



The MSX Performance Assurance Program

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The structure and organization of the Performance Assurance Program developed for the Midcourse Space Experiment (MSX) spacecraft are discussed. Included is an overview of the engineering disciplines of the program: reliability, quality assurance, and system safety. The performance assurance role in each of the four MSX development phases is explained, followed by a review of MSX integration and test history as it relates to performance assurance. A discussion of lessons learned summarizes the results of the Performance Assurance Program.

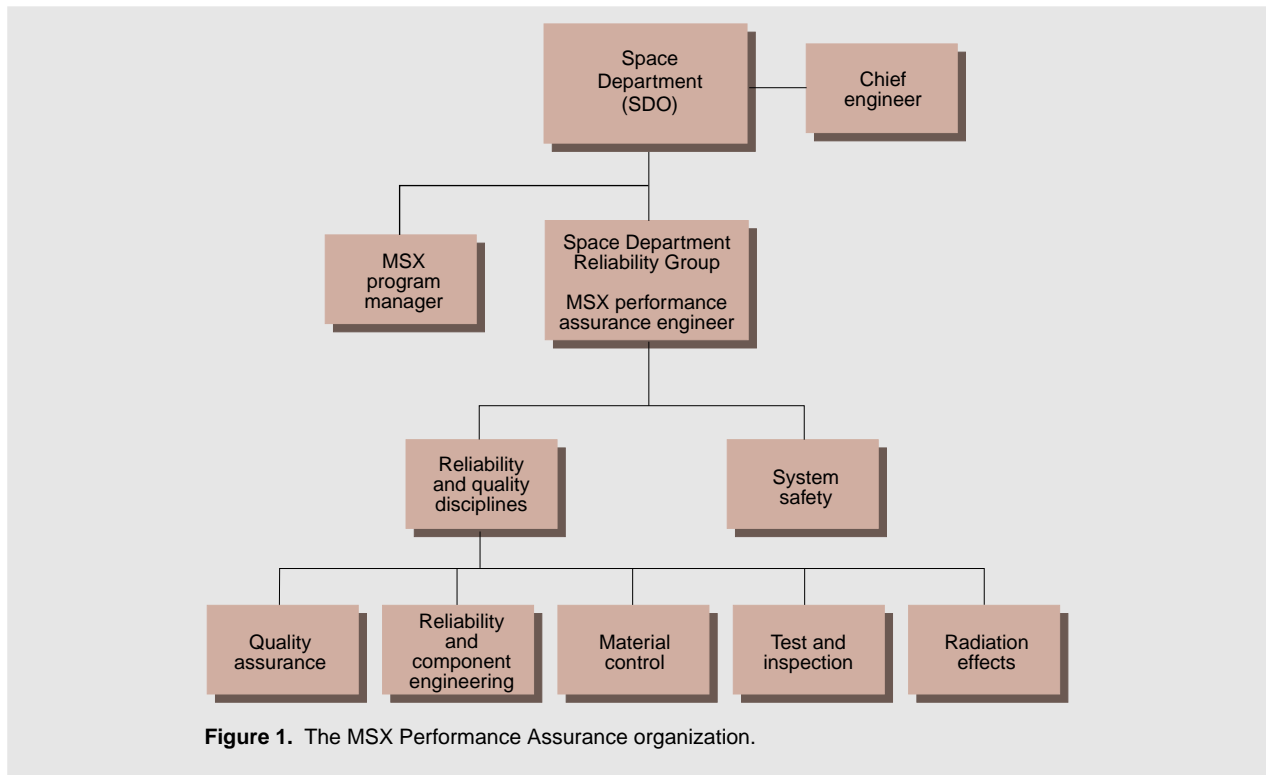
INTRODUCTION

It is generally agreed that the performance assurance role involves two basic activities: engineering and product assurance. Engineering functions include reliability, quality assurance, and system safety. Product assurance consists of elements needed to establish confidence that the product is being designed and manufactured as intended to meet the reliability goal. In addition to these engineering and product assurance fundamentals, the Midcourse Space Experiment (MSX) Performance Assurance Program emphasized design integrity by specifying conformance to the APL Space Department's *Engineering Notebook*, which includes guidelines for part usage and test, software quality assurance, and design reviews. Figure 1 presents the organization of the MSX Performance Assurance Program, and shows that the performance assurance engineer reports directly to APL's Space Department management.

MSX PERFORMANCE ASSURANCE PROGRAM STRUCTURE

Management

The Performance Assurance Program established for MSX was governed by the APL *Product Assurance Plan*, a detailed document tailored for MSX from a generic master plan. Other important documents that helped shape the MSX Performance Assurance Program included the *MSX Integrated Safety Program Plan*, the *MSX Accident Risk Assessment Report*, interface control drawings, individual equipment specifications for subcontracted hardware, and detail drawings. The MSX performance assurance engineer, who is part of the APL Space Department's Satellite Reliability Group (SOR), managed the program and documented its status with monthly reports. This engineer was also responsible for reviewing as-built documentation and other test and inspection records to ensure conformance to the



program. Complete hardware documentation, as well as integration and test records such as problem/failure reports (P/FRs), were presented to the sponsor at MSX pre-ship and flight readiness reviews.

Reliability Engineering

The MSX spacecraft hardware was designed, fabricated, and tested to achieve a 4-year (5-year-goal), on-orbit operational life while operating under environmental guidelines specified for each subsystem. Reliability engineers in design reviews verified proper part selection and stress derating, using the Goddard Space Flight Center (GSFC) Preferred Parts List as a guideline. In addition, critical functions and single-point failures were examined and selectively analyzed for redundancy and cross-strapping needs.

Parts lists submitted by all APL designers and subcontractors were reviewed by the SOR Reliability Engineering Section for correct grade level, nonstandard part approval request (NSPAR) requirements, and part usage concerns. Nonstandard parts required a destructive physical analysis to be performed and were upgrade screened (screened to standard part level requirements) before use.

Quality Assurance Engineering

The SOR Quality Assurance Section inspected both in-house hardware and subcontracted items. The section also coordinated the use of contract inspectors,

although critical precap (inspection of the integrated circuit die before package lidding) and other source inspections were performed by APL personnel. Other quality assurance functions included verification of equipment calibration, setup of an electrostatic discharge monitoring and control system, parts and assembly problem investigation, failed parts analysis, quality and configuration audits, and personnel training for electrostatic discharge and clean room certification.

Software quality assurance was performed on an audit basis, where conformance to the *Software Quality Assurance Plan* was verified by the performance assurance engineer. The plan was written by the MSX software system engineer, and covered such topics as management of the Software Quality Assurance Program, documentation and record collection, standards and practices, reviews and audits, configuration management, problem reporting and corrective action, and software testing.

Parts Test and Material Control

Electrical, electronic, or electromechanical parts were selected, to the extent possible, from the APL Space Department Preferred Parts List, which includes approved parts from the GSFC Preferred Parts List and MIL-STD-975. APL-fabricated hardware used in construction of the MSX spacecraft required 140,000 electrical, electronic, or electromechanical parts, consisting of approximately 1600 different line items. Over 4000 parts constituting 1140 line items underwent

destructive physical analysis performed by one outside test house. Upgrade screening was performed by four outside test houses as well as by SOR personnel using in-house facilities, and was coordinated by the SOR Test and Inspection Section. Over 700 parts kits were assembled by the SOR Material Control Section, inspected by the SOR Test and Inspection Section, and sent to APL fabrication shops. Including subcontracted hardware, the total MSX parts count was estimated to approach 300,000.

Radiation Effects

The SOR Advanced Technology and Radiation Effects Section characterized over 100 different part types used on MSX for total dose exposure, displacement damage, and single-event upset/latch-up. These part types were not tested previously for radiation effects, and characteristics were not available from the part manufacturers. For example, field-programmable gate arrays, such as those made by ACTEL, are very effective in reducing volume and power consumption in spacecraft systems, but are vulnerable to space radiation effects, particularly single-event upset. Extensive testing and analyses were performed to optimize circuit designs implemented in these arrays, with a triple-redundant register/comparison scheme used to minimize upset probability.

System Safety Engineering

A system safety program was developed to ensure compliance with the Western Space and Missile Center Range safety requirements. The *MSX Integrated Safety Program Plan* describes organizational relationships, responsibilities, and engineering and management criteria to ensure comprehensive accident risk assessment. Safety requirements applicable to spacecraft subcontractors were based on the inherent safety risks of the particular hardware and the scope and complexity of the procurement.

Various system safety working groups were established by the APL system safety engineer or the Western Space and Missile Center Range safety organization to review, track, and resolve outstanding safety issues, most notably those related to the SPIRIT III dewar, which contained 944 L of solid hydrogen to maintain optics and instrument temperatures. System safety analysis methods provided for inclusion of potential hazards into a closed-loop analysis and tracking system, with assigned qualitative values for hazard probabilities and severity levels. An *Accident Risk Assessment Report* was prepared to address system-level hazards and hazards of spacecraft interfaces. Each risk from an identified hazard was listed along with rationale for acceptance, actions taken to preclude accidents, and data to support compliance certification to

MSX safety requirements. Results of the preliminary hazard analysis were included in the report, as were the subsystem and system hazard analyses.

Other system safety tasks included preparation of hazardous operation procedures, emergency and contingency procedures, and ground safety plans for use during integration at APL, testing at GSFC, and launch operations at Vandenberg Air Force Base (VAFB). Safety training for all personnel having facility access was also provided. Table 1 presents how the system safety program was integral to various MSX program elements.

PERFORMANCE ASSURANCE IN THE FOUR PHASES OF THE MSX PROGRAM

The MSX program comprises four phases: mission definition; system design; subsystem design, fabrication, and test; and spacecraft integration, test, and launch. Performance assurance was an integral part of each of these phases.

Mission Definition

During the mission definition stage, the mission requirements were used to help conceptualize accomplishment of the mission and tailor the MSX Performance Assurance Program. The necessary spacecraft lifetime was used to set the mission reliability goal and help determine part levels and definition. For MSX, grades 1 and 2 (much like the grade levels described in the GSFC Preferred Parts List) defined standard parts, and lower grades were classified as nonstandard. Mission and documentation requirements specified drawing levels and hardware types. Table 2 defines hardware types and their required documentation levels,¹ and Table 3 presents the configuration requirements used for MSX.

At this mission definition stage, the MSX conceptual design review was held. System block diagrams were presented at this time, and SOR reliability engineers performed parts reliability predictions using MIL-HDBK-217E, although APL experience has shown these failure rates to be extremely pessimistic. The reliability of systems was calculated for a 4-year mission, with each subsystem's operating environment considered. For example, the electronics section was required to operate from -29 to 66°C , and the instrument section from -35 to 35°C ; SPIRIT III and other subsystems had unique requirements.

System Design

During the system design phase, instrument interface definitions were established. Typically, the various electrical, mechanical, and thermal engineers worked

Table 1. System safety interfaces with MSX program elements.^a

Program element	Program requirement	Output from system safety
Program management	Customer requirements	<i>MSX Integrated Safety Program Plan</i>
	Program requirements document	Safety requirements
	Program policy	Hazard reports
	Program plan	Unresolved safety problems
	Risk acceptance criteria	Safety program status
	Safety/performance/operational trade-offs	Accident risk assessments
	Signature approval authority	Test operations risk assessments Other safety deliverables
Spacecraft hardware	Design specifications	Design safety criteria
	Design criteria	Hazard analyses
	Design drawings	Hazard controls
	Requests for deviations and waivers	Hazard reports
	Engineering changes	Safety impact determinations
Software	Software specifications and requirements	Software safety criteria
	Functional flow diagrams	Safety-critical software
	Program structure documentation and code	Software safety analyses
	Software changes	
	Input and review of software safety analysis	
Ground operations	Safety-critical ground support equipment specifications	Test and operational safety criteria
	Design criteria and drawings	Hazard analyses
	Integration	Hazard controls
	Processing and test plans	Hazard reports
	Hazardous procedures	Approval of hazardous procedures
	Input and review of hazard analyses and safety deliverables	Ground safety plans On-site monitoring Training
	Flight operations	Space test operations and mission operations requirements
Orbital operations handbook		Hazard analyses
Test operations instructions		Hazard controls
Emergency test plans		Hazard reports
Input and review of hazard analyses		Review of operations documentation
Safety deliverables		Real-time safety control Training
Performance assurance		Problem summaries
	Failure reports	Hazard controls
	Inspection plans	Safety-critical components
	Acceptance criteria	
	Material deficiencies	
	Nonstandard parts lists	

^a From *MSX Integrated Safety Program Plan*, APL Doc. No. 7334-9049.

Table 2. Hardware types and corresponding documentation levels.

Hardware type	Documentation level ^a			
	Level 1	Level 2a	Level 2	Level 3
Type A Deliverable outside APL (“production” or fully qualified)	Not applicable (insufficient documentation to verify configuration)	Not recommended (insufficient documentation to verify configuration)	Minimum recommended	Required (when technology transfer is intended)
Type B Deliverable outside APL (prototype)	Not recommended (insufficient documentation to verify configuration)	Minimum recommended	Recommended	Required (when production by outside vendor is anticipated)
Type C Deliverable for APL internal use only (breadboard)	Minimum recommended	Recommended (if design is to be duplicated at a later date)	Not recommended (not normally necessary)	Not applicable

^a Documentation level descriptions

Level 1

- Breadboard/brassboard development
- Informal drawings allowed
- Configuration control not possible

Level 2a

- Uses redlined control prints
- Limited capability to reproduce the design
- Will not support a configuration audit

Level 2

- Assured capability to reproduce the design
- Can provide spare parts to support the design
- Can verify correctness of hardware by documentation
- Prepared in accordance with DoD-STD-100
- Drawings stored in vault after release

Level 3

- For quantity production
- Provides data to permit competitive procurement of items
- Allows for outside manufacture of hardware

together to refine subsystem needs. Individual designers worked with SOR reliability and materials engineers to select parts of the proper grade level to meet reliability and availability parameters. Preliminary electrical, electronic, or electromechanical parts and materials lists were submitted to the performance assurance engineer for review.

The Performance Assurance Program established the need for upgrade screening of nonstandard parts, based on the requirements of the GSFC Preferred Parts List. This screening was controlled in-house by the

SOR Test and Inspection Section for all APL-manufactured hardware; much of the destructive physical analysis and screening were subcontracted because of the quantity of parts involved. Parts upgrading for subcontracted hardware was handled by the individual subcontractors, and approval and status were documented by NSPAR forms. A total of 793 NSPARs were submitted, and all but 16 were approved. NSPAR approval required concurrence by SOR reliability, quality assurance, and parts engineers. Part histories were studied, screening results were reviewed, radiation concerns were checked, and part quality level and application were verified. Unapproved NSPARs were either withdrawn or used with waiver approval.

Table 3. MSX configuration requirements.

Hardware unit	Drawing level	Hardware type
Flight model	2	A
Safety-critical ground support equipment	2	A
Selected ground support equipment	2a or 2	B or A
Breadboard	1	C
Other ground support equipment	1	C

Subsystem Design, Fabrication, and Test

Subsystem design included more box-level detail involving all aspects of electronic, mechanical, structural, and thermal disciplines. Positioning of the various subsystems on the spacecraft structure was completed. Most of the design reviews took place during this phase. Figure 2 presents the MSX design review process. Design reviews were also conducted at subcontractor facilities and were attended by cognizant APL engineers. Component hardware inspections were completed during this phase, as were the subcontracted hardware equipment acceptance reviews.

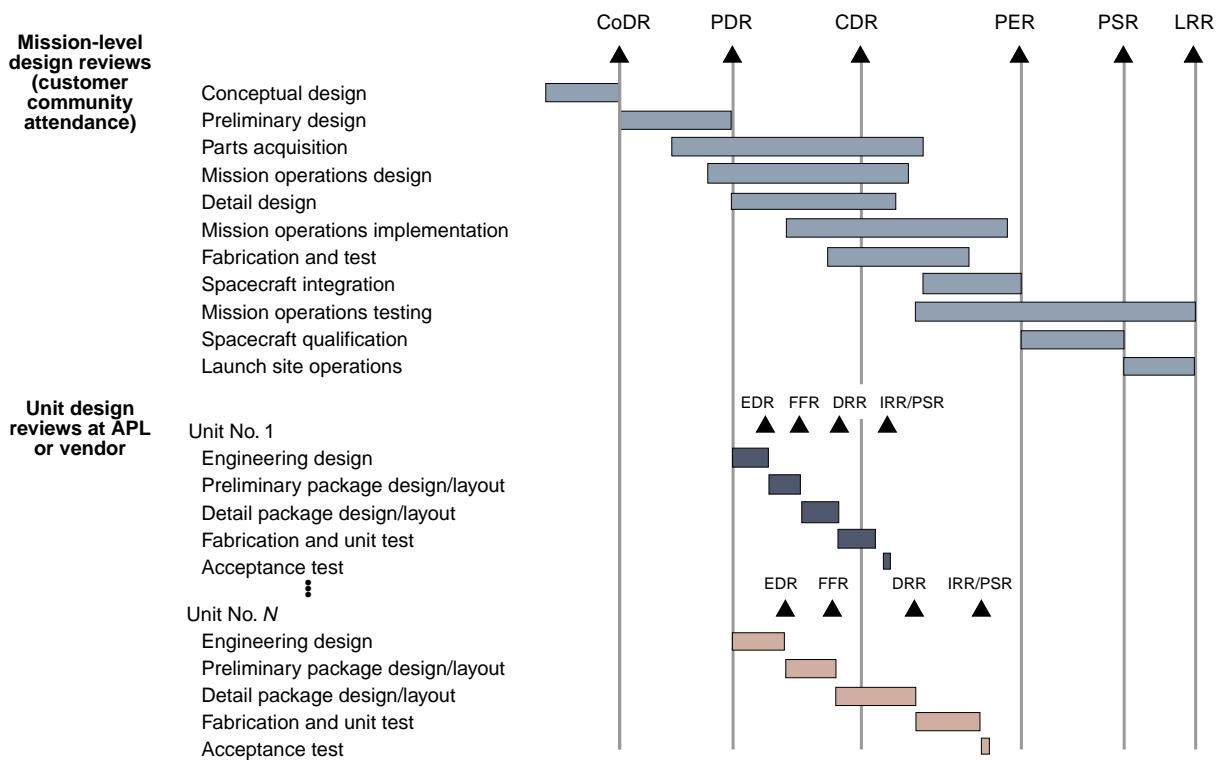


Figure 2. The MSX design review process. CoDR = conceptual design review, PDR = preliminary design review, CDR = critical design review, PER = pre-environmental review, PSR = pre-ship review, LRR = launch readiness review, EDR = engineering design review, FFR = fabrication feasibility review, DRR = drawing release review, and IRR = integration readiness review.

For APL-manufactured hardware, material review board actions documented problems occurring before spacecraft integration. After integration, problems or failures were recorded on P/FRs. Material review board and P/FR documentation helps ensure proper reinspection of hardware, as well as adding to the as-built configuration record, which can be a valuable design resource for future programs. For subcontracted hardware, the facility’s internal material review board system was used prior to system acceptance testing. After acceptance testing had begun, but before delivery to APL, the problem or failure was documented by the subcontractor, and the MSX program manager and performance assurance engineer were notified.

Spacecraft Integration, Test, and Launch

Spacecraft integration and test have been defined as assembling the mechanical, electrical, and thermal subsystems into an integrated spacecraft and performing tests on the spacecraft to ensure that it will operate properly in the specified environment.² The bulk of the integration and test work for MSX was established in the *MSX Program Test Plan*, which contains performance requirements, tests to be conducted, facilities required, and specification of environment. The test plan was reviewed by the MSX performance assurance engineer for conformance to Space Department test requirements. Quality assurance aspects of the plan

included delineation of responsibilities, definition of quality assurance inspection points, compilation of results, description of logbook use, documentation of problems or failures, application of corrective action, equipment calibration, and setup of a test review board.

Spacecraft integration and test can be considered the final phase of spacecraft design. At the point of integration, box-level reliability and quality have already been determined and built into the hardware via existing design and fabrication. The performance assurance engineer now monitors and documents all the variables that may affect spacecraft reliability, as well as ensures that the high quality of the hardware is maintained. This was done for MSX by diligently maintaining the P/FR system, and enforcing program quality assurance, electrostatic discharge, and cleanliness requirements.

The MSX integration period began in May 1992. At that time, roughly half of the subcontracted systems and boxes had not yet been delivered, which necessitated a dual role for the performance assurance engineer. First, the engineer had to continue to oversee the product assurance requirements for MSX subcontracted hardware along with associated ongoing SOR reliability and quality assurance reviews. The effort included such things as performing hardware inspections, participating in failure review board meetings, attending equipment acceptance reviews (where test results and

product documentation were reviewed to determine the suitability of the product to ship and integrate), as well as reviewing industry alerts for potential part problems.

The performance assurance engineer's second task included verifying subsystem readiness to integrate by participating in integration readiness reviews, maintaining the P/FR system, tracking corrective action, and preparing monthly reports for the MSX Program Office. The performance assurance engineer also monitored conformance to the *MSX Program Test Plan*.

MSX integration and test took place in four different locations: the APL clean room, the GSFC clean room/thermal vacuum chamber, the Astrotech payload processing facility at VAFB, and aboard the Delta launch vehicle at the launch complex. These different integration and test sites required the performance assurance engineer to be especially alert to transportation and handling concerns. Ad hoc and system safety technical interchange meetings were also conducted to discuss system safety, ground support issues, and spacecraft design interactions.

Other ancillary performance assurance activities that occurred during the integration and test phase involved integration readiness reviews and problem/failure or test review board meetings to discuss and resolve software or hardware problems, failures, or anomalous test results. Ground support systems were monitored to ensure that there were no spacecraft risks resulting from connections to flight hardware. Contamination and facilities engineers established clean areas at each of the four spacecraft locations. The *MSX Contamination Control Plan* was issued, which addressed materials selection, fabrication, integration and test, GSFC operations, and launch site operations. In addition, MSX spacecraft cleaning procedures for integration and test were issued.

POSTLAUNCH ACTIVITIES

The MSX postlaunch performance assurance activities basically involved archiving of quality assurance documentation, records, notes, and logbooks, as well as summary report preparation. Reports were based on all available MSX documentation of program activity in both the reliability/quality assurance and system safety areas. Thoroughness in both documentation and its review is important so that lessons learned can be extracted from the records and applied to future programs.

Summary of Major Performance Assurance Issues

Subcontracted Hardware

In order to thoroughly investigate, document, and oversee corrective action initiated by subcontractors

due to critical hardware problems or failures before delivery, failure review boards were convened. Eight instances of hardware failure occurring at subcontractor facilities were serious enough to require review:

1. Multilayer circuit board defects. Circuit boards exhibited many internal shorts and opens during test. Investigation showed that the boards were manufactured at a facility not employing adequate process control.
2. Transistor lead solderability problems. Inadequate lead plating yielded poor solder joints and led to circuit failure. Incoming part inspection criteria were changed to screen for potential solderability issues.
3. Cracked solder joints. A poorly designed lap joint and improper lead bending resulted in equipment failure. Manufacturing procedures and design were changed.
4. Unmonitored and poorly planned acceptance tests. One failure was due to a reverse-polarity hookup of a battery in test. Although protection diodes helped save the circuit's electronic parts, the heat generated destroyed a portion of the multilayer circuit board. A new board was built.
5. Inadequate facility coordination. Part failure resulted when a room's air conditioning equipment automatically shut off for the weekend, allowing higher ambient temperatures in the test lab. The failed part was replaced.
6. Damaged high-voltage power supply. During a thermal vacuum test, technicians unfamiliar with corona effects applied power to a subsystem while making the transition to vacuum, causing damage to a high-voltage power supply. The supply was rebuilt and internal procedures were changed.
7. Cracked transformer core. Excessive torque on a transformer mounting device caused the crack. Procedures were modified and the cracked core was replaced.
8. A manufacturer's design anomaly in a key data encryption chip. A circuit work-around was designed and added to the hardware by the subcontractor.

Also investigated were many specific technology, manufacturing, or quality assurance documentation problems. It was found that the use of a high-temperature solder on feed-through capacitors caused internal damage; the capacitor manufacturer required a low-temperature solder to prevent device failure due to excessive heat. Several instances were noted of unauthorized work performed on flight hardware after acceptance testing was completed. In such cases, subcontractor corrective action was reviewed, and the hardware was either reinspected or retested. SOR review of documentation prior to hardware delivery revealed several instances of nonstandard parts use with NSPAR approval, but without the required upgrade screening being completed. Residual parts from the same lot were then screened and put through

destructive physical analysis to determine lot acceptance, and a decision to replace the affected part or leave it in place was made jointly by the subcontractor and the performance assurance engineer.

APL-Fabricated Hardware

APL hardware was affected by the need for stringent electrostatic discharge control procedures. For example, a special procedure was developed to control the mating and demating of connectors going to the spacecraft's data handling system, where certain HS9-1840RH-Q chips were sensitive to as little as 14 static volts. Nonconductive spacecraft materials such as the beta cloth on the multilayer thermal blankets were determined to be electrostatic discharge sensitive. Late in the MSX fabrication process, it was discovered that data supplied by the IDT72104 integrated circuit manufacturer were erroneous. The device, which was used throughout the spacecraft, was susceptible to single particle-induced latch-up, and a command and data handling "autonomy rule" protection scheme was developed and implemented via hardware or power cable modifications and software changes. A small box was fabricated and inserted in series with the affected unit's power cable to perform current sensing. For the mission-critical command processor, internal modifications were made. During spacecraft testing at GSFC, misconnected battery cables in the thermal vacuum chamber caused an unexpected "conditioning" of the flight battery when the battery was subsequently discharged.

Problem/Failure Reports

The MSX P/FRs provided a summary of the MSX integration and test experience. The test conductor's log provided backup details and a cross-reference for the events documented on the P/FRs. The problems and anomalies recorded using the P/FR system were varied. Part and design problems seemed to affect subcontracted hardware more than APL-constructed hardware, although the design problems were more related to fabrication than actual circuit design. A majority of these problems were discovered and corrected in the early stages of integration. In fact, there were no hardware failures during GSFC testing that affected the test schedule or that required the return of any hardware to the vendor.

Figures 3 and 4 show how the approximately 260 P/FRs written for the MSX program were apportioned. Figure 3 presents the relative relationship among the various sources of MSX hardware: subcontracted, built at APL, furnished as an instrument, or the APL-built Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI). Figure 4 presents how the total number of P/FRs was distributed among six listed anomaly

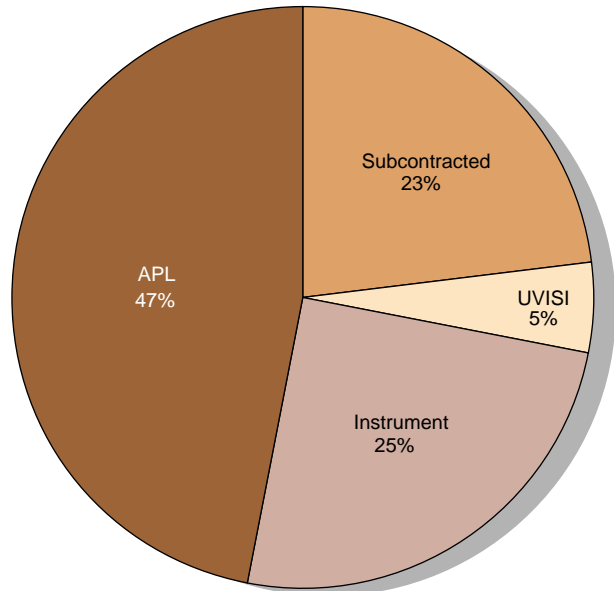


Figure 3. Problem/failure reports by hardware source.

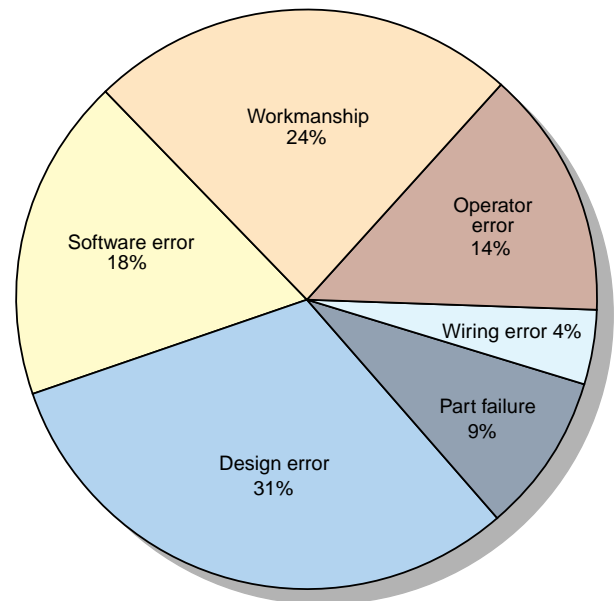


Figure 4. Problem/failure reports by anomaly type.

types, and includes all spacecraft hardware and software. Percentages of the total number of P/FRs are shown. The category of "operator error" represented a learning curve for ground support equipment and spacecraft operation, and included P/FRs written for such things as ground test software errors, tester problems, and simulator malfunctions. Design errors included such things as incorrect part application, poor board layout, and faulty material choice. Many part failures were actually due to misapplication and therefore were considered design errors. Wiring error P/FRs consisted of subsystem, harness, or connector wiring issues. The P/FR database is available to designers throughout the APL Space Department for future reference.

Lessons Learned

Results of the MSX Performance Assurance Program seem to suggest that parts-related problems are becoming less significant, except for mechanical parts like relays and connectors. Data from the *Quality Control Handbook*³ indicate that, in general, defective parts are responsible for approximately 30% of failures in un-screened development systems. However, the MSX record is much better. Process, manufacturing, and other human factor issues require more attention, including personal discipline in following the rules for electrostatic discharge control, cleanliness, and consistent use of connector savers. Also requiring attention are strict control of design changes after the critical design review, training in proper soldering technique and connector mating and assembly, controlled procedures for bench checkout of flight hardware, and procedures for areas not normally considered critical, such as cable hookup at GSFC.

It appears that there was an expectedly large proportion of design-related problems during the MSX program. This situation suggests that more fabrication-type design reviews should be conducted, especially at subcontractor facilities, and that the reviews be overseen by a manufacturing engineer.

Several observations can be made as a result of operational safety experience during integration, test, and launch preparations. It would have been beneficial to enhance safety oversight during APL integration by using the same formal safety practices that were later used by GSFC and VAFB. Use of the same procedures at APL, for example, would have provided the MSX operational personnel with a better understanding of the safety role and the safety requirements of the other facilities. A more structured effort for review of operating procedures with a greater lead time for feedback of comments from reviewers would enhance the usability of safety-critical procedures.

Configuration of the spacecraft electrical ground support equipment was a major consideration in

planning for emergency shutdown of non-explosion-proof equipment, so as to avoid creation of a hazardous or detrimental situation should facility power be removed. Also, the vast maze of cables and cryogenic transfer and vent lines necessitated daily safety walk-throughs. It may be prudent in the future to examine ground support equipment cable and cryogenic line routing to maximize its layout for personnel safety. The importance of end-to-end checkout of emergency systems in the integration, test, and launch preparation facilities cannot be overemphasized. In several cases, safety-critical systems failed upon initial checkout, even though the equipment was new, and locations of some of the hydrogen sensors in the payload processing facility at VAFB had to be changed. Remote monitoring and recording of hydrogen sensor output had to be provided, and the emergency vent/roof louvre system had to be modified.

The SPIRIT III cryostat failure in November 1994 forced many additional enhancements to the payload processing facility configuration, including an emergency button override on the air shower doors, improved power distribution to the spacecraft, and provisions for monitoring cryostat status in the payload processing facility control room. Finally, ground support equipment, test equipment, and ground test software often slowed the test schedule by giving erroneous and conflicting results that required investigation.

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ACKNOWLEDGMENTS: The author wishes to thank the various members of the SOR Satellite Reliability Group for their support during the MSX effort. Also, the contributions of Joyce McDevitt and Clay Smith in the system safety area were noteworthy. Finally, the understanding and cooperation of the APL MSX Program Office were key factors in MSX Performance Assurance Program success. The MSX mission is sponsored by the Ballistic Missile Defense Organization. This work was supported under contract N00039-94-C-0001.

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