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Achievements and Challenges of Space Station Freedom's Safety Review Process

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ACHIEVEMENTS AND CHALLENGES OF SPACE STATION FREEDOM'S SAFETY REVIEW PROCESS

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SUMMARY

The most complex space vehicle in history, Space Station Freedom, is well underway to completion, and System Safety is a vital part of the program. The purpose of this paper is to summarize and illustrate the progress that over one-hundred System Safety engineers have made in identifying, documenting, and controlling the hazards inherent in the space station. To date, Space Station Freedom has been reviewed by NASA's safety panels through the first six assembly flights, when Freedom achieves a configuration known as Man Tended Capability. During the eight weeks of safety reviews spread out over a year and a half, over 200 preliminary hazard reports were presented. Along the way NASA and its contractors faced many challenges, made much progress, and even learned a few lessons.

INTRODUCTION TO SPACE STATION FREEDOM

Space Station Freedom is a complex vehicle, and some would say it is an even more complex program. Figure 1 shows the baseline configuration as of May 1993, and Figure 2 provides some key space station performance details. Since Freedom will be the largest space vehicle ever created, the work has been split up among several NASA centers in discrete "Work Packages" which are detailed in Figure 3. The first of Freedom's 17 assembly flights is scheduled for 1996 and the last is planned for the year 2000. After completion, four astronauts will live there on 90-day rotational assignments performing life science and materials processing experiments in microgravity.

Freedom is a self-contained world orbiting around the earth that must supply all the needs for its crew including air, water, food, electricity, and climate control, just to name a few. Because evacuation of the space station in case of a fire, system loss, or mishap is expensive and risky, Freedom must have an extremely robust and failure tolerant design yet be simple enough that a crew of four can operate and maintain it.

The space station has something of interest for every kind of System Safety engineer. Freedom presents hazards one might expect in an earth-bound industrial facility, and more. Space station hazards that would be familiar to every System Safety engineer include fire, electric shock, and pressure vessel rupture. Many hazards, however, sound like something out of a Buck Rogers episode. Impacts by orbital debris, atomic oxygen corrosion, loss of reboost capability, and electrical arcing between station and the plasma environment of low earth orbit all could cause a catastrophic loss. These are the most worrisome hazards since NASA has little or no prior experience with them.

NASA's SAFETY REVIEW PROCESS AND ITS OBJECTIVES

The objective of NASA's System Safety effort is to prevent injury or death to personnel and major system loss. The primary means to accomplish this objective is to characterize and document all hazards for NASA management so that they are cognizant of all risks. NASA program management has the authority to either eliminate, mitigate, or accept these risks. In keeping with this policy, all aspects of Space Station Freedom are being thoroughly reviewed by NASA for hazards to ground processing facilities, the crew, the space shuttle, and the station itself. All HRs must be approved and closed out by the program manager before the space station is launched.

The system safety process used by NASA in the manned spaceflight world is similar to the MIL-STD-882 approach--with a few modifications. Hazard analyses are performed to identify all hazard causes and controls, and a Hazard Report (HR) is written to document each hazardous condition. Depending on the type of hazard, engineers from the responsible prime contractor will present each HR to as many as three different NASA safety review panels. HRs are reviewed by the panels at several points during the design and development of the space station as shown below:

PHASE	TIMEFRAME	HR MATURITY
Phase 1	PDR (Prelim Design Review)	Hazard Causes/Controls identified
Phase 2	CDR (Critical Design Review)	Control verifications established
Phase 3	DCR (Design Certification)	Control verifications closed out

By signing off on these HRs at the Phase 3 safety reviews, NASA program management formally accepts the risk imposed by each hazard.

NASA's three safety panels consist of the Ground Safety Review Panel (GSRP), the Shuttle Payload Safety Review Panel (PSRP) and the Freedom Safety Review Panel (FSRP). The GSRP is composed of Kennedy Space Center engineers who assess compliance with Kennedy Space Center's ground processing safety requirements document KHB 1700.7B and the risk posed by the payload to the facilities and personnel. The PSRP is composed of Johnson Space Center engineers who assess compliance with the shuttle payload safety requirements of NSTS 1700.7B and the risk posed by the payload to the Space Shuttle and astronauts. Providing substantial credibility and depth to the PSRP, a small army of experts supports the panel in various fields such as flammability, fracture mechanics, and toxicity. The FSRP is composed primarily of System Safety managers from the NASA centers working on Freedom who review hazards causing crewmember injury or loss/damage to the space station. In contrast to the PSRP and GSRP, the FSRP cannot accept risk, and acts as an independent oversight committee making risk recommendations to space station program management.

SPACE STATION FREEDOM SAFETY REVIEWS

Between September 16, 1991 and January 28, 1993, the PSRP and FSRP jointly held a total of eight safety reviews, each lasting an average of a week. The first meeting in September of 1991 was labelled a "Pathfinder." Its purpose was to convene the FSRP for the first time and establish rules, meeting protocol, and safety philosophy. Both the PSRP and FSRP were also given presentations of the preliminary design of Freedom. At the Pathfinder an extraordinary number of System Safety engineers were present from various NASA centers and numerous aerospace corporations from around the country. Since every center and company brought its own "safety culture" to the meeting, extensive safety philosophy discussions were needed to gain consensus from this diverse group on the process and procedures for the upcoming series of Freedom safety reviews.

Over the following sixteen months, Space Station Freedom was reviewed through the Man Tended Capability configuration, or first six assembly flights. All aspects of Freedom (except ground processing) were covered, including launch, on-orbit payload deployment, assembly by spacewalking astronauts, system startup, and nominal operation. 210 HRs were presented to the panels, and 188 were signed by them. Signature at Phase 1 indicates that the panels believe hazard causes are properly identified and the controls are adequate. Figure 4 shows the detailed breakdown of HRs signed and submitted per flight and Work Package.

The HRs that were not signed were unacceptable to the panels for a variety of reasons. A few of the HRs documented procedures or designs which violated safety requirements. Other HRs were simply incomplete or vague. For example, one unsigned HR described the structural failure of an appendage, but after extensive questioning the PSRP determined that not all the failure modes were accounted for. Therefore, the HR was not sufficiently developed to the Phase 1 level. The Work Package revised the HR and returned at a subsequent review for concurrence.

To resolve issues or discrepancies unearthed in the reviews, the panels assigned action items to the appropriate Work Package. Responses to these action items were presented at subsequent reviews and closed out if deemed acceptable by the panels. A typical action item levied on a Work Package was to determine if a particular subcontractor's honeycomb panel adhesive bonding process specification was adequate and to report the findings at the next safety review. Figure 4 details the number of action items assigned per Work Package at the reviews. As a rough indicator of the quality of the review, more thorough presentations received fewer action items.

The safety reviews prompted the program to eliminate many hazards. In many instances the safety reviews served as the forum for management to see the whole scope of a hazard for the first time. Increased management appreciation of the total risk of a hazard sometimes resulted in design or procedural modifications to mitigate or reduce those risks. A typical example of a hazard eliminated as a result of the safety review process was the elimination of sharp edges on the radiant heat fins of some electronic boxes. Since sharp edges could puncture the space suit, they are a potentially catastrophic hazard to the astronaut during an extra-vehicular activity. The simple solution was to round the sharp edges into a benign shape. Indeed, this was a design requirement, but in this application it was either not fully understood or deemed inconvenient by the designers. However, with the penetrating spotlight of the PSRP on the problem, it was not too long before a design change was implemented.

Another more complex design change involved upgrading the thermal control system from zero to single failure tolerance. The electrical power system has its own thermal control system consisting of ammonia coolant loops throughout the structure which pick up heat from the electronics and reject it into space at the radiator. In a previous weight scrub exercise, the redundant ammonia coolant loops for the thermal control system were merged into one loop. A single impact from a chunk of orbital debris, although unlikely, could have penetrated this loop and caused the loss of all the coolant, in turn reducing the electrical power output from 18.75 kilowatts to nearly zero on the early flights--a catastrophic hazard. This risk had previously been accepted by NASA program management, but after the attention it received during the safety reviews, NASA reconsidered the risk and approved the design change back to two independent coolant loops.

Many more examples of eliminated or controlled hazards exist, but the public probably will never hear about those successes because controlled hazards do not make newspaper headlines. That is the bittersweet nature of System Safety--its effectiveness is often intangible and only measured by degrees of failure. When Safety is successful, mishaps are prevented, but when Safety is unsuccessful, tragic loss occurs and everyone learns--too late--that the system was not safe enough.

The safety reviews provided a valuable benefit to Freedom's System Safety engineers as well. By having a credible and highly visible forum to air the risk inherent in space station, System Safety moved higher in the esteem of the design community. Whereas previous system safety efforts and opinions were viewed by many as a nuisance, after the safety reviews System Safety began receiving more calls from various design groups to interact with them on design decisions. Management began soliciting Safety's opinions more often, and as a result more favorable risk decisions were made by the program. NASA benefitted immensely by having risk documented and presented in an impartial manner so that decisions could be made with full awareness of how the outcome would affect overall station safety.

CHALLENGES AND ACHIEVEMENTS

Streamlining the Safety Review Process

The task of successfully completing the safety reviews was not easy for NASA and its contractors. Many challenges and obstacles had to be met and overcome. Perhaps the greatest challenge was to present the ocean of information about Freedom to the panels in the time allowed. Approximately 10,000 pages of data were sent to the PSRP and FSRP. Contributing to the flood of data are the many different safety perspectives that NASA must consider. For example, Space Station Freedom is at times a payload processed at Kennedy Space Center, a payload in the Shuttle, a cargo element which must be attended to by spacewalking astronauts during assembly operations, and a free-flying autonomous space vehicle required to survive 30 years in low earth orbit. Nothing in the history of spaceflight has had as many interfaces, contractors, facilities, and operations involved.

To minimize the time required to complete a safety review, the Work Packages learned to give more efficient safety presentations. Early reviews tended to be filled with parameters and design details of interest to the designers (cost, weight, and performance trade studies) but of limited interest to the safety panels. As the reviews progressed, the presenters became better able to focus on the safety-related aspects of designs such as hazard causes and controls. Progress was measurable: the first safety review (MB-01) required about eight days to complete and only 20 HRs were submitted, while the last safety review (MB-06) was completed in five days and 56 HRs were submitted. Assuming each review was equally adequate, this represents an increase in meeting efficiency of 448% !

Coordinating multiple interfaces

Another challenge which complicated the safety reviews was the incredible number of people, organizations, and interfaces involved in the Freedom program. Three NASA centers and several international partners are responsible for different pieces of station, and each attended the safety review with their own prime contractors and subcontractors. Representatives from other NASA committees would attend as well. Aside from the "people interfaces", there are a number of mechanical and software interfaces. For example, Work Package 2's main computer system partially controls Work Package 1's life support system and both are supplied power by Work Package 4's electric power system. A failure that knocks out a power bus could also take down the life support system unless power is rerouted quickly by the main computer system. Intermingled hazards like these create considerable room for debate about which organization should write and present each hazard.

To coordinate the agenda and flow of each safety review, a telephone conference, or "dry run," was held a few weeks before. At the dry run, the NASA centers attempted to set up a logical sequence of presentations and HRs. Sometimes interface issues, such as which center would write a hazard report on which subject, would be worked also. A few times small telephone conferences were held with key PSRP and FSRP members to brief them on upcoming high-profile safety issues. The dry-run and coordination meetings reduced the time spent at the safety review working the mundane administrative issues and allowed the Work Packages to focus more on the technical issues and HRs.

Another resource saving measure was minimizing the attendance at the reviews. Approximately one-hundred people attended the first couple of reviews, perhaps because of the novelty. As the reviews became more commonplace, attendance by non-participants slackened. Also as presenters became more familiar with the types of questions asked by the panels, fewer engineers were needed at the review to provide supporting information. One technique was to have engineers "on-call" back at the contractor's site. Questions not answerable by those present at the review were phoned to those on-call, and answers could be given to the panels minutes later. As a result, attendance at later reviews was probably one-third that of the first. Also, a few times NASA saved money by flying the safety panels to a Work Package rather than sending the Work Package to the safety review panels.

Reducing HR Development Time

In the beginning, a long lead-time--6 months not being unusual--was required to gather the safety data, write the hazard reports, review and revise them internally, and release them to the panels. Since designs sometimes changed radically in 6 months, much effort was made to reduce the safety package preparation time to a more responsive 2-3 month cycle.

Because hazard reports are somewhat sensitive documents, initially program management was hesitant to air them in public without extensive coordination and scrutiny. Various internal "pre-review reviews" and other forums were set up among the Work Packages so that program management would not be surprised by the content of the HRs at the safety review. Over time, however, Work Package management became more comfortable with the safety reviews and some of the extra meetings were dropped. Program managers and System Safety engineers developed proactive lines of communication as System Safety was brought more into the decision making process. Many managers found that by paying attention to Safety early on, they had no need to set up additional "hoops" for Safety to jump through later.

Reviewing Cutting Edge Technology

Another factor which slowed the pace of the reviews was that many of the space station designs and operations are on the cutting edge of technology. More lines of software code will be written for Freedom than for any previous space vehicle. More functions will be autonomously monitored, cycled, and reconfigured by the on-board computers without the crew in the loop. Thousands of hours of extra-vehicular activity will be required to assemble and maintain Freedom. Also several different robots will be installed on Freedom to assist with maintenance and assembly tasks. All these represent new genres of hazards to work. Since little or no experience base exists to guide the safety panels on these subjects, review of these designs and operations proceeded slowly and cautiously.

Safety Panels Adjusted, too

The panels, too, had challenges to overcome. Both the PSRP and FSRP had to adjust to the sheer volume of data. More homework was required of members before a review than with other, simpler payloads. Many different requirements or definitions existed in the Freedom program than in other payloads, at times causing some confusion among panel members.

A major adjustment had to be made in the authority traditionally granted to the PSRP. Usually the absolute authority in matters of Shuttle and Crew safety, the PSRP was confronted with a program that would not and could not always yield to their mandates. For all other payloads, the PSRP has "fly/no-fly" authority and ensures that any undue risk to the Shuttle is eliminated or shifted into the payload, regardless of cost and schedule. With Freedom however, a larger, holistic risk management approach is required. Since the Space Station Freedom program is every bit as important to NASA as the Space Shuttle Program, sometimes it is in the best interest of NASA to accept a small risk to Shuttle rather than to accept a large risk to Freedom. In the spirit of Station/Shuttle joint risk management, some longstanding payload requirements have been relaxed--although not forgotten--by the vigilant members of the PSRP.

One example of a relaxed requirement pertains to electrical connectors. During assembly operations on Freedom, many electrical connections have to be made by spacewalking astronauts. According to the PSRP's NSTS 1700.7B requirements, three inhibits (open switches) must be in place to permit the electrical connection. Due to the unreasonable weight and cost increases to implement this on Freedom, the PSRP decided to allow a single inhibit for electrical connections, provided that the Work Packages prove that no arcing hazard is present should that inhibit fail.

Generic Hazards

Early on during the reviews it was noted hazards such as micrometeoroid impact, atomic oxygen degradation, and battery leakage were not unique to any particular flight or mission stage but rather recurred throughout the life of Freedom. After considerable debate, the panels agreed to accept "generic" hazard reports for these situations. Generic HRs would be presented and signed only once. For each subsequent flight or stage where that generic hazard was present, the HR would be included in the safety data package but not presented again to the panels, greatly reducing the paperwork. For example, during the reviews, Work Package 4 presented 34 generic HRs to the panels versus 204 HRs that would have been required if each flight's hazards had to be handled individually.

Keeping track of the paperwork

With so many different flights, contractors, review panels, HRs, and systems to consider, it quickly became confusing who had presented what to whom and when. To alleviate the confusion, a "master matrix" was developed by the Work Packages to record what HR had been presented to which panel and when. Figure 5 shows an example of a master matrix. The idea is to simultaneously show what flight a hazard is present, when the HR was presented to which panel, and if the HR was generic or specific to a particular flight.

In addition to matrices, Work Packages began presenting "Hazard Trees" at the beginning of each review. Figure 6 is an example tree from Work Package 4. The tree illustrates the coverage of each HR and where it fits in relation to the rest of the HRs, much like an illustrated table of contents. Hazard trees reduced the confusion of where a particular hazard was documented in the HRs, and minimized questions from the panel members.

CONCLUSION

The primary achievement of the safety reviews was that for the first time in the Freedom program, NASA management received a comprehensive look at the overall risk of Space Station Freedom. Managers and engineers alike gained a greater appreciation of the discipline of System Safety. Safety organizations gained more credibility and stronger lines of communication within the design community. While it is difficult to measure the amount of risk eliminated as a result of these safety reviews, there is no question that the overall risk has been reduced. Design changes prompted by the reviews have eliminated several catastrophic hazards.

The safety review process has been streamlined considerably. System Safety engineers and panel members are gaining proficiency in the process, and as a result, fewer resources are required to review more material. Several new techniques and tools have been developed to make the reviews more efficient such as the "generic" HR and the hazard tree. Fewer engineers are required to support the reviews, and fewer "pre-reviews" are necessary within each NASA center.

The task of System Safety in the Space Station Freedom Program is ongoing, and sometimes it seems never-ending. There are at least 11 more flights to be reviewed at the Phase 1 level, and then all 17 flights must be reviewed again at the Phase 2 and Phase 3 level before Freedom is complete in 2000. With so many more reviews ahead, there is no doubt that further improvements will be made along the way.

BIOGRAPHY

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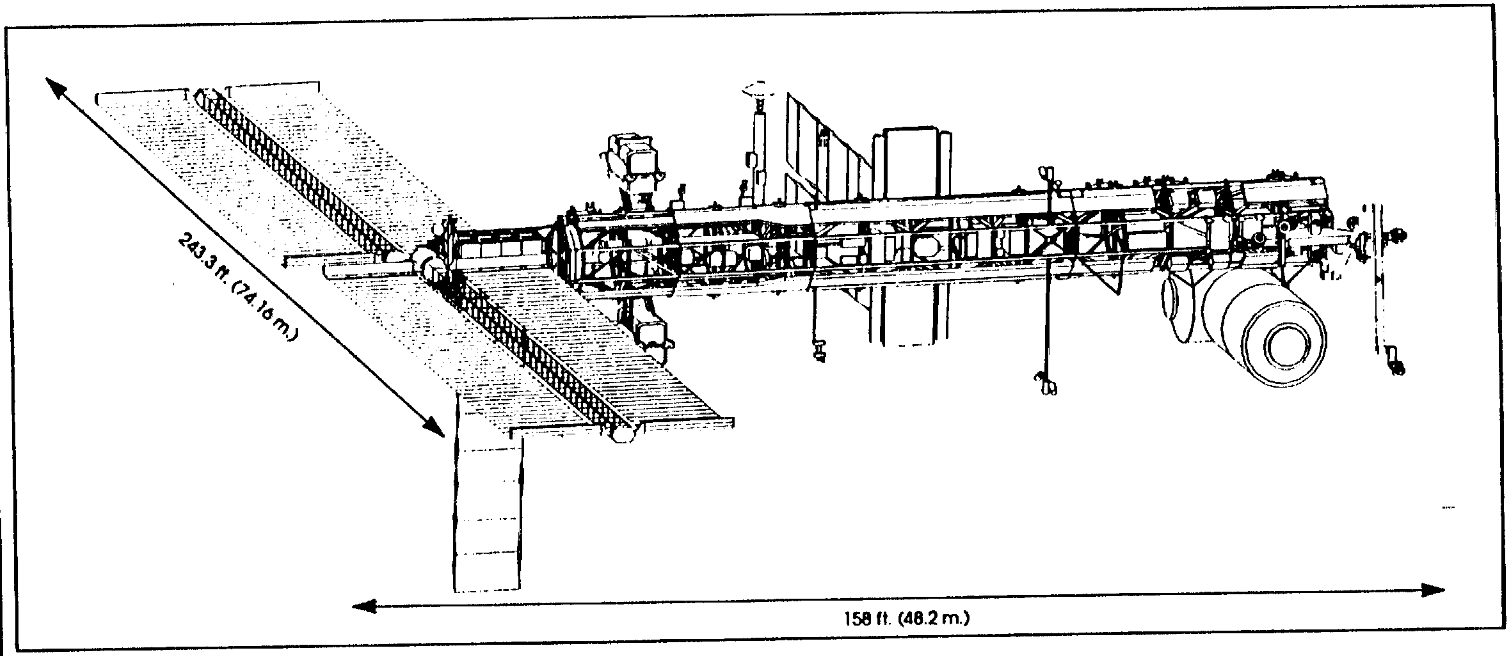
David Robinson is a System Safety engineer at the Lewis Research Center. He has been working on the Space Station Freedom Program since receiving a B.S in Aerospace Engineering from the University of Virginia in 1990.

Configuration shown at Man-tended Capability



Configuration shown at Permanently Manned Capability

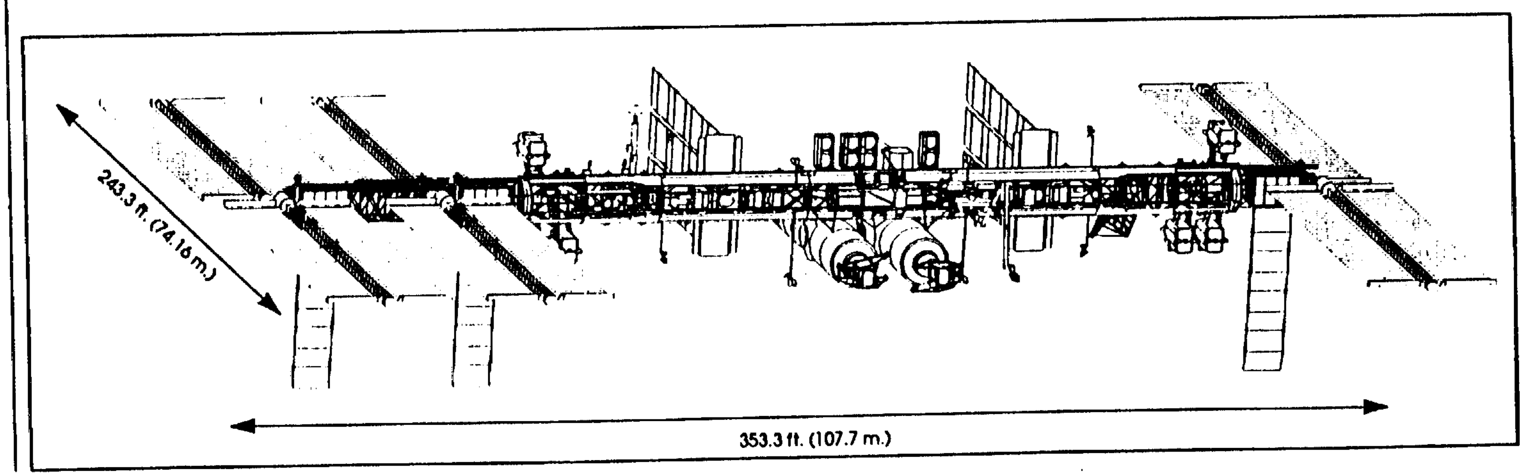


Figure 1.

Configuration Capabilities

	Man Tended Capability 1997	Permanently Manned Capability 2000
Power	18.75 kW - 1 PV module	56.25 kW - 3 PV modules
Module length	27 ft. - 1 microgravity lab	27 ft. - 1 lab, 1 hab
U.S. lab user racks (ISPRs)	12	12
User research power	11 kW	30 kW
Logistic module capacity	MPLM - 8 racks	PLM - 20 racks
Command uplink	70 kbps	70 kbps
Data downlink	43 Mbps	43 Mbps
Gravity level	1μg	1 μg
Attached payload accommodations	2 ports	4 ports
U.S. assembly and logistics flights	6	17
Permanent crew size	0	4 expandable to 8
Dedicated crew for research	4 (while on station)	2 (continuous)
Utilization flights (MTC to PMC)	8	N/A
Truss	4 segments built and checked out on ground	7 segments built and checked out on ground
Length (total)	158 ft.	353
Pressurized resource nodes	1	2
International hardware: Canada	Mobile Servicing System (simplified)	Mobile Servicing System
Japan	none	JEM - 10 ISPRs
Europe	none	APM - 20 ISPRs
Life Support	Shuttle supported	regenerative water loop
Propulsion	2 downsized modules	4 modules
Pressurized docking adapter	1	2
Airlock	0	1
Assured Crew Return Vehicle	0 - use Shuttle	1

Figure 2.

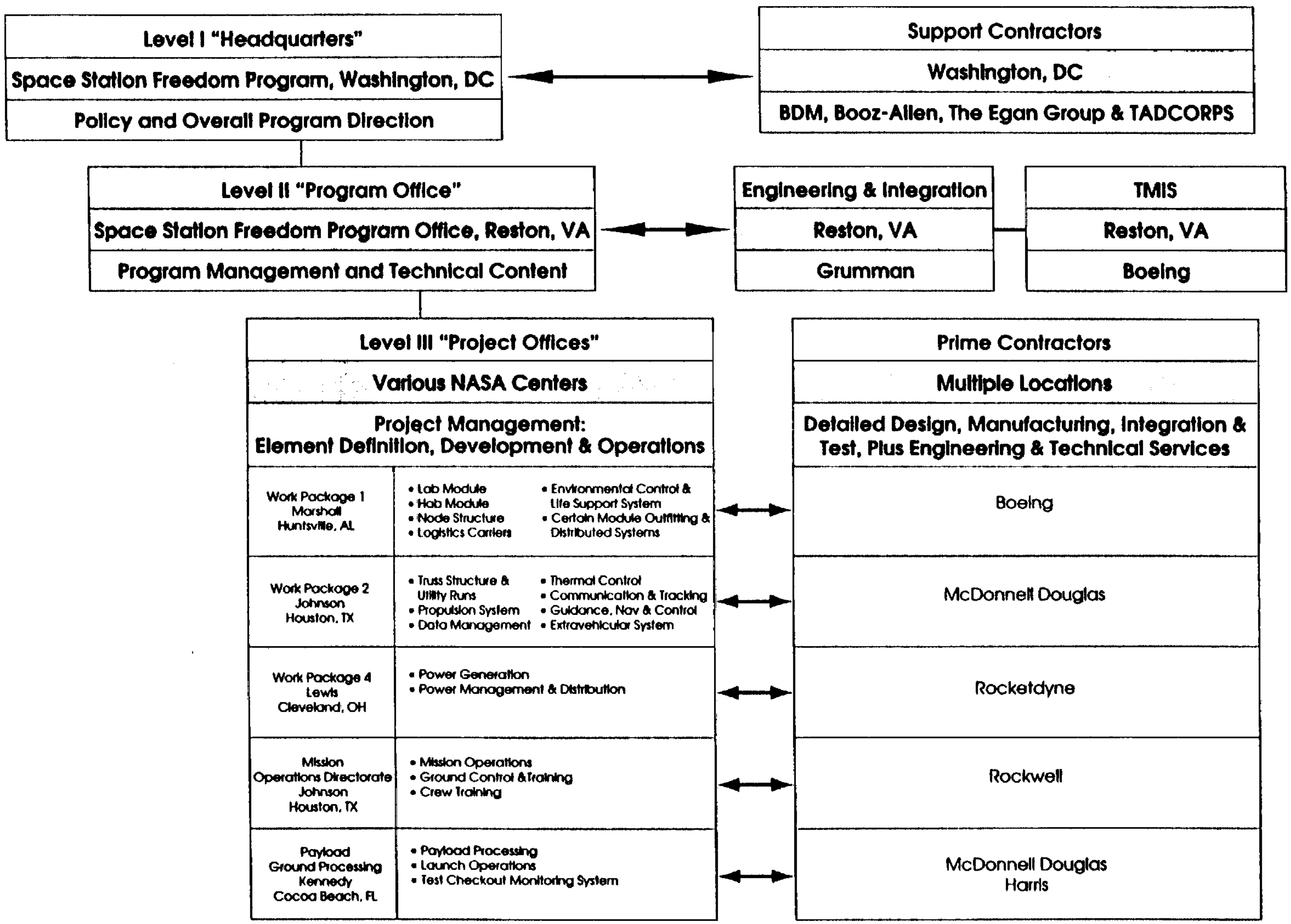


Figure 3.

NASA Space Station Freedom Program Organization: Space Station Freedom program uses a three-tiered management structure.

Space Station Freedom
Safety Review Statistics

Assembly Flights 1 - 6

FLIGHT NUMBER	WP-01		WP-02		WP-04		CSA		OTHERS		TOTALS	
	HRs signed/ presented	AIs	HRs signed/ presented	AIs	HRs signed/ presented	AIs	HRs signed/ presented	AIs	HRs signed/ presented	AIs	HRs signed/ presented	AIs
MB-01	0 / 0	0	11 / 11	29	9 / 9	5	0 / 0	0	0 / 0	3	20 / 20	37
MB-02	0 / 0	0	16 / 16	7	15 / 16	1	0 / 0	0	0 / 0	5	31 / 32	13
MB-03	0 / 0	0	16 / 16	3	0 / 0	0	0 / 0	0	0 / 0	0	16 / 16	3
MB-04	9 / 9	4	17 / 19	12	15 / 15	4	1 / 4	8	0 / 0	1	42 / 47	29
MB-05	12 / 14	4	17 / 25	8	0 / 0	0	0 / 0	0	0 / 0	1	29 / 39	13
MB-06	23 / 24	3	17 / 20	4	9 / 11	2	0 / 0	1	0 / 0	4	50 / 56	14
	44 / 47	**11**	**94 / 107**	**63**	**48 / 51**	**12**	**1 / 4**	**9**	**0 / 0**	**14**	**188 / 210**	**109**

MB = Manned Base (MB-01 = Manned Base Assembly Flight #1)
WP = Work Package (WP-01 = Work Package #1)
CSA = Canadian Space Agency
HRs = Hazard Reports
AIs = Action Items assigned

NOTE: Figures do not include HRs deleted, withdrawn, or combined

Figure 4.

MASTER MATRIX

HR No.	Hazard Description	MB-01	MB-02	MB-03	MB-04
7512	CREW INDUCED HARDWARE DAMAGE DURING ASSEMBLY OPERATIONS	*, ,*	@, ,@	*, ,*	*, ,*
7513	SHARP EDGES, CORNERS, PROTRUSIONS; EVA INJURY DURING MB-01 ASSEMBLY OPERATIONS	F, ,P	, ,	, ,	, ,
7518	PREMATURE DEPLOYMENT OF APPENDAGES DURING MB-01 ASSEMBLY OPERATIONS	F, ,P	, ,	, ,	, ,
7521	FAILURE OF MB-01 CARGO ELEMENT ATTACHMENTS	, ,P	, ,	, ,	, ,
7525	EPS HIGH TRANSIENT CURRENT SURGES DURING START-UP	, ,	F, ,	, ,	, ,
7540	NI-H2 BATTERIES STRUCTURAL FAILURE	, ,	@, ,	*, ,	*, ,

Legend:

F = Flight-specific Hazard report presented to the FSRP
G = Flight-specific Hazard report presented to the GSRP
P = Flight-specific Hazard report presented to the PSRP
* = Generic Hazard Report applicable to one or more flights
@ = Generic Hazard Report presented at a safety review
_,_,_ = Three columns: 1st column denotes applicability to FSRP
2nd column denotes applicability to GSRP
3rd column denotes applicability to PSRP

Figure 5.

Example Hazard Tree

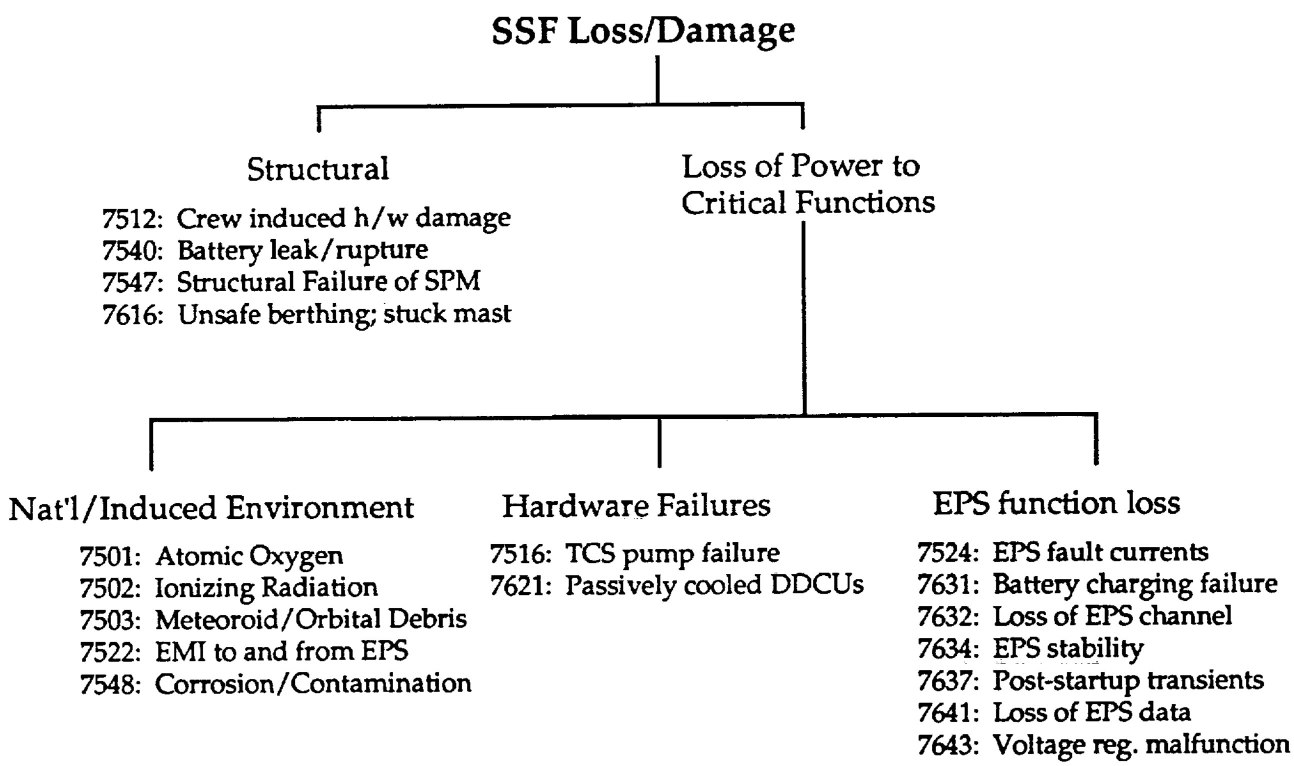


Figure 6.

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