. Therefore control of the problem must come by adopting procedures which prevent the deposition from occurring.

Operations which violate such procedures, whether they are antisatellite operations or debris released during normal operations, might, if they are maintained, lead to a state where the near-Earth environment is so heavily populated by debris as to be virtually impossible to use. (282)

Such procedures, which tend to decrease the collision hazards caused by Space Debris and contribute to the safety of the space environment are briefly discussed in the following.

Eliminate Fragmentation Sources

The most promising strategy appears to be the design technology development to prevent rocket explosions in space and thereby eliminating the major source of fragment debris.

These explosions can be categorized as follows:

- Accidental explosions caused by engineering problems, during the earlier stages of space exploration.
- Since 1972, the only U.S. explosions have come from the Delta rockets. Steps have recently been taken to stop these explosions thru engineering changes.
- The solution to planned rocket explosions is political in nature and must be addressed in the overall International Space Object Management Philosophy, if this fragmentation source is to be eliminated. This category covers military weapons testing, such as:
- Fragments caused by the eight USSR antisatellite tests. (283)

Minimize Number of Targets

To exercise effective control of man-made debris, the number of objects being placed in long-life orbits without their having an onboard mechanism for removal from orbit must be minimized. Once debris is deposited in orbit it is extremely expensive, if not impossible to retrieve. (282)

The eventual disposition of a rocket body or payload could be planned before it is placed into space. (283)

Three possible design solutions to this problem can be summarized as follows:

- Eliminate Detachment of Components
- Facilitate Out-Of-Orbit maneuvers
- Control time of launch

Eliminate Detachment of Components - First, satellites should be constructed to ensure that components can not become detached after geostationary orbit insertion. Solar panel tie-down clamps, apogee motors and radiometer covers need to be designed to remain fixed to the satellite after deployment. Specific examples are the following:

The apogee motors of USSR communication satellites are attached to the outside of the spacecraft structure and separated, after firing, by a spring mechanism. The spent apogee motor is left to drift.

Titan-3C transstages enter geosynchronous orbits after injecting their payloads into geostationary orbits. (265)

Facilitate Out-Of-Orbit Maneuvers - Second, all spacecraft operating at geostationary altitudes should be designed with sufficient residues of onboard thruster propellant to ensure that a final, out-of-oribt maneuver will remove the satellite completely from the geostationary arc. Spacecraft simply abandoned at geostationary altitude will drift aimlessly until they collect at one of two gravitational anomaly areas, near longitudes 75° East and 105° West, thus creating a potential disaster zone.

Satellite operators today are taking positive steps to alleviate the problem created by defunct geostationary satellites. The last of a spacecraft's thruster fuel is used to push the payload out of the geostationary arc. If performed correctly, this maneuver successfully places the satellite well above, or below the 24-hour orbit.

NASA's Applications Technology Satellite 6, for example, was successfully kicked out of its geostationary orbit at the end of its active life and now drifts around Earth in a subsynchronous orbit at the rate of 6° East per day. More recently, Canada's Telesat-1 was boosted into a superior orbit using the last of its onboard propellant. It is now moving around Earth at about 5° West per day.

Intelesat has announced that defunct Intelsat 4-series spacecraft will be moved away from the geostationary orbit in a similar manner. However, not every maneuver of this kind achieves is intended aim. Canada's Communications Technology Satellite 1, for example, was moved out of geostationary orbit, but not quite far enough. The result was that this satellite drifts back and forth between longitudes 65° West and 140° West, crossing the geostationary arc's most crowded region immediately above the United States. (265)

Control Time of Launch - Techniques have been developed to cause geosynchronous transfer orbits to reenter simply by controlling the time of their launch. (283, 399)

The solution to the problem rests with establishing international design technology and operational guidelines as part of an all encompassing Space Environment Management Policy.

Retrieve Space Debris

Retrieval of space debris appears to be the most unattractive solution to the problem, considering the present state of technology and the enormous costs involved. Furthermore the retrieval of space debris would serve its purpose only in isolated, special cases without resolving the overall problem.

The only viable option is the use of the space shuttle.

- The space Shuttle may retrieve specific old payloads, such as misfired or malfunctioning satellites stranded in LEO or drifting rocket bodies. The economics of such a mission are to be evaluated for each individual case.

Other options are mentioned in the following, even though, these solutions are outside the present state of technology and do not appear to be economically viable:

- Collection by "Orbiting Garbage Truck" spacecraft would be extremely difficult and expensive. (199)
- Dedicated space tug for scooping up orbiting trash.
- Scavenger rockets that fly through space scooping up stray garbage. Any scavenger rocket would have to switch from one orbit to another to catch each object. Changing orbits would consume large amounts of energy.
- The designation of an area of space to become a "garbage dump" may be useful. (283)

None of the above options is presently under active consideration.

Achieve Space Object Management Philosophy

The inability to introduce controllable and effective debris removal into the problem increases the possiblity for catastrophic debris growth, in which the onset of debris, with debris collisions, would introduce an extremely large and uncontrollable source of debris objects. These could remain in the environment sufficiently long to trigger a runaway collision process. (282)

Natural drag by the atmosphere is the major factor operating in our favor, but it can take a very long time to be effective, especially from the "busy" higher altitudes; and it causes debris to migrate from higher to lower orbits (thus complicating tracking problems even further). (199)

Effects of sunspot and solar-flare activity on earth's upper atmosphere change the air density, increasing the drag rate (happened on Skylab).

In theory, the debris hazard could be controlled by limiting the rate of debris deposition or by balancing deposition and growth with debris removal. However, only the institution of programs to control (minimize) the rate of debris deposition is an effective alternative since an active debris removal program, which would require many thousands of feet per second of propulsion capability to acquire each debris object, is not feasible with the present propulsion technology, and removal by atmospheric drag is generally ineffective on short time scales. (282)

More accurate tracking of all objects in orbit is needed. Apart from the fact that untracked space debris poses a high risk to operational satellites, compensation (and insurance) problems arise if, for example, a piece of debris of unknown origin collides with, and disables a multi-million dollar communications satellite. Only by increasing global space object detection and tracking capability will such potential disasters be averted. Advanced warning of the approach of drifting Titan transstage, for example, could allow the satellite operator to move the satellite out of the way.

So far, there have been no orbital collisions at geostationary altitudes. Today's non-functional space population at geostationary altitudes poses limited hazards to the 150 or so active satellites in the arc, but uncontrolled proliferation of geostationary space junk in the future could have catastrophic consequences. (265)

In 1981, the American Institute of Aeronautics and Astronautics (AIAA) produced a "position paper" on Space Debris to encourage debate: a similar paper was also read at the International Astronautical Federation Congress that year. The AIAA concluded that "at the present time the collision hazard is real but not severe." However, "the probability of collision will increase and eventually reach unacceptable levels, perhaps within a decade". (199)

The AIAA concluded that the problem can be forestalled by immediate action in five areas:

1. Education on the critical nature of the problem; education of space designers on the need for litter-free systems.
2. Technology; detection techniques, monitoring systems.
3. Space Vehicle Design; especially encouraging disposal by retrieval, re-entry, earth escape, or transfer to selected "dump" orbits.
4. Operational Procedures ə Practices: avoiding crowding spacecraft orbits; limiting explosions to low orbits so that particles re-enter quickly; planning launch trajectories to ensure early re-entry of spent rocket stages and dead payloads.
5. International Cooperation; to answer such questions as "Should a policy be adopted that requires all spacecraft to be boosted out of geostationary orbit at the end of its useful lifeμ Should a policy be adopted to regulate which objects may be left in long-life orbitsμ" (199)

Since the problem of space debris and its solution is international, the need for defining an International Space Object Management Philosophy becomes apparent. With international cooperation a Space Environment Management Policy may result as this appears to be the only viable solution to the growing problem of man-made space debris, affecting all nations participating in the exploration of space.

The Space Object Management Policy would encompass the following objectives:

- Education on the critical nature of the problem.
- Explosion prevention policy.
- Debris monitoring and control.
- Collision hazard assessment.
- Measures to limit the likelihood of a collision or minimize damage.
- Review of space vehicle design guidelines ə operations.
- Evaluate the best orbits.
- International Space Environment Management Policy.

10. THREAT/CRITERIA

The following pages identify each of the criteria with the threat driver. It should be noted that more often than not, multiple threats are involved with a single criterion. The criteria were futher expanded into implementing guidelines. See Appendix D, Volume IV of this report.

CREW SAFETY CRITERIA RELATED THREATS

GROUP: DAMAGE TOLERANCE

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
A-1	No credible single space station failure, operational error or radio frequency signal should result in damage to space station or mission/payload equipment or in the use of emergency equipment; some limited degradation in mission/payload accommodations, crew convenience/comfort, or space station attitude or orbit may be allowed	●	●	●	●		●		●	●	●		●	●	●		●	●			●	●	●	
A-2	No credible combination of space station failures, mission/payload equipment failures, operator errors, or radio frequency signals should result in the potential for crew injury or permanent loss of the space station or primary mission/payload capability; institution of emergency procedure/equipment may be necessary but no hazardous operational level will be reached	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
A-3	All subsystem/equipment critical to preservation of life and space station survival should be fail-operational/ fail-safe (excepting primary structure and pressure vessels)			●	●	●					●	●	●			●	●	●		●	●	●	●	
A-4	Fail-operational/fail-safe designed subsystems should allow maintenance to upgrade the subsystem/equipment without being degraded below fail-safe during the maintenance actions following the second failure		●				●		●		●		●				●		●					

CREW SAFETY CRITERIA RELATED THREATS

GROUP: DAMAGE TOLERANCE

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
A-5	Potentially rupturable containers should contain less material (gas, liquid, solid) than would cause unacceptable overpressure if all the material were released in a leakage, rupture or explosion	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
A-6	Redundant accommodations for command and control of the space station should be provided such that the primary control center has complete capability, but the backup control center will have, as a minimum, control of critical functions	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
A-7	Design inhibits to prevent failure propagation from one volume/subsystem/component to another should be incorporated	●	●		●				●	●	●						●					●		
A-8	The space station should be designed and operated so that any damaged module can be isolated as required. Provisions shall be made foR pressure isolation within the volumes. Modules should be equipped and provisioned so that the crew can safely continue a degraded mission and take corrective action to either repair or replace the damaged module	●	●		●				●	●	●					●	●					●	●	

CREW SAFETY CRITERIA RELATED THREATS

GROUP: DAMAGE TOLERANCE

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
A-9	Any volume should be capable of sustaining the whole crew, and capability should be provided for performing critical functions at an emergency level until the crew can be rescued. Electrical and fluid lines in each pressure-isolatable volume required for critical functions should be protected against the effects of explosion, fire, vacuum, and corrosion	●	●	●					●	●	●			●	●		●	●		●	●	●		
A-10	Capability should be provided for performing critical functions with a portion of a subsystem inoperative for maintenance, and any pressure-isolatable volume inactivated and not accessible	●	●	●					●	●	●			●	●		●	●		●	●	●	●	
A-11	Redundant equipment, lines, cables, and utility runs which are critical for safety of personnel or mission continuation should either be located and routed in separate compartments (i.e., separated by a structural wall) or should be protected against fire, smoke, contamination, loss of pressure, overpressure, and shrapnel	●			●			●	●														●	
A-12	All walls, bulkheads, hatches and seals whose integrity is required to maintain pressurization or atmospheric isolation should be readily accessible for inspection and repair by crewmen in pressurized suits		●								●										●		●	

CREW SAFETY CRITERIA RELATED THREATS

GROUP: DAMAGE TOLERANCE

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS.TO MATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
A-13	AS A DESIGN GOAL, INSPECTION, MAINTENANCE AND REPAIR OF CRITICAL SUBSYSTEMS BY SHIRT SLEEVED CREW MEMBERS SHALL BE ACCOMMODATED					●			●		●				●							●		

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-1	Provisions should be made for a safe haven within the space station, isolatable from the hazard capable of sustaining the crew for 22 days beyond normal resupply and allowing rescue by a Shuttle. Provisions shall be made to monitor the health of the remaining habitable modules from this safe haven	●	●		●				●	●	●						●					●		
B-2	Personnel protection from electrical shock, radiation, mechanical and thermal hazards should be provided					●																		
B-3	Accessways between compartments should be sized such that an IVA/EVA-suited crewman is allowed free passage												●			●					●			●
B-4	Provisions shall be made for the protection and survival of the whole crew during solar storm activity as defined by the TBD design mission radiation model											●												
B-5	Personnel escape routes should be provided in all hazardous situations			●			●									●								
B-6	Provisions and habitable facilities should be adequate to sustain the entire crew for a minimum of 22 days during an emergency situation requiring rescue															●								

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-7	Atmospheric stores and subsystem capacity sufficient for two full repressurization of each pressurized habitable volume should be maintained on/at the space station during manned operations		●								●						●							
B-8	Access to EVA and IVA airlock and suit station(s) should be provided for all credible emergency conditions. Airlock chamber(s) should be provided to permit crew access for EVA/IVA operations		●	●		●					●		●	●										
B-9	Two or more suited crewmen should participate in any pressure suit activity and rescue provisions should be provided to allow safe return to space station following the incapacitation of any one crewman			●									●											●
B-10	Real-time monitoring of the atmospheree constituents, including harmful airborne trace contaminants and odors should be performed. Control shall be provided for each pressurized habitable volume				●	●																		
B-11	Two or more entry/egress paths should be provided to and from every module or pressure-isolatable volume. The two paths should be separated by airtight partitions, or shall be at least 10 feet apart, and should each lead to an area in which the crew can survive until escape, rescue or removal of the hazard																				●			

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-12	Materials used in the habitable areas should not outgas toxic constituents in the lowest pressure environment and highest temperature to which they will be exposed				●																			
B-13	All EVA and unpressurized compartment IVA should be conducted using the "buddy system." (Note: buddy system criteria can be met with suited crew to station exit in visual contact with subject). The buddy system should also be used during shirtsleeve operations in hazardous areas			●									●											●
B-14	A margin of consumables should be provided onboard, sufficient for performing critical functions for TBD hours at a reduced level following any credible accident which renders one pressure-isolatable compartment unavailable																	●						
B-15	At least two egress paths should be available from each module for emergency egress of personnel during manned ground operations																				●			
B-16	Emergency suits required in the space station, sized to fit any crewman, should be in readily accessible locations within each pressure-isolatable volume	●	●							●	●													
B-17	Provisions should be made for emergency medical treatment of credible accidents and illnesses for durations compatible with the rescue provisions					●																		

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-18	The safe environment and the safe operational status of activated subsystems within the space station should be verified prior to personnel entry, initially and prior to reentry following temporary station abandonment		●		●						●					●								
B-19	Deployment and initiation of operations considered hazardous should be checked out from a safe location before exposing crewmen to the potential hazards													●	●									
B-20	Provision should be made for the return of a crewmen incapacitated while performing EVA					●							●											●
B-21	Provisions should be made for the detection, containment and/or disposal of toxic contaminants				●																			
B-22	Pressurized volumes should have adequate free volume (not occupied by equipment) to allow crew freedom of movement to support long-duration habitation					●																		
B-23	Hazardous or toxic fluid storage, conduits and interconnects between modules should be external to the pressurized volume. Exceptions may be made for flammable but nontoxic gases where the maximum possible quantity released by a leak cannot result in a flammable mixture	●	●		●					●														

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-24	**Provisions should be made for detection and control of pathogenic agents onboard the space station using methods harmless to crew and equipment**				●	●																		
B-25	**Planned crew tasks should be assessed initially, for compliance intent with TBD regulations before performing such tasks**					●																		
B-26	**Provision should be made for handling irrational crewmembers and the remains of deceased crewmembers**					●																		
B-27	THE OCCUPIED COMPARTMENT'S ACOUSTICAL NOISE ENVIRONMENT SHOULD BE WITHIN HUMAN TOLERANCE NOISE EXPOSURE LIMITATIONS, PERMIT INTELLIGIBLE AUDITORY COMMUNICATIONS, HAVE A MINIMUM OF PURE TONE OR NARROW FREQUENCY BAND(S), A MINIMUM OF INTERMITTENT OR DISCONTUOUS NOISES AND A MINIMUM OF HIGH FREQUENCY NOISES. SYSTEM AND EQUIPMENT DESIGN SHOULD BE ACCOMPLISHED FROM THE OUTSET TO PRODUCE AND ACCEPTABLE NOISE ENVIRONMENT. DESIRABLY, THE NOISE ENVIRONMENT SHOULD MEET NC-TBD-OR-LOWER NOISE CONTOUR FOR WORK PERIODS AND NC-TBD-OR LOWER FOR SLEEP PERIODS.					●								●	●									

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-28	ANY MODULE DESIGNATED AS A SAFE HAVEN SHALL BE PROVIDED WITH AND AIRLOCK CHAMBER AT THE PORT ASSIGNED FOR ORBITER DOCKING AND RESCUE, TO ALLOW CREW TRANSFER AND RESCUE FROM A DEGRADED AND/OR MARGINAL SAFE HAVEN. THE RESCUE HATCH SHALL PROVIDE FOR ACTUATION FROM THE INSIDE OR OUTSIDE TO ACCOMMODATE CONTINGENCIES					●										●								
B-29	SUBSYSTEMS SHALL BE DESIGNED TO PREVENT INADVERTENT OR ACCIDENTAL ACTIVATION OR DEACTIVATION OF FUNCTIONS OR EQUIPMENT THAT WOULD BE HAZARDOUS TO PERSONNEL OR THE SPACE STATION													●	●									
B-30	RADIATION DOSES THAT AFFECT PERSONNEL SAFETY MUST BE CONSIDERED FROM ALL SOURCES, INCLUDING NATURAL ENVIRONMENT, EXTERNAL ISOTOPE AND REACTOR SOURCES (IF ANY), ELECTROMAGNETIC SOLAR RADIATION AND INTERNALLY ALLOWABLE RADIATION LEVELS FROM EXPERIMENTS, PROCESSES AND HEALTH MAINTENANCE/DIAGNOSTIC EQUIPMENT					●																		
B-31	EXPOSED SURFACES WITHIN HABITABLE MODULES SHALL NOT EXCEED A TEMPERATURE OF 113°F (WITH A DESIGN GOAL OF 105°F) AND A LOW TEMPERATURE OF NO LESS THAN 40°F					●																●		

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CREW PROTECTION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
B-32	EXCEPT FOR CONTINGENCIES EVA SHALL NOT BE USED FOR HAZARDOUS OPERATIONS OR WHEN A MANEUVERING SPACECRAFT IS WITHIN THE PROXIMITY OPERATING ZONE (±5NM)					●								●										●

CREW SAFETY CRITERIA RELATED THREATS

GROUP: STATION INTEGRITY

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
C-1	Primary pressure structural materials should be nonflammable. Interior walls and secondary structure should be self-extinguishing	●																						
C-2	Normally exposed nonmetallic materials should be self-extinguishing in the most severe oxidizing environment to which they will be exposed. Means shall be provided for fireproof storage of medical supplies, maintenance supplies, food, tissue, clothing, trash, and for other non-self-extinguishing items, when they are not in use	●			●																			
C-3	Potentially explosive containers such as high pressure vessels or volatile gas storage containers should be placed outside of and as remotely as possible from personnel living and operating quarter. Wherever possible the containers should be isolated and protected so that failure of one will not propagate to others	●						●	●	●									●				●	
C-4	Containment of all materials requiring return via the STS to prevent contamination of the space station environment should be provided to reduce the hazard of potential fire and toxic conditions				●																			
C-5	Tank supports should be designed to restrain the tank under propulsion effect of rapidly escaping gas						●			●														

CREW SAFETY CRITERIA RELATED THREATS

GROUP: STATION INTEGRITY

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
C-6	Design provisions should be incorporated to prevent uncontrollable hatch opening due to pressure differentials, and to allow controlled closing of hatch openings with or against pressure differentials, for the worst case pressure differentials anticipated		●								●										●			
C-7	Equipment or materials sensitive to contamination should be handled in a controlled environment. Fluids and materials should be compatible with the combined environment in which they are employed				●							●												
C-8	Provisions should be made to allow communication between any and all isolatable/habitable volumes on a primary and backup basis													●	●									●
C-9	Provisions should be made for material usage, identification and location mapping to allow real-time evaluation to determine adequate inspection/maintenance replacement frequencies				●			●										●						
C-10	FLUID OR GASEOUS FLOW SUCH AS PRESSURE RELIEF VALVES/EXHAUSTS, FUEL TRANSFER DISCONNECTS, ETC., SHOULD BE DESIGNED TO PREVENT TORQUING/TURNING OR UNDESIRABLE TRANSLATION TO THE SPACE STATION	●	●							●	●													

CREW SAFETY CRITERIA RELATED THREATS

GROUP: STATION INTEGRITY

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
C-11	ALL REACTION CONTROL THRUSTING DEVICES USED PRIMARILY FOR ALTITUDE POSITIONING OF THE SPACE STATION, AND OCCASIONALLY FOR VELOCITY CHANGES, SHOULD BE LOCATED SUCH THAT THE EXHAUST PLUME DOES NOT IMPINGE UNPON OTHER STRUCTURAL ELEMENTS SUCH AS SOLAR CELLS, AREAS REQUIRING EVA MAINTENANCE OR OTHER VEHICLES DOCKING WITH THE SPACE STATION			●		●	●		●	●			●						●			●		
C-12	SPACE STATION MODULES SHOULD BE TUMBLED TO RID THEM OF INTERNAL DEBRIS AND CONTAMINANTS IMMEDIATELY PRIOR TO PREPARATION FOR LAUNCH			●																				
C-13	PROVISIONS SHALL BE MADE FOR IN-FLIGHT SERVICING, ADJUSTING, CLEANING, REMOVAL AND REPLACEMENT OF OFFENDING COMPONENTS, TESTING AND REPAIRING OF ALL CRITICAL SUBSYSTEMS					●								●										
C-14	WEAR ITEMS SHOULD BE LIFE CYCLE TESTED IN A REALISTIC ENVIRONMENT					●												●						
C-15	ALL PERSONAL ITEMS SHOULD BE SCREENED FOR FLAMMABILITY AND TOXICITY				●	●																		
C-16	SPACE STATION PROTECTIVE ENCLOSURES SHALL BE PROVIDED FOR ALL HIGH MASS/HIGH SPEED ROTATING MACHINERY					●			●															

CREW SAFETY CRITERIA RELATED THREATS

GROUP: STATION INTEGRITY

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO MATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
C-17	ACTIVE/PASSIVE COMPARTMENTATION SHOULD BE PROVIDED TO CONTAIN AND/OR PREVENT FIRE/ EXPLOSION/DEPRESSURIZATION INITIATION OR IMPACT PROPAGATION. COMPARTMENTS SHOULD BE INSPECTABLE TO SUPPORT DAMAGE CONTROL AND MAINTENANCE OPERATIONS	●	●							●	●													

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CONTINGENCY CONTROL

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
D-1	Identified hazards should be eliminated, reduced to controlled hazards, or specified as residual hazards	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
D-2	Provision should be made for detecting, containing/confirming, controlling and restoring to a safe condition emergencies such as fire, toxic contamination, depressurization, structural damage, etc. The tools, tasks, spares, workspace, storage volumes necessary for these provisions shall be included in space station design planning	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
D-3	For those malfunctions and/or hazards which may result in time-critical emergencies, provision should be made for the automatic switching to a safe mode of operation and for caution and warning of personnel			●						●	●		●										●	
D-4	The capability should be provided on the space station for the detection of malfunctions and/or hazards, tracing to the failed replaceable unit and the display of information to the crew necessary for corrective action	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
D-5	Provisions should be made for the crew to ascertain the hazard status of any habitable module external to the inhabited module and to mitigate or control remotely those hazards which would preclude safe entry to the module in question		●		●						●	●						●						

CREW SAFETY CRITERIA RELATED THREATS

GROUP: CONTINGENCY CONTROL

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
D-6	The crew should be able to override any automatic safing or switchover capability. All overrides should be two-step operations with positive feedback to the initiator, which report impending results of the override command, prior to the acceptance of an execute command													●	●									

CREW SAFETY CRITERIA RELATED THREATS

GROUP: SELECTION/INDOCTRINATION

ITEM		FIRE	LEAKAGE	TUMBLING/LOSS CONTROL	CONTAMINATION	INJURY/ILLNESS	GRAZING/COLLISION	CORROSION	MECHANICAL DAMAGE	EXPLOSION/IMPLOSION	LOSS OF PRESSURIZATION	RADIATION	OUT-OF-CONTROL IVA/EVA	INADVERTENT OPS	LACK OF CREW COORD	ABANDONMENT	METEOROID PENETRATION	CONSUMABLES DEPLETION	STRUCTURAL EROSION	ORBIT DECAY	ACCESS TO HATCH	TEMPERATURE EXTREMES	DEBRIS	FREE ORBIT
E-1	Crew selection should be based on selectees cross-trainability in fields other than specialty.													●	●									
E-2	Orbital crews should be an integral part of the air/ground system active interface with on-orbit crews.														●									
E-3	Station crews and teaming should allow equal thirds of schedule for on-orbit, ground interface operation and recycle operations (post orbit rehabilitation, leave, additional training, public relations, etc.)					●								●	●									
E-4	Assurance should be provided that each mission segment crew is familiar with 1) Station Operations and Maintenance as concerns critical subsystem and 2) Procedures necessary to render SAFE all experiments and/or user-processes.					●								●	●									
E-5	Screening criteria should include assessment of attitudes, physical needs, psychological needs, personality traits, ability to function under stress, ability to accept direction, and TBD														●									

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11. CRITERIA IMPACT

The following table relates each criterion to the areas it impacts. In the same manner as the Threat/Criteria relationships, the criteria usually have more than one area impact. This table can be helpful to systems or design engineers in flagging a criterion as it impacts their discipline.

CREW SAFETY CRITERIA IMPACTS

GROUP: DAMAGE TOLERANCE

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
A-1	No credible single space station failure, operational error or radio frequency signal should result in damage to space station or mission/payload equipment or in the use of emergency equipment; some limited degradation in mission/payload accommodations, crew convenience/comfort, or space station attitude or orbit may be allowed	●			●	●					●
A-2	No credible combination of space station failures, mission/payload equipment failures, operator errors, or radio frequency signals should result in the potential for crew injury or permanent loss of the space station or primary mission/payload capability; institution of emergency procedure/equipment may be necessary but no hazardous operational level will be reached		●		●						●
A-3	All subsystem/equipment critical to preservation of life and space station survival should be fail-operational/ fail-safe (excepting primary structure and pressure vessels)		●		●						
A-4	Fail-operational/fail-safe designed subsystems should allow maintenance to upgrade the subsystem/equipment without being degraded below fail-safe during the maintenance actions following the second failure		●	●					●		●

CREW SAFETY CRITERIA IMPACTS

GROUP: DAMAGE TOLERANCE

ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
		SPACE STATION IMPACT									
A-5	Potentially rupturable containers should contain less material (gas, liquid, solid) than would cause unacceptable overpressure if all the material were released in a leakage, rupture or explosion	●	●		●						●
A-6	Redundant accommodations for command and control of the space station should be provided such that the primary control center has complete capability, but the backup control center will have, as a minimum, control of critical functions	●	●		●	●					●
A-7	Design inhibits to prevent failure propagation from one volume/subsystem/component to another should be incorporated	●	●							●	
A-8	The space station should be designed and operated so that any damaged module can be isolated as required. Provisions shall be made for pressure isolation within the volumes. Modules should be equipped and provisioned so that the crew can safely continue a degraded mission and take corrective action to either repair or replace the damaged module	●	●	●	●	●			●		●

CREW SAFETY CRITERIA IMPACTS

GROUP: DAMAGE TOLERANCE

ITEM		SPACE STATION IMPACT REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
A-9	Any volume should be capable of sustaining the whole crew, and capability should be provided for performing critical functions at an emergency level until the crew can be rescued. Electrical and fluid lines in each pressure-isolatable volume required for critical functions should be protected against the effects of explosion, fire, vacuum, and corrosion	●	●		●	●		●	●		●
A-10	Capability should be provided for performing critical functions with a portion of a subsystem inoperative for maintenance, and any pressure-isolatable volume inactivated and not accessible	●	●	●	●						
A-11	Redundant equipment, lines, cables, and utility runs which are critical for safety of personnel or mission continuation should either be located and routed in separate compartments (i.e., separated by a structural wall) or should be protected against fire, smoke, contamination, loss of pressure, overpressure, and shrapnel	●	●								
A-12	All walls, bulkheads, hatches and seals whose integrity is required to maintain pressurization or atmospheric isolation should be readily accessible for inspection and repair by crewmen in pressurized suits			●		●			●	●	●

CREW SAFETY CRITERIA IMPACTS

GROUP: DAMAGE TOLERANCE

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
A-13	AS A DESIGN GOAL, INSPECTION, MAINTENANCE AND REPAIR OF CRITICAL SUBSYSTEMS BY SHIRT SLEEVED CREW MEMBERS SHALL BE ACCOMMODATED			●							●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT: REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-1	Provisions should be made for a safe haven within the space station, isolatable from the hazard capable of sustaining the crew for 22 days beyond normal resupply and allowing rescue by a Shuttle. Provisions shall be made to monitor the health of the remaining habitable modules from this safe haven				●	●					●
B-2	Personnel protection from electrical shock, radiation, mechanical and thermal hazards should be provided			●				●	●		●
B-3	Accessways between compartments should be sized such that an IVA/EVA-suited crewman is allowed free passage			●			●		●		●
B-4	Provisions shall be made for the protection and survival of the whole crew during solar storm activity as defined by the TBD design mission radiation model					●				●	●
B-5	Personnel escape routes should be provided in all hazardous situations					●			●		●
B-6	Provisions and habitable facilities should be adequate to sustain the entire crew for a minimum of 22 days during an emergency situation requiring rescue					●					●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT: REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-7	Atmospheric stores and subsystem capacity sufficient for two full repressurization of each pressurized habitable volume should be maintained on/at the space station during manned operations		●			● (ECS)	●				
B-8	Access to EVA and IVA airlock and suit station(s) should be provided for all credible emergency conditions. Airlock chamber(s) should be provided to permit crew access for EVA/IVA operations			●		●	●		●		●
B-9	Two or more suited crewmen should participate in any pressure suit activity and rescue provisions should be provided to allow safe return to space station following the incapacitation of any one crewman	(EVA operational provisions)									●
B-10	Real-time monitoring of the atmospheree constituents, including harmful airborne trace contaminants and odors should be performed. Control shall be provided for each pressurized habitable volume		(Monitoring of each pressurizeable volume)		●	●					●
B-11	Two or more entry/egress paths should be provided to and from every module or pressure-isolatable volume. The two paths should be separated by airtight partitions, or shall be at least 10 feet apart, and should each lead to an area in which the crew can survive until escape, rescue or removal of the hazard	●				●	●		●		●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
		SPACE STATION IMPACT									
B-12	Materials used in the habitable areas should not outgas toxic constituents in the lowest pressure environment and highest temperature to which they will be exposed							●			
B-13	All EVA and unpressurized compartment IVA should be conducted using the "buddy system." (Note: buddy system criteria can be met with suited crew to station exit in visual contact with subject). The buddy system should also be used during shirtsleeve operations in hazardous areas						●				●
B-14	A margin of consumables should be provided onboard, sufficient for performing critical functions for TBD hours at a reduced level following any credible accident which renders one pressure-isolatable compartment unavailable					●					
B-15	At least two egress paths should be available from each module for emergency egress of personnel during manned ground operations	●							●		
B-16	Emergency suits required in the space station, sized to fit any crewman, should be in readily accessible locations within each pressure-isolatable volume				●		●				●
B-17	Provisions should be made for emergency medical treatment of credible accidents and illnesses for durations compartible with the rescue provisions					●	●				●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT: REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-18	The safe environment and the safe operational status of activated subsystems within the space station should be verified prior to personnel entry, initially and prior to reentry following temporary station abandonment				●	●					●
B-19	Deployment and initiation of operations considered hazardous should be checked out from a safe location before exposing crewmen to the potential hazards				●						●
B-20	Provision should be made for the return of a crewmen incapacitated while performing EVA										●
B-21	Provisions should be made for the detection, containment and/or disposal of toxic contaminants					●		●			
B-22	Pressurized volumes should have adequate free volume (not occupied by equipment) to allow crew freedom of movement to support long-duration habitation						●				●
B-23	Hazardous or toxic fluid storage, conduits and interconnects between modules should be external to the pressurized volume. Exceptions may be made for flammable but nontoxic gases where the maximum possible quantity released by a leak cannot result in a flammable mixture						●	●			

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-24	**Provisions should be made for detection and control of pathogenic agents onboard the space station using methods harmless to crew and equipment**				●	●		●			
B-25	**Planned crew tasks should be assessed initially, for compliance intent with TBD regulations before performing such tasks** (Standard industrial safety practice for work areas)			●		●		●	●		●
B-26	**Provision should be made for handling irrational crewmembers and the remains of deceased crewmembers**						●				●
B-27	THE OCCUPIED COMPARTMENT'S ACOUSTICAL NOISE ENVIRONMENT SHOULD BE WITHIN HUMAN TOLERANCE NOISE EXPOSURE LIMITATIONS, PERMIT INTELLIGIBLE AUDITORY COMMUNICATIONS, HAVE A MINIMUM OF PURE TONE OR NARROW FREQUENCY BAND(S), A MINIMUM OF INTERMITTENT OR DISCONTUOUS NOISES AND A MINIMUM OF HIGH FREQUENCY NOISES. SYSTEM AND EQUIPMENT DESIGN SHOULD BE ACCOMPLISHED FROM THE OUTSET TO PRODUCE AND ACCEPTABLE NOISE ENVIRONMENT. DESIRABLY, THE NOISE ENVIRONMENT SHOULD MEET NC-TBD-OR-LOWER NOISE CONTOUR FOR WORK PERIODS AND NC-TBD-OR LOWER FOR SLEEP PERIODS.				●						●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-28	ANY MODULE DESIGNATED AS A SAFE HAVEN SHALL BE PROVIDED WITH AND AIRLOCK CHAMBER AT THE PORT ASSIGNED FOR ORBITER DOCKING AND RESCUE, TO ALLOW CREW TRANSFER AND RESCUE FROM A DEGRADED AND/OR MARGINAL SAFE HAVEN. THE RESCUE HATCH SHALL PROVIDE FOR ACTUATION FROM THE INSIDE OR OUTSIDE TO ACCOMMODATE CONTINGENCIES					●	●				
B-29	SUBSYSTEMS SHALL BE DESIGNED TO PREVENT INADVERTENT OR ACCIDENTAL ACTIVATION OR DEACTIVATION OF FUNCTIONS OR EQUIPMENT THAT WOULD BE HAZARDOUS TO PERSONNEL OR THE SPACE STATION	●									●
B-30	RADIATION DOSES THAT AFFECT PERSONNEL SAFETY MUST BE CONSIDERED FROM ALL SOURCES, INCLUDING NATURAL ENVIRONMENT, EXTERNAL ISOTOPE AND REACTOR SOURCES (IF ANY), ELECTROMAGNETIC SOLAR RADIATION AND INTERNALLY ALLOWABLE RADIATION LEVELS FROM EXPERIMENTS, PROCESSES AND HEALTH MAINTENANCE/DIAGNOSTIC EQUIPMENT									●	●
B-31	EXPOSED SURFACES WITHIN HABITABLE MODULES SHALL NOT EXCEED A TEMPERATURE OF 113°F (WITH A DESIGN GOAL OF 105°F) AND A LOW TEMPERATURE OF NO LESS THAN 40°F										●

CREW SAFETY CRITERIA IMPACTS

GROUP: CREW PROTECTION

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
B-32	EXCEPT FOR CONTINGENCIES EVA SHALL NOT BE USED FOR HAZARDOUS OPERATIONS OR WHEN A MANEUVERING SPACECRAFT IS WITHIN THE PROXIMITY OPERATING ZONE (±5NM)										●

CREW SAFETY CRITERIA IMPACTS

GROUP: STATION INTEGRITY

ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
		SPACE STATION IMPACT									
C-1	Primary pressure structural materials should be nonflammable. Interior walls and secondary structure should be self-extinguishing							●		●	
C-2	Normally exposed nonmetallic materials should be self-extinguishing in the most severe oxidizing environment to which they will be exposed. Means shall be provided for fireproof storage of medical supplies, maintenance supplies, food, tissue, clothing, trash, and for other non-self-extinguishing items, when they are not in use							●		●	
C-3	Potentially explosive containers such as high pressure vessels or volatile gas storage containers should be placed outside of and as remotely as possible from personnel living and operating quarter. Wherever possible the containers should be isolated and protected so that failure of one will not propagate to others							●		●	
C-4	Containment of all materials requiring return via the STS to prevent contamination of the space station environment should be provided to reduce the hazard of potential fire and toxic conditions							●			
C-5	Tank supports should be designed to restrain the tank under propulsion effect of rapidly escaping gas							●			

CREW SAFETY CRITERIA IMPACTS

GROUP: STATION INTEGRITY

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
C-6	Design provisions should be incorporated to prevent uncontrollable hatch opening due to pressure differentials, and to allow controlled closing of hatch openings with or against pressure differentials, for the worst case pressure differentials anticipated				● (Hatch detail design)	●	●			●	
C-7	Equipment or materials sensitive to contamination should be handled in a controlled environment. Fluids and materials should be compatible with the combined environment in which they are employed							●			
C-8	Provisions should be made to allow communication between any and all isolatable/habitable volumes on a primary and backup basis	●			●	●					●
C-9	Provisions should be made for material usage, identification and location mapping to allow real-time evaluation to determine adequate inspection/maintenance replacement frequencies			●			●				●
C-10	FLUID OR GASEOUS FLOW SUCH AS PRESSURE RELIEF VALVES/EXHAUSTS, FUEL TRANSFER DISCONNECTS, ETC., SHOULD BE DESIGNED TO PREVENT TORQUING/TURNING OR UNDESIRABLE TRANSLATION MOTIONS TO THE SPACE STATION		●			●	●			●	

CREW SAFETY CRITERIA IMPACTS

GROUP: STATION INTEGRITY

ITEM		SPACE STATION IMPACT									
		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
C-11	ALL REACTION CONTROL THRUSTING DEVICES USED PRIMARILY FOR ALTITUDE POSITIONING OF THE SPACE STATION, AND OCCASIONALLY FOR VELOCITY CHANGES, SHOULD BE LOCATED SUCH THAT THE EXHAUST PLUME DOES NOT IMPINGE UNPON OTHER STRUCTURAL ELEMENTS SUCH AS SOLAR CELLS, AREAS REQUIRING EVA MAINTENANCE OR OTHER VEHICLES DOCKING WITH THE SPACE STATION						●				
C-12	SPACE STATION MODULES SHOULD BE TUMBLED TO RID THEM OF INTERNAL DEBRIS AND CONTAMINANTS IMMEDIATELY PRIOR TO PREPARATION FOR LAUNCH										
C-13	PROVISIONS SHALL BE MADE FOR IN-FLIGHT SERVICING, ADJUSTING, CLEANING, REMOVAL AND REPLACEMENT OF OFFENDING COMPONENTS, TESTING AND REPAIRING OF ALL CRITICAL SUBSYSTEMS			●							
C-14	WEAR ITEMS SHOULD BE LIFE CYCLE TESTED IN A REALISTIC ENVIRONMENT			●				●			
C-15	ALL PERSONAL ITEMS SHOULD BE SCREENED FOR FLAMMABILITY AND TOXICITY							●			
C-16	SPACE STATION PROTECTIVE ENCLOSURES SHALL BE PROVIDED FOR ALL HIGH MASS/HIGH SPEED ROTATING MACHINERY						●				

CREW SAFETY CRITERIA IMPACTS

GROUP: STATION INTEGRITY

ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
		SPACE STATION IMPACT									
C-17	ACTIVE/PASSIVE COMPARTMENTATION SHOULD BE PROVIDED TO CONTAIN AND/OR PREVENT FIRE/EXPLOSION/DEPRESSURIZATION INITIATION OR IMPACT PROPAGATION. COMPARTMENTS SHOULD BE INSPECTABLE TO SUPPORT DAMAGE CONTROL AND MAINTENANCE OPERATIONS			●			●				

CREW SAFETY CRITERIA IMPACTS

GROUP: CONTINGENCY CONTROL

		SPACE STATION IMPACT									
ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
D-1	Identified hazards should be eliminated, reduced to controlled hazards, or specified as residual hazards	(Safety program administration)									
D-2	Provision should be made for detecting, containing/ confirming, controlling and restoring to a safe condition emergencies such as fire, toxic contamination, depressurization, structural damage, etc. The tools, tasks, spares, workspace, storage volumes necessary for these provisions shall be included in space station design planning			●	●	●	●	●	●	●	●
D-3	For those malfunctions and/or hazards which may result in time-critical emergencies, provision should be made for the automatic switching to a safe mode of operation and for caution and warning of personnel	●	● (Automatic redundancy management)		●						
D-4	The capability should be provided on the space station for the detection of malfunctions and/or hazards, tracing to the failed replaceable unit and the display of information to the crew necessary for corrective action				●						●
D-5	Provisions should be made for the crew to ascertain the hazard status of any habitable module external to the inhabited module and to mitigate or control remotely those hazards which would preclude safe entry to the module in question			(Remote switching)	●						●

CREW SAFETY CRITERIA IMPACTS

GROUP: CONTINGENCY CONTROL

		SPACE STATION IMPACT									
ITEM		REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
D-6	The crew should be able to override any automatic safing or switchover capability. All overrides should be two-step operations with positive feedback to the initiator, which report impending results of the override command, prior to the acceptance of an execute command				●						●

CREW SAFETY CRITERIA IMPACTS

GROUP: SELECTION/INDOCTRINATION

ITEM		SPACE STATION IMPACT: REDUNDANT	DUAL REDUNDANT	MAINTAINABLE	C&W/COMM	SAFE HAVEN	SS SIZING	MATERIAL CONTROL	ACCESS/DUAL EGRESS	BARRIER SYSTEM	HUMAN FACTORS
E-1	Crew selection should be based on selectees cross-trainability in fields other than specified.			●							●
E-2	Orbital crews should be an integral part of the air-ground system active interface with on-orbit crews.				●						●
E-3	Station crews and teams should allow equal thirds of schedule for on-orbit, ground interface operation and recycle operations (post orbit, ground interface operation and recycle operations (post orbit rehabilitation, leave, additional training, public relations, etc.)										●
E-4	Assurance should be provided that each mission segment crew is familiar with 1) Station Operations and Maintenance as concerns critical subsystem and 2) Procedures necessary to render SAFE all experiments and/or user processes..										●
E-5	Screening criteria should include assessment of attitudes physical needs, psychological needs, personality traits, ability to function under stress, ability to accept direction and TBD.										●

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12. AREAS FOR FURTHER EMPHASIS

The following tabular listing extracts areas identified in the human factors follow-on study that should be given more attention. Some of the items may be underway or have been completed. The listing in no way comments on completness or status of the related items. Rather, the list indicates that within the data reviewed there seemed to be areas of data deficiency.

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	THREAT
1. Airlock for lab module vs. dual egress study	Contamination Loss of Access to Hatch
2. Airlock for lab module vs. delta P pressure curtain study	Contamination
3. External stowage of EVA suit (cost impacts) vs. internal contamination	Contamination
4. Free flyer for "dirty" payloads vs. on-board decontamination/clean room costs	Contamination
5. Up-front costs vs. program costs for regenerative ECLSS or a consumable-using ECLSS	Contamination Stores Depletion
6. User safety requirments documents vs. user safety ombudsman	Program
7. Refurb module on orbit vs. return and refurb	Program
8. User guide to automate vs. manual approach to experiments/processes	Program
9. Testing one-of-a-kind payload vs. recommending encapsulation	Program
10. On-board material/inventory control vs. on-ground control with data link (expanded MATCO-RI-System)	Corrosion Contamination Inadvertent Ops Stores Depletion
11. Costs of measuring internal contamination vs. risk of accepting contamination	Program
12. Dedicated (module) vs. centralized ECLSS	Contamination Loss of Pressurization
13. Relaxed contaminant allowables per zone (hazard critical/contamination sensitive) vs. minimum contamination allowables for entire station	Contamination Injury/Illness
14. Threshold Level Values (TLV's) for 24-hour station vs. TLV's for 8-hour work week regimes	Injury/Illness
15. EVA dedicated module (w/decontamination capability) vs. decontamination in dedicated airlock	Contamination

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	THREAT
16. Level of material assessment and control for station vs. user	Program
17. Cost of medical care on-orbit vs. medical screening (appendectomies, radiation max-out, etc.)	Injury/Illness
18. Realtime contamination monitoring vs. "snap shot" monitoring	Contamination
19. Classified Materials Controls vs. "Industrially Sensitive" material control	Lack of Crew Coordination
20. High altitude (Debris/Radiation) vs. lower altitude (oxygen bombardment)	Debris, Radiation, Structural Erosion, Contamination
21. Re-orienting station mass vs. providing shielding from solar flares	Radiation
22. Optimum repair level: Unit vs. Component	Program
23. Walk-around bottles vs. plug-in O_2 system	Loss of Pressurization Contamination
24. Synergistically develop barrier system (module pressure wall) to accommodate debris, meteoroids, radiation, oxygen bombardment, pressure redundancy, shrapnel shielding and structural inspection/repair	Radiation, Debris, Meteoroid Reduction, Loss of Pressure, Mechanical Damage, Grazing/Collision, Leakage
25. Develop body vital signs monitoring system for each crew member with data aggregated for control panel display or down listing	Injury/Illness
26. Define medical facilities for build-up, initial and growth stations	Injury/Illness
27. Provide orbit changing maneuvering capability of station to avoid debris, including determining cycle-rate and total propulsion requirements	Debris
28. Develop on-going international protocols for traffic control in space. Expand NORADS capability to identify debris down to Xmm diameter	Debris

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	THREAT
29. Define fragmentation dispersion of pressure vessels in a vacuum: calculated disperson or actual disperson (291)	Explosion
30. Definition of blastwave characteristics for typical gas storage vessels (291)	Explosion
31. Better definitions of fragment impact effects on a variety of strutures and facilities typical of those occurring in aerospace vehicle explosions (291)	Explosion
32. Centrallized/Decentralized work stations (station subsystem maintenance, EVA/EMU maintenance and storage, module repair/refurb, user equipment maintenance and repair)	Lack of Crew Coordination
33. EVA suit vs. chamber/airlock for hyperbaric treatment of the bends	Injury/Illness
34. EVA suit external surface material compatibility or selected overgarments	Contamination
35. Small tool "pass through" compartment to support EVA vs. cost of module or airlock press/depress	Stores Depletion
36. Remote actuating of airlock outer hatch vs. manual actuation by EVA crewman	Injury/Illness
37. Assessment of personal and equipment restraints and tether	Lack of Crew Coordination
38. Minimize types and sizes of fastening devices (weight vs. logistics impact)	Stores Depletion
39. Free flying (permanently co-orbiting station) EVA tool box vs. space station mounted tool box	Injury/Illness
40. Clear definition of EVA ionizing radiation impact to crewmember and shielding capability of EVA suit materials	Injury/Illness
41. Experiments to investigate and determine properties of combustion and propogation of fire in Micro g.	Fire

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	HUMAN FACTORS ISSUE
1. Develop realistic allowable radiation dose rate tables for part of body for EVA, flight, quarter, year and whole life	Violation of Safety
2. Dedicated module tasks for crew vs. common task, all-module assignment	Scheduling
3. Less than 90 day recycles vs. on-station expandable costs and crew personal equipment needed to support extended stay	Scheduling
4. Generalist vs. specialist for crew training guidelines	Scheduling
5. Polarized shades vs. opaque shades	Confinement/Isolation
6. Define crewmember psychologial and physiological screening elements to support functioning in a long term confined/isolated environment - an extended application of submarine screening techniques	All
7. Aggregate man-machine design trades to determine interface point for each trainable task. This is needed to support crew training for task as well as crew training for tool use	Scheduling
8. Define a private electronic center for each stateroom to include, at least an entertainment center (visual/aural), a private television link to Earth, background (white noise) mood generator	Recreation
9. Allow personalization of staterooms or workareas (photos, cartoons, books, etc.) including decor options	Confinement/Isolation Recreation
10. Include architectural/interior decoration consultation in habitable module desing	All
11. Look into feasibility of UP-DOWN station orientation (accepting semi-fetal crewman micro-g position) in overall station design	All
12. Develop color coding system for all tubing, piping, emergency passageway, damage control equipment and tasks including "warnings", "cautions", and "notes"	Violation of Safety

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	HUMAN FACTORS ISSUE
13. Consider possibility of single, large-volume space (inflatable or structurally built-up) to provide "open" environment for crew on growth station	Confinement/Isolation
14. Develop chemical/physical restraint system for abberant crew members	Behavorial Protocols
15. Look into concept of ground teaming and early orientation of complete teaming to staff the space stations, including coordinated on-orbit, on-leave, at ground console, in-training segments	Scheduling
16. Specify the need for a maximum allowable NC-acoustic requirement per module (work area vs. habitable area) and require acoustic subsystem input apportionment within each module. Include a qualification test to apportioned acoustical requirements	Acoustics
17. Develop standard decision-making and techniques to be used for insulation vs. isolation of noise	Acoustics
18. Include crewman noise tolerance testing in screening procedures	Sensory Deprivation
19. Screen crewmembers for "open" vs. "closed" interaction acceptance pattern	Behavorial Protocols
20. Develop authority hierarchy for station-to-ground and intra-station so crewmembers understand the lines of authority and individual responsibilities (this includes station assigned vs. transient scientist/specialist interactions)	Behavorial Protocols
21. Provide education/orientation for crewmembers regarding cross-cultural issues and problems	Behavorial Protocols
22. Consider the need to schedule health maintenance equipment and consider its placement with respect to sleeping areas. Exercise is mandatory, not a recreational option.	Scheduling

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	HUMAN FACTORS ISSUE
23. Consider adequate capability for storage, inventoring, handling and disposition of servicing, maintenance, cleaning and repairing consumables and just plant garbage	Cleaning/Disinfecting
24. Identify family of cleaning/disinfecting chemicals compatible with the selected ECLSS approach	Cleaning/Disinfecting
25. Isolate/decontaminate/quarantine crewmembers for X-days before being sent to station, considering the possibility of being contaminated in the orbiter while in route	Cleaning/Disinfecting
26. Train cremembers in all places of station tasks, housekeeping	Cleaning/Disinfecting
27. Define minimum crew cleanliness requirements (this may be an intra-cultural issue)	Cleaning/Disinfecting
28. Define requirements (total volume and flow rates for potable and non-potable water	Cleaning/Disinfecting
29. When teaming, screen crewmembers for compatible recreation interests	Recreation
30. Prepare specification for recreation equipment/kit - with options per person	Recreation
31. Determine method of measuring reasonable personal "space bubble" - flat vs. the sphere within which an individual feels threatened. Then, screen for crewman who can function within this volume.	Territorial Issues
32. Define/provide personal storage space	Territorial Issues
33. Include personal consumables (toilet articles, etc.) in master logistics planning list	Territorial Issues
34. Orient crew toward "non-violation" of personal territory	Territorial Issues
35. Consulting with astronauts, develop a standard for clothing options and hygiene consumables options	Hygiene
36. Consider scheduling hygiene (common) equipment	Scheduling, Hygiene

AREAS FOR FURTHER STUDY

AREA OF RECOMMENDED FUTURE EMPHASIS	HUMAN FACTORS ISSUE
37. Clearly identify (hardware, procedural software) safety critical segments of tasks to ensure mandatory compliance	Violation of Safety
38. Prepare task flow charts that identify as many contingency operations as possible to determine response need	Violation of Safety
39. Screen <u>all</u> carry-on personal equipment	Violation of Safety

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15. Supplementary Notes

Langley Technical Monitor: Robert D. Witcofski
Final Report

16. Abstract

The scope of this study considered the first 15 years of accumulated space station concepts for Initial Operational Capability (IOC) during the early 1990's. Twenty-five threats to the space station are identified and selected threats addressed as impacting safety criteria, escape and rescue, and human factors safety concerns. Of the 25 threats identified, eight are discussed including strategy options for threat control: fire, biological or toxic contamination, injury/illness, explosion, loss of pressurization, radiation, meteoroid penetration and debris. This report consists of five volumes as noted:

Vol. I - Final Summary Report (NASA CR-3854)
Vol. II - Threat Development (NASA CR-3855)
Vol. III - Safety Impact of Human Factors (NASA CR-3856)
Vol. IV - Appendices (NASA CR-3857)
Vol. V - Space Station Safety Plan (NASA CR-3858)

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