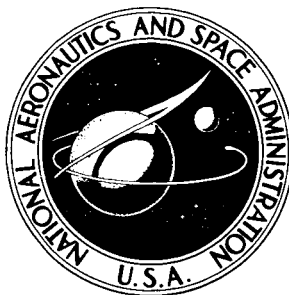


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**APOLLO EXPERIENCE REPORT -  
RELIABILITY AND QUALITY ASSURANCE**

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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1973**

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# APOLLO EXPERIENCE REPORT

## RELIABILITY AND QUALITY ASSURANCE

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### SUMMARY

The reliability and quality of the Apollo spacecraft and associated equipment resulted from the application of reliability and quality assurance practices and from the techniques developed and adopted during the engineering and manufacturing phases. Two reliability and quality practices adjusted as the program developed included: (1) the establishment of NASA Lyndon B. Johnson Space Center (formerly the Manned Spacecraft Center) and contractor reliability and quality assurance management review meetings, and (2) specifying in the contract the scope, format, and content of reliability and quality plans.

A contractor parts program was implemented to increase the integrity of the equipment. This program included requirements for parts derating and screening, control of the use of nonmetallic materials in the spacecraft, procedures and controls for assuring cleanliness of both the equipment and fluid systems, and a comprehensive testing program. These engineering and manufacturing techniques were developed as the program progressed.

The more significant experiences are presented in this report as guidance for future space-flight programs. The experiences described indicate in many specific ways deficiencies that were detected and corrected to improve the reliability and quality of the equipment.

### INTRODUCTION

A summary of the reliability and quality assurance (R&QA) experiences in the Apollo Program is presented. The report was written primarily to be used by Government and industry program managers who contribute to the design, fabrication, testing, and operation of safe and reliable equipment for space applications. Reliability and quality are presented as product attributes, not as organizations.

## MANAGEMENT OF RELIABILITY AND QUALITY ASSURANCE

The basic policy for the R&QA activities in NASA programs establishes the responsibilities for NASA program directors and managers. This policy provides for the planning, organizing, conducting, and evaluating of the activities to ensure the required levels of reliability and quality. The R&QA activities are intended to ensure that the equipment produced for the Government is in accordance with the requirements of the contract; however, the R&QA functions performed by the Government do not in any way relieve contractors of the responsibility for the integrity of equipment or services.

During the early developmental phase of the Apollo Program, some R&QA personnel were organizationally a part of the Apollo Spacecraft Program Office (ASPO) while the rest of the R&QA personnel were decentralized. These personnel that were not a part of ASPO and their associated R&QA effort were a part of other Lyndon B. Johnson Space Center (JSC), formerly the Manned Spacecraft Center (MSC), organizational elements such as the Flight Safety Office, technical divisions of the Engineering and Development Directorate, or the Resident Apollo Spacecraft Program Office (RASPO) that was established at the prime contractor plants.

The MSC Flight Safety Office (with specialized safety, reliability, and quality personnel) provided assistance to the ASPO and RASPO elements during program development. This office also performed the inspection function for all equipment fabricated, assembled, and tested at JSC. The R&QA personnel associated with the technical divisions ensured the implementation of R&QA requirements in the contracts for which the divisions were responsible. The RASPO R&QA elements performed required functions associated with the contractors' R&QA effort.

This decentralization of R&QA functions and responsibilities between these JSC elements resulted in differences regarding the establishment and interpretation of requirements, the degree of implementation, and the monitoring of contractor R&QA activities. These differences occurred because of the variances of opinions between the personnel in the organizational elements. Program-oriented personnel have a different philosophy about R&QA disciplines than the R&QA management and policy personnel have.

In 1968, all but two groups of the R&QA elements were reorganized into one central R&QA office responsible for all R&QA activities associated with all spacecraft hardware and providing appropriate support to all program offices and JSC organizational elements. The two groups not included in the reorganization were the Mission Control Center of the Flight Operations Directorate and the Aircraft Operations Office of the Flight Crew Operations Directorate. This centralization aided in establishing coordinated requirements and provided for the uniform interpretation and implementation of the R&QA tasks including the monitoring activities.

To achieve the most uniform and useful implementation of R&QA policies, the R&QA should be an integrated, centralized organizational element reporting to the Center Director. This organizational element should have defined functions stating

its responsibility for all R&QA activities. To be effective in contributing to the overall goals of a program, the organization should be both hardware and problem oriented; have a close working relationship with program elements such as engineering, design, and procurement; provide rapid response capability in all technical skill areas; and have direct access to top management.

The management of R&QA functions consists of the establishment of R&QA requirements and assessment of the R&QA functions that implement the requirements and of the deliverable equipment to ensure continued effectiveness. To be effective, the functions must be planned, continually monitored, and adjusted as the program advances.

## Reliability and Quality Assurance Requirements for Space Systems Contractors

Background. - The R&QA requirements are disciplines that, if properly implemented by appropriate elements of a contractor organization, will enhance the probability of producing and delivering reliable equipment. The reliability requirements are defined in NASA Handbook 5300.4(1A), "Reliability Provisions for Aeronautical and Space System Contractors," April 1970. The quality requirements were published in NASA Handbook 5300.4(1B), "Quality Program Provisions for Aeronautical and Space System Contractors," April 1969. These requirements include the activities that should be implemented for major aerospace systems such as the Apollo Program and are the result of inputs solicited from NASA centers, other Government agencies, and industry. Much experience gained from the Apollo Program and from other aerospace programs is reflected in the publications. In addition, the NASA R&QA publications include associated efforts to be performed by the engineering, manufacturing, purchasing, logistics, and program-management elements of a contractor.

Experience. - The JSC experience indicates that the R&QA requirements should be selected or "tailored" to meet the needs of the procurement and to ensure achievement of the desired discipline at the lowest possible cost. This tailoring is accomplished by using the basic requirement document as a guideline. The requirements selected are included in purchase orders and contract statements of work only to the extent necessary as determined by an evaluation of the equipment criticality, characteristics, and end use. The evaluation is performed jointly by the technical monitors and R&QA personnel. This tailoring concept was developed as the Apollo Program progressed.

Reliability requirements. - The requirements for reliability are grouped into reliability management, reliability engineering, and testing and reliability evaluation. The management of reliability functions is most effective when resources are directed to the following tasks.

1. Review of design specifications
2. Review of failure mode and effects analyses (FMEA)
3. Review of single failure point (SFP) summaries



4. Review of maintainability analyses and maintenance plans
5. Participation in design reviews
6. Participation in the investigation and analysis of failures and other problems
7. Review of proposed corrective action resulting from participation in the investigation and analysis of failures and other problems
8. Assessment of the use of electrical, electronic, and electromechanical (EEE) parts
9. Control of materials specified by designers
10. Assessment of test plans, procedures, and results

Quality assurance requirements. - The quality assurance requirements are grouped into the following major activities.

1. Quality assurance management and planning
2. Design and development controls
3. Identification and data retrieval
4. Procurement controls
5. Fabrication controls
6. Inspections and tests
7. Nonconforming article and material control
8. Metrology controls
9. Stamp controls
10. Handling, storage, preservation, marking, labeling, packaging, packing, and shipping
11. Sampling plans, statistical planning, and analysis
12. Government property control

The JSC experience in the management of contractor R&QA functions indicates that, in most procurements, some of all the preceding requirements are needed for a well-managed program. These requirements are not concentrated in a single R&QA organization and are intended for use by those contractor elements responsible for the design, development, fabrication, assembly, and testing of the equipment. By participating in the evaluation of contractor proposals before contract award, the R&QA

Office can advise program managers of any excessive or unnecessary cost items and of the R&QA effort to be implemented by the contractor.

After a contract award, contract changes that affect the deliverable equipment are reviewed by the R&QA Office to ensure that the original R&QA requirements negotiated in the contract are still valid. In addition, the contractor R&QA tasks are continually monitored to ensure that the effort is maintained at the proper level.

## Government Source Inspection

Background. - The NASA requires the contractor quality organizations to review procurement documents before release to ensure that appropriate quality assurance requirements have been included. The NASA quality assurance representative is required to review the procurement documents to determine if Government source inspection is necessary and to prepare a letter to the Government agency at the supplier facility delegating quality assurance functions to that agency.

This review at the prime contractor plant slowed down the release of the procurement documents to an unacceptable flow. This reduction in flow was caused by limited NASA R&QA staffing for the review. The procurement document release process was enhanced by having the prime contractor R&QA personnel review and re-release the documents using the guidelines prepared by the JSC R&QA. The Government review of the documents was made after their release. The JSC experience may be summarized as follows.

The contractor and NASA R&QA organization must have adequate staffing for review of a large number of procurement documents early in the procurement cycle for large contracts. In conjunction with this, the program management must allot a reasonable time for this procurement review or risk hardware delivery and quality control problems later.

## Lyndon B. Johnson Space Center Procurement of Space-Flight Equipment

Background. - The Government-furnished equipment (GFE) for the Apollo Program consisted initially of the guidance and navigation system, the flightcrew suits, the portable life-support system, and miscellaneous other items. For each of these procurements, the JSC R&QA Office elements adequately supported the JSC technical personnel. As additional GFE and new experiments were authorized for the Apollo missions, the number and the rate of initiation of GFE procurements increased significantly.

Experience. - As the additional GFE and experiments contracts increased in number and began reaching the hardware stages, it became apparent that the limited JSC R&QA staff could not monitor and support each contract to the extent applied to the spacecraft hardware. A decision was made to concentrate the R&QA efforts on the critical hardware (such as flight cameras, lunar experiment equipment, communication headsets, and others) and to provide only minimal surveillance to the rest except

for significant problems. The hardware contractors were thus required to provide the maximum available R&QA functions with only a relatively small amount of Government direct support.

## Quality Assurance Functions of Government Agencies

Background. - Quality assurance functions are performed by other agencies of the Government under delegations issued by the appropriate NASA or JSC contracting officer. These agencies, which include the Air Force, the Army, the Navy, the Atomic Energy Commission, and the Defense Contract Administration Service, are referred to as other Government agencies.

Contract administration services costs (including quality assurance) are reimbursable under NASA/Government-agency agreements. When the NASA work is dominant or extensive, NASA or JSC R&QA personnel are placed in the contractor facilities to assist and provide technical direction regarding quality matters to the Government agency.

Experience in the selection of Government quality assurance functions. - For reasons of cost effectiveness, the practice of tailoring the R&QA requirements to the procurement was established at JSC. The procurement documents are reviewed by reliability and quality engineering personnel for equipment complexity, criticality, special processes, test requirements, and value. From this review, the quality functions to be performed by the Government agency are selected or tailored from the basic requirement document (NASA Handbook 5300.4(2B), "Quality Assurance Provisions for Government Agencies," November 1971 edition) and forwarded to the contracting officer for transmittal to the delegated agency.

Typical functions performed by the Government agencies for JSC are inspection of equipment and incoming material, witness tests, failure notification to JSC, review of nonconforming equipment, and surveys of suppliers quality assurance operations. At the beginning of the Apollo Program, the delegation of quality assurance functions to the Government agencies caused some concern because of the difference between the JSC requirements and the procedures normally implemented on Department of Defense (DOD) and other Government contracts. The JSC quality assurance representatives were designated to assist the Government agencies to ensure that the requirements were understood and implemented properly. The JSC experience indicates that the services of Government agencies can be used most effectively if timely quality direction and assistance are given and points of contact are provided. This direction, which is provided by the JSC quality assurance representative, includes interpreting R&QA requirements, evaluating the adequacy of fabrication and inspection processes, providing guidance in the preparation of procedures, assisting in the disposition of nonconforming equipment, and resolving any problem or question the Government agency may have in performing the delegated functions.

## Documentation Requirements

General. - The planning and assessment of R&QA functions requires the receipt and review of several types of documents. Initially, documentation as required in the

NASA R&QA publications was requested from the contractors without any additional documentation criteria such as format, scope, and content. It soon became evident that the documentation requirements must be adjusted and tailored for each procurement in a similar manner as the R&QA requirements, and that the scope, format, and content of documentation must be specified in the procurement documents. Examples of documents used by the JSC R&QA organization include reliability and quality plans, EEE parts specifications, parts list, certification and acceptance test plans, failure reports, and failure analyses. Except for the R&QA plans, the other documents listed are required by JSC engineering and program office elements.

Background - R&QA plans. - The Apollo spacecraft contractors were required to prepare R&QA plans and submit them to JSC for approval. This requirement was new to the aeronautics industry. Quality control system requirements imposed on DOD contractors require them to document the system including procedures subject to disapproval by the Government. Submittal of this document is not required but it must be available to the Government.

Experience - R&QA plans. - In the judgment of the JSC R&QA personnel who assisted the contractor in the development of the R&QA plans, the plans constitute a good medium for contractor and Government management to understand the objectives, procedures, and milestones of the R&QA functions. For maximum benefits, this same discipline should be used by the prime contractor in the review and approval of sub-contractor plans.

Experience in the area of documentation has shown that the scope, format, and content of R&QA plans must be specified in the contract to preclude arbitrary changes in acceptance criteria. To be fully effective, these plans must be established in the contract as documents requiring customer approval. The JSC R&QA personnel have found that R&QA plans are most beneficial on complex or costly procurements. Technical and financial risks are the greatest for equipment the design of which is new or unproved, especially for costly and very complex hardware. For these types of procurements, the submittal and implementation of R&QA plans help provide confidence and assurance that technical problems and costs associated with these risks are minimized. It was found that normally no benefits were obtained by requesting the development and submittal of plans for short-term, less costly, off-the-shelf procurements.

R&QA status reports. - In the early stages of the Apollo spacecraft development, major contractors were required to submit periodic reports on the progress of the reliability and quality assurance activities. Scope, format, and content of these reports were determined by the contractors. These status reports proved to be ineffective because the program was moving ahead rapidly and the data in the reports were not current and not in sufficient detail to permit effective assessment of the R&QA activities. The Apollo prime contractors were directed to discontinue the status reports and to prepare monthly briefings for JSC R&QA management personnel. These briefings were given by the contractor R&QA managers to the JSC R&QA manager and division chiefs. The meetings were conducted in accordance with an established agenda and were documented. Action items were established, and handout material was provided for the participants. Topics normally discussed were budget control (including manpower and costs), supplier hardware problems, quality trend data showing defects, rework, material review actions, failure information, and corrective actions taken to resolve problems.

These management review meetings are effective, especially in the early phases of a program. The NASA personnel from Washington, the John F. Kennedy Space Center (KSC), MSC, the White Sands Test Facility, and the quality assurance offices resident at prime contractor plants participated in the briefings, providing valuable viewpoints from several perspectives. Many briefing topic problems, which would have taken considerable time to resolve if correspondence or telephone conversation media had been used, were discussed at the briefings. Action was assigned and, in most cases, the problem was resolved before the next regular meeting. These meetings proved to be very effective for bringing to focus quickly many of the difficult problems that could only be resolved with the proper representation of both contractor and NASA personnel.

As the Apollo Program progressed and assumed some measure of routine, many of the meetings were conducted by teleconference. It would have been desirable to have similar briefings with the GFE contractors, but it was considered impractical because of the large number of GFE procurements. In these cases, assessment of the R&QA activities continued to depend on status reports supplemented by contractor plant visits and frequent teleconferences.

## Reliability and Quality Information

Background. - Procedures for the storage and retrieval of R&QA information were developed for the Apollo Program. Requirements for automated storage and retrieval of failure information were established with Apollo contractors. These files were supplemented by a library of inspection records, test reports, and other documents required by R&QA, engineering, and program management personnel.

Experience in failure information. - Apollo spacecraft contractors were required to provide for the storage and retrieval of failure information on magnetic tape at their facilities and to transmit a duplicate tape to JSC. This procedure did not adequately support the spacecraft milestone reviews because the elapsed time from date of failure to first printout at JSC frequently was several weeks, which was too late to permit the review and approval of the proposed corrective action by the responsible JSC personnel. Therefore, a method for obtaining more current information was needed. The JSC procedure was changed, and the magnetic tape file was retained as a historical data file on failures. Requirements were revised for the submittal of failure information to JSC. The contractors were required to notify JSC within 24 hours after receipt of failure notification by reliability if failures occurred during certification, acceptance vibration and acceptance thermal tests, catastrophic failures during development and acceptance testing, or failures that had a direct impact on vehicles in prelaunch checkout at KSC. Similar notification had to be provided for significant unsatisfactory conditions (fire, explosion) or ground support equipment (GSE) safety failures. A failure-information focal point (clearinghouse) was established by R&QA to receive and distribute failure reports at JSC (Houston) to the program office and to engineering. As a part of this clearinghouse activity, R&QA kept a current list of all unresolved (open) failures and related problems. Special emphasis was placed on early resolution of the problems affecting the vehicles at the launch site, using specially prepared lists for frequent reviews with program office management.

## Assessment of Reliability and Quality Assurance Functions

Background. - The management of R&QA functions consisted of two principal activities. These activities were the establishment of R&QA requirements and, thereafter, assessment of the functions and of the deliverable equipment to ensure that the activities were effective. The JSC assessment of R&QA functions was not a one-time, one-type action; rather, it was a continual series of planned and integrated actions. These actions include the following.

1. Audits of contractor and subcontractor R&QA functions and assessment of corrective action
2. Management review meetings between JSC and contractor R&QA managers and supervisors and assessment of contractor responses to action items
3. Weekly reports of significant events from the resident JSC R&QA personnel at prime contractor facilities
4. Monthly reports from the JSC representative at subcontractor facilities
5. Analyses of test and inspection records
6. Reports generated by JSC R&QA in the performance of R&QA tasks

Background - R&QA audits. - Audits of contractor and supplier R&QA activities to determine compliance to contractual R&QA requirements were performed by JSC as required by NASA policy and program directives.

Experience. - Many contractors and suppliers providing space-flight equipment to NASA centers and to DOD agencies were audited several times each year. These independent audits by the centers and agencies created a problem with the contractors because many R&QA manpower resources had to be used to participate in the audit. This, in turn, affected the functions of the R&QA organization because key personnel supporting the audits were unable to concentrate on their day-to-day operations. To ensure that these audits would not be performed independently at least within NASA, the R&QA Office established a central focal point to coordinate audits with NASA Headquarters and its centers. This coordination included the establishment of schedules of the audits to be performed for the next 6 months and invited the other centers to participate and become members of the audit team. Before the audit, a determination was made about which R&QA activities were to be audited, the type of checklists to be used, and how the audit would be conducted. Audits that are planned, scheduled, and coordinated have been beneficial to NASA and the centers in terms of cost effectiveness because of less travel expenditures and in terms of better contractor and supplier R&QA management because there was less disturbance in their operations.

## Assessments of Space-Flight Equipment

Background. - Two major assessments or reviews of the individual Apollo spacecraft were made by the program office before each launch. The first assessment, a

Customer Acceptance Readiness Review (CARR), was performed to assess the readiness for the initiation of individual subsystem, integrated testing, and Government acceptance of the spacecraft before shipment to KSC. The second assessment, a Flight Readiness Review (FRR), was to evaluate the spacecraft and related GSE before launch and to accomplish the mission. The R&QA personnel assisted in these assessments by being members of the data review teams and also as members of the formal CARR and FRR Boards. The purpose, composition of the review teams and formal boards, and procedures are defined in the program office CARR Plan and FRR Plan. The R&QA representatives documented the results of these reviews in the form of assessment statements signed by the Manager of the R&QA Office. These statements were presented to the CARR Board stating there were no constraints to shipment of the vehicle or to the FRR Board indicating that the spacecraft was ready for launch. In the event there was a constraint (such as open items), the assessment statement would indicate that at satisfactory completion of open items there would be no constraint.

Experience. - Initially, formal reviews of spacecraft records were not performed before shipment of the spacecraft to the launch site. The reviews of vehicle records made by JSC were performed on a noninterference basis. For the early missions, the records and documentation were reviewed immediately before the FRR. The review of these records was concentrated mainly on nonconformance records and evaluation of the action taken to correct discrepancies; certification test reports; parts replacement records; and other inspection and test data, including nonmetallic materials (NMM) usage, EEE parts application, pressure vessel histories, and contamination and cleanliness records. As the program progressed, the amount of documentation increased significantly, and it was not possible to do this data and document review in the time allotted before the FRR. With the establishment of an additional program milestone review such as the CARR, the assessment procedures were revised to include incremental reviews by R&QA at the milestone reviews, supplemented by continual R&QA assessment of failures and problems. This procedure was much more effective in ensuring early detection and correction of problems that occurred after the incremental reviews, thereby permitting program management to be aware of the latest readiness status of the space-flight equipment and allowing adequate time for actions and corrective measures in the event of problems.

## Training

Background. - Early in the Apollo Program, the fabrication and operations related to special processes, particularly the soldering operations, were of concern to NASA Headquarters. Because of the unknown environments that the critical space-flight equipment may be subjected to, NASA considered it necessary to ensure that uniform soldering operations and techniques be used by industry fabricating this equipment. The NASA published a soldering requirements document (ref. 1) defining these operations and techniques. Because NASA as well as contractor personnel required training for these operations and techniques, soldering schools were established by NASA for the training and certification of contractor and supplier operators, inspectors, and instructors. In addition, NASA personnel were trained and certified, thereby enabling them to evaluate the contractor operations and techniques effectively. As the required skills were developed and the personnel were trained, the schools were discontinued and the contractors were responsible for the training and certification of the soldering personnel.

Experience. - The NASA publication requirements included detailed "how to" techniques for solder operations, and the training of personnel in these techniques was extensive. As the Apollo Program progressed, many contractors requested waivers and deviations to the NASA document. These were normally granted when the contractor soldering operations and techniques proved to be equally reliable. These requested deviations revealed that the NASA how-to techniques were not flexible enough to permit the use of equally good techniques developed by contractors, thus causing an unnecessary increase in costs to retrain personnel. Review of the NASA publication by the NASA centers considered the recommendation that industry be permitted to use their process specifications and techniques. A revised NASA soldering document deleting the rigid how-to techniques was published, and the quality and workmanship of equipment were maintained with reduced training costs not only for the contractors but also for NASA and delegated Government agencies.

Contractors are required to document the soldering program including information regarding qualification of instructors, procedures for training, lesson plans, instruction hours, and procedures for the certification and recertification of solder personnel. Early development and implementation of the training program and procedures are requisites to ensure the availability and maintainability of reliable equipment.

## Design and Procedural Standards

Significant spacecraft design and operational problems identified during Project Mercury and the Gemini Program were investigated to develop a clear and complete understanding of each problem and to determine if preventive requirements were technically feasible for spacecraft in future programs. Requirements considered feasible were developed into design standards, procedural standards, and engineering criteria bulletins. A Criteria and Standards Board was established with representatives from key JSC management and technical disciplines to review and recommend approval of the bulletins. After concurrence by the board, the bulletins were submitted to the JSC Director for approval signature. After publication of the bulletins, the appropriate JSC elements and program office technical monitors were responsible for including the bulletin requirements in hardware procurement contracts.

As the Apollo Program progressed, other significant problems were identified and investigated, and design and procedural standards (formerly bulletins) were published. When issued, standards were reviewed by the technical monitors to determine their applicability to active contracts. In many cases, the implementation costs prohibited retroactive application. When it was considered necessary to make retroactive application, the standards were imposed by Configuration Change Board action. Procedures were developed whereby R&QA personnel in their review of new purchase requests verified if standards were included as requirements. If standards were not cited, the technical monitor was contacted to verify that the standards were not applicable to the procurement.

Experience at JSC indicated that, for new programs and contracts, it was necessary to have the current standards imposed in the statement of work, requiring the contractor to review and determine the degree of compliance with each standard. Approval must be obtained from JSC for those standards not complied with by the contractor.



## ENGINEERING FUNCTIONS

The reliability of space-flight equipment is a function of the emphasis applied during equipment development by equipment designers, stress analysts, and other engineering personnel. The most effective contributions to product integrity are made by the engineer who appropriately considers the environments involved, selects the parts and materials, establishes the tolerances, and prepares the documents from which the product is purchased, fabricated, assembled, tested, and handled. Many of the NASA provisions for reliability and quality assurance, which are cited in the published NASA handbooks, can be implemented only by the equipment designers and engineers.

Unreliable parts, use of incompatible materials, and insufficient attention to environments were a few examples of problems encountered during the program that clearly indicated a need for emphasizing the role of the designer in product integrity.

### Reliability Predictions

Background. - Overall reliability numbers were generated as goals for the safety and success of the Apollo missions and were used as the basis for apportioning subsystem reliability goals. Initially, contractors were required to continue to develop reliability predictions and assessments as the Apollo design matured.

Experience. - Rigorous numerical reliability predictions and assessments can be calculated only by using failure-rate information developed from actual hardware. Because of (1) the relatively limited amount of hardware developed for the Apollo Program, (2) the deletion of reliability testing, and (3) the relatively limited operating time accumulated on the hardware in actual environments, the requirement for the generation of rigorous reliability predictions and assessments was deleted. Therefore, the use of reliability numerical techniques has been relegated to use only in initial trade-off studies during the conceptual design phases of hardware development.

### Failure Mode and Effects Analysis

Background. - As an integral part of the early spacecraft design phase, the flight hardware design should be analyzed to determine possible modes of failure and the effects of failures on mission objectives and crew safety. Ideally, analyses should be conducted at the system, subsystem, and component levels including individual switches, relays, and so forth. The primary objective of these analyses is to identify the failures that could affect mission success or crew safety, so that redundant systems can be added to the design where possible.

Experience. - The spacecraft FMEA was an effective tool for design evaluation. Each potential failure was categorized for worst-case effect on mission success. For each case in which a single failure could cause a risk to the mission success or crew safety, the hardware in question was listed separately in an SFP list. Each portion of the design that had an SFP then got special attention, and the SFP was eliminated where possible. In many cases, the complete elimination of the bad effects of an SFP malfunction was not desirable because such action would make the normal function

more difficult to obtain. For example, the use of single switches to initiate parallel sequences of events with redundant crossovers that require precise timing and the use of series-parallel contacts for safety could have jeopardized normal sequencing. In such cases, procedures were devised to minimize vulnerability to inadvertent switch closure, such as keeping the system disarmed and using circuit breakers at all times except when arming was required.

In other cases, any backup for an essential function was simply impractical, such as the case of the lunar module (LM) ascent stage engine used to leave the lunar surface. In such cases, extensive testing programs for qualification and flight engines were used, together with rigid configuration control and quality assurance surveillance of each flight article to minimize the risk.

Although the FMEA and SFP information provided by contractors was usually in different formats and the data were presented in various manners, an analysis was accomplished. To overcome this problem and to ensure a uniformity of data on the spacecraft FMEA and SFP summaries, a recommended format was established for documenting the information (figs. 1 and 2).

FAILURE-MODE AND EFFECTS ANALYSIS

SYSTEM \_\_\_\_\_ PREPARED BY \_\_\_\_\_ PAGE \_\_\_\_\_ OF \_\_\_\_\_  
 SUBSYSTEM \_\_\_\_\_ APPROVED \_\_\_\_\_ DATE \_\_\_\_\_  
 ASSEMBLY \_\_\_\_\_ SUPERSEDING \_\_\_\_\_

ITEM IDENTIFICATION				FUNCTION	FAILURE MODE AND CAUSE	MISSION PHASE	FAILURE EFFECT ON			FAILURE-DETECTION METHOD	CORRECTIVE ACTION TIME AVAILABLE/TIME REQUIRED	FAILURE-MODE CRITICALITY CATEGORY	REVISION
NAME	IDENTIFICATION NUMBER	DRAWING REFERENCE DESIGNATION	SYSTEM LOGIC DIAGRAM NUMBER				ASSEMBLY	SUBSYSTEM	SYSTEM				
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)

Figure 1. - Format for failure mode and effects analysis.

SINGLE-FAILURE-POINT SUMMARY					
SYSTEM _____		CRITICALITY CATEGORY _____		REFERENCE FMEA _____	
SUBSYSTEM _____		PREPARED BY _____			
ASSEMBLY _____		APPROVED _____		DATE _____	
SUPERSEDING _____					
ITEM IDENTIFICATION	FAILURE MODE AND CAUSE	FAILURE EFFECT	FAILURE-DETECTION METHOD	RATIONALE FOR ACCEPTABILITY	REVISION
(a)	(b)	(c)	(d)	(e)	(f)

Figure 2. - Format for single failure point summary.

The FMEA and the SFP summaries were not required for all flight hardware. In some cases in which the hardware was not essential to the completion of the mission (for example, a simple experiment) and a malfunction could not be hazardous, the FMEA and the SFP summaries were omitted.

The JSC experience with failure mode and effects analyses and SFP analyses indicates that these analyses are most effective when used in conjunction with design reviews. The Apollo spacecraft engineers performed comprehensive failure mode and effects analyses and SFP summaries and, through a series of iterative design reviews, eliminated or minimized the number of potential failure points (ref. 2).

### Electrical, Electronics, and Electromechanical Parts

**Background.** - The original NASA provisions for control of EEE parts included the use of parts specialists to act as advisers to the design groups and to conduct the parts activities. The specific parts provisions included selection of parts, preparation of specifications, qualification tests, preparation of approved parts lists, and review of parts applications.

Experience. - These provisions were only partially effective. Design reviews conducted at the parts level disclosed several problems that required changes in the provisions to ensure the reliability of the Apollo equipment. A parts reliability requirement document was developed by JSC that required that a parts program plan be developed by contractors. This plan included requirements for development of specifications, one-way traceability, derating of parts, screening, and burn-in procedures and techniques.

Review of the stress analyses for electronic assemblies revealed several cases in which the parts were stressed beyond the values established in the parts specifications. Several failures of Apollo equipment were attributed to parts overstress. On the basis of this experience, the current goal is to have any new parts design stresses (voltage and so forth) no higher than 75 percent of the rated capability. This understressing is usually referred to as derating.

The practices of screening parts for defects before use and burn-in (to eliminate infant mortality parts) were not implemented for some of the early Apollo equipment, and several failures of this equipment were traced to defective parts. In many cases, analysis disclosed that the failures could have been averted if screening and burn-in techniques had been used. As a result of these lessons, a dedicated effort was made to secure screened and burned-in parts for each critical flight application.

Background - parts information. - An automated file of information on EEE parts was established at JSC. Parts usage information was obtained from contractors and suppliers and processed into the file, and reports were made and distributed to contractors. This allowed the contractors to compare parts test plans with the report information to determine if the same or similar parts had already been tested by another contractor. More than \$2 million in planned testing was avoided in this manner.

Experience. - Initially, it was thought that the parts usage information would be extremely valuable to the designers of the next generation of space systems. However, it was soon realized that the rapid technological advances in the EEE parts field makes much of the information obsolete within a short time unless updated parts usage and application information is continuously inserted into the system. Therefore, the usefulness of the file may be limited primarily to current programs. In addition, the file is useful for assessing the reliability of space-flight equipment at milestone reviews. For example, when equipment failures occur and the failure cause is isolated to an EEE part, the parts master file can be used to determine where the part type is used other than the failed equipment. The file is effective to a limited degree, but, like all automated files, it may not be current. In those cases when current data are missing, it becomes necessary to have the contractor search their records (such as material and parts lists) for the usage and application of suspect parts. However, the JSC file does permit the initial rapid location and investigation of the equipment.

## Nonmetallic Materials

Background. - From a materials standpoint, a significant experience of the Apollo Program is the use of nonmetallic materials in the oxygen-rich spacecraft cabin atmosphere. The reliability tasks contained in the NASA handbook "Reliability Program

Provisions for Aeronautical and Space Contractors'' included general requirements regarding materials but did not emphasize the importance of nonmetallic materials.

Experience. - At the start of the spacecraft design effort, the amount of data on the flammability of NMM in pure oxygen at 5 psia and the toxicity of NMM was limited. Extensive testing of a variety of nonmetallic materials was required to find the least flammable and toxic material for each application. As the program progressed, many changes in materials were made as data were developed and requirements were included in contracts. The control of the NMM used in the Apollo spacecraft contributed largely to the enhancement of crew safety in the spacecraft. However, other important factors that must be considered for crew safety include control of ignition sources, control of the environment, fire-detection capability, and fire-extinguishment provisions. A systems engineering approach to firesafety (ref. 3) must be established early in the development of space-flight programs.

Offgassing, the term used to describe the evolution of gaseous products from liquid or solid material, represents one of the hazards associated with the use of NMM. In some cases, the offgassed products are toxic. In other cases, the offgassed products can coat sensitive equipment and degrade its performance. Although most organic materials offgas to some extent at normal atmospheric conditions, many materials do not offgas significantly unless exposed to elevated temperatures, reduced pressures, or a combination of elevated temperature and reduced pressure. In the Apollo spacecraft, offgassing characteristics of materials must be evaluated during the material selection process. Material selection criteria are presented in reference 4.

Background - materials information. - Materials tests were conducted at contractor and JSC facilities. However, JSC soon realized that performing the tests at several different locations could result in duplicate testing and unnecessary expense. Data on the tests performed were accumulated and reproduced at JSC and distributed to contractors for review and analysis with the objective that contractors would not have to test materials already tested by other contractors.

Experience. - The automated file of NMM information was designed to provide test data to contractors, Government organizations, and other organizations that wanted the data and also to yield NMM usage information for each Apollo spacecraft (material type, location in the spacecraft, weight, and so forth). Data from standardized tests on flame propagation, ignition temperature, and toxicity of offgassed products were accumulated and published periodically in JSC document MSC-02681, "Nonmetallic Materials Design Guidelines and Test Data Handbook." The current issue of this document contains information on approximately 15 000 standard tests (conducted at six test facilities) that have been made on approximately 3700 different nonmetallic materials that are used or were considered for application on the Apollo spacecraft. Results from approximately 2600 special tests are also included in the document. The document provided Government and industry personnel with test data and made possible the development of a cooperative program of data exchange between Government agencies and industry for the avoidance of duplicate testing.

## Fluid Systems

**Background.** - On a typical Apollo mission, 71 tanks are installed in the command and service module (CSM) and LM. These tanks contain items such as water, gaseous and liquid oxygen, liquid hydrogen, gaseous helium, gaseous nitrogen, nitrogen tetroxide, and Aerozine-50. The tanks have relatively thin walls and are highly stressed. For this reason, small surface imperfections can be significant stress risers and potential failure points.

**Experience.** - Some of the more significant problems encountered in the fabrication, installation, and testing of fluid systems are discussed in the following paragraphs.

**Pressure vessels.** - The service propulsion system (SPS) tanks installed in the Apollo service module are shown in figure 3. The two helium tanks are spherical, are more than 40 inches in diameter, and are fabricated of titanium alloy. The oxidizer storage tank is 45 inches in diameter, is more than 153 inches long, and has a wall thickness of 0.047 inch. The large size and thin walls make these tanks awkward to handle and thus extremely susceptible to inadvertent damage.

Special handling procedures were developed and used during the manufacturing, installation, and testing phases of these tanks, making all personnel aware of the critical operations associated with the handling of the pressure vessels. Experience related to pressure vessels used in the Apollo Program is discussed in detail in reference 5. Eighteen tank failures were reported during operations before flight. Some failures attributed to stress corrosion, weld cracks, and materials defects are described as follows.

**Stress corrosion:** The failures caused by stress corrosion were caused principally by the use of fluids that contained substances that were incompatible with the tank materials. In one case, methanol was used as a test fluid for the SPS tanks. Analysis and testing in this case disclosed that a particular methanol and the titanium used are incompatible materials (ref. 6). In another case, impure water was used as a test fluid and failure resulted from incompatible materials. Experience with these problems showed that controls must be implemented to assure that fluids used in pressure vessels are compatible with the tank material.

**Weld cracks:** An SPS propellant tank failed during an acceptance proof test; the failure was attributed to contamination in the weld joint between the cylindrical portion of the tank and the domed ends. Although the source of the contamination was not

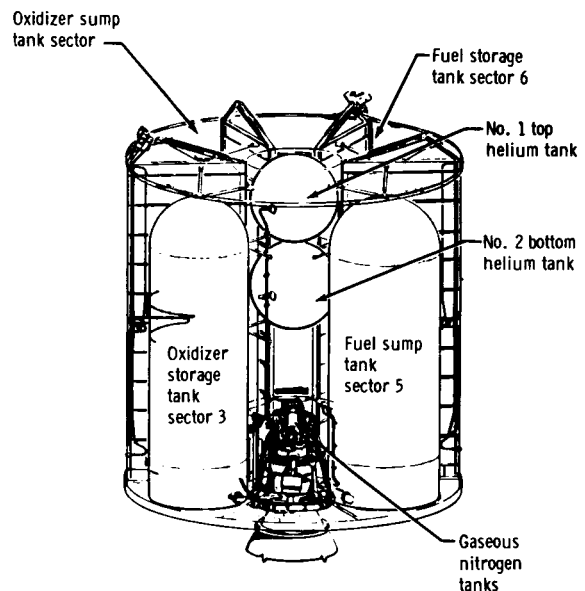


Figure 3. - Service propulsion system tanks installed in the Apollo service module.

definitely established, it most likely occurred during the welding operation. Special controls were instituted to preclude recurrence of this problem including vapor blast cleaning before welding, control of the working and wetting environments, and the use of clean gloves during the welding process. These procedures apparently have been effective because no further problems have occurred with this type of weldment.

**Material defects:** An LM descent propulsion system pressure vessel failed during a hydrostatic acceptance proof test. Investigation revealed that the failure was caused by localized microstructure abnormality, consisting of "massive" alpha-phase structure in the upper dome. Alpha inclusions of this sort are rare and cannot be detected in the raw material with existing nondestructive testing techniques. Proof testing is the only practical approach for screening finished pressure vessels.

The major nondestructive test methods implemented on the Apollo pressure vessels are ultrasonic inspection, X-ray photography, dye-penetrant inspection, and magnetic particle inspection (steel tanks only). Nondestructive test methods have limitations. For example, X-ray photography can reveal surface and subsurface flaws but is sensitive to flaw orientation. Penetrant inspection is limited to the detection of surface flaws. These techniques must be used despite the limitations, and experience indicates that acceptance proof testing is the only way to ensure the integrity of the completed tanks.

Background - pressure vessel historical records. - Every pressure vessel in the Apollo spacecraft was pressurized and vented many times before flight. The vessels were pressurized during acceptance tests by the suppliers and several times after installation in the spacecraft. These pressurization cycles vary in pressure levels attained, elapsed time at pressure, fluids used, and temperature while under pressure. In addition, the tanks were frequently exposed to fluids for cleaning and purging.

Experience. - Investigation of tank failures early in the program disclosed that detailed historical records had not been maintained for the individual tanks. Without such records, the flightworthiness of each flight tank could not be determined because of lack of knowledge about pressure levels and cycles attained; duration at pressure and temperature; fluids used for fabrication, cleaning, and testing; and any nonconformances recorded against the tank. Historical record cards were developed by JSC and requirements were imposed on the tank manufacturers and spacecraft contractors to maintain the cards current and to record the information and data just mentioned.

Fluids. - The quality of the fluids used in the Apollo spacecraft systems was vital to the reliability of the systems; many failures of equipment were attributed to impurities and contaminants in the fluids. In some cases, fluid system qualification tests were conducted with fluids that were of a higher purity (less contaminants) than the fluids used in acceptance tests or system operation. Many of the problems associated with fluids occurred from the lack of adequate standards or specifications for fluid cleanliness and fluid sampling. Guideline documents have been prepared to ensure proper control of fluids used in the spacecraft. Whenever changes are made to manufacturing processes, handling procedures, or procurement sources for any fluids (liquids or gases), consideration should be given to requalifying a system that has been previously qualified using a particular fluid.

Contamination. - Contamination was one of the major problem categories on the Apollo spacecraft. The equipment contamination problems were attributable directly to inadequate knowledge in the disciplines required to maintain the level of cleanliness established during the equipment design phase.

Basically, contamination in fluid systems can be categorized as follows.

1. Fluids used for testing or operating the system; specifications or sampling procedures inadequate
2. Fluid transmission systems (GSE and launch site facilities) not maintained to same level of cleanliness as the spacecraft
3. Fluid system components not properly cleaned or sealed before installation
4. Contaminants introduced into the system during system installation (brazing and soldering fluid lines, environment not controlled while fluid lines and components were being installed, and so forth)
5. Fluid system components, such as quick disconnects, generating particles upon assembly or disassembly

To prevent the occurrence of these problems, it was essential that controls including proper filtering be established at the start of fluid system design. The levels of cleanliness specified for the system by the designer must be maintained in the fluids, the system components, and the ground support equipment, at all locations. Controlled environments must be maintained during component assembly, installation, and removal. Plans and procedures were developed to ensure that the required disciplines were maintained by all participants, including suppliers.

## Problem Control

Background. - A system was developed by JSC for managing the disposition of problems (failures and anomalous performance) occurring on hardware during the Apollo Program. The system included all program participants (contractors, subcontractors, NASA test sites, and KSC) and provided for the recording and reporting of failures and other deficiencies, assessment of problems for cause and responsibility, corrective action to preclude recurrence, and screening operations that allowed problems to be solved at the lowest management level. Only the most significant problems (high risk and unresolved) were presented to program management for review. The system was designed to support the spacecraft prelaunch reviews by providing summaries of subsystem problems occurring on the spacecraft in review as well as other problems that may affect the vehicle in review. The problem control system also was integrated with the NASA-wide ALERT system for dissemination of parts and materials problems.

Experience - recording and reporting of problems. - A reasonable degree of awareness of problems and the impact of these problems on the program was difficult to maintain because of the large number of different problem reporting forms used by many contractors. Another difficulty developed concerning the report of failures to



JSC. The spacecraft contractors expressed concern about the definition of the term "failure" and the feasibility of reporting failures before acceptance test. To assure that all problems were properly documented and assessed, a failure was defined by JSC as "the inability of any part, component, or subsystem to perform its intended function under specified conditions and for a specified period of time" regardless of outside influence such as procedural or human error. All such problems were reportable to JSC after the beginning of hardware acceptance testing and required JSC approval of the fixes by subsystem managers and R&QA personnel before the problems could be closed out.

Problem assessment. - Some problems had their origin in the design and had to be solved by the designers. Other problems, which originated in the manufacturing activities, had to be corrected by the department responsible for the problem. Many problems of manufacturing origin were reported to JSC, where it was recognized that the investigation and closeout of this type of problem should be performed by contractor personnel at the contractor facility, with JSC personnel participating and concurring in the actions.

This experience led to the establishment of problem assessment groups at the CSM and LM contractor facilities and at JSC. The prime function of the problem assessment groups was to review and screen the problem reports for manufacturing or design origin. All problems of design origin and significant manufacturing problems were transmitted to the JSC problem assessment group, where they were redistributed to the JSC subsystems managers, the reliability engineers, and the program office. Experience indicates that the problem assessment function was effective in prompt resolution and closeout of problems.

Corrective action and closeout. - The ideal procedure was to review each problem and implement corrective action immediately. However, experience shows that this ideal condition could not be achieved. Discipline was required to assure that the most critical problems were addressed first and that the remaining problems were attacked on a priority basis. The contractor problem assessment groups were charged with the responsibility of assigning and approving corrective action. Final approval for closeout of problems of design origin was provided by the JSC subsystem manager and reliability engineer. Closeout of problems of manufacturing origin was provided by the local quality personnel at the contractor plant or by JSC (Houston) quality assurance office, together with the appropriate subsystem manager.

The NASA ALERT system. - Parts and materials application, failure, malfunction, or problems of common interest were reported in the ALERT system. This NASA-wide system, established in 1964, provides for distribution of problem notices to NASA and contractors through coordinators at the various centers and to DOD through the Interservice Data Exchange Program (presently called Government-Industry Data Exchange Program (GIDEP)). The Apollo contractors were required to respond to JSC on each ALERT, stating whether or not the contractor hardware was affected. If the hardware was affected, a resolution to the problem was worked out.

# MANUFACTURING FUNCTIONS

## General

Analysis of the Apollo spacecraft failure records disclosed that a large percentage of the failures were caused by workmanship (10.6 percent), contamination of equipment (8.2 percent), and other manufacturing causes (8.0 percent). Some of the more significant experiences are discussed in the following paragraphs.

## Spacecraft Wiring

Background. - Because of weight limitations, much of the wiring in the Apollo command module was insulated with thin-walled Teflon covered with a thin polyimide coating. This wire was extremely susceptible to damage, and many special procedures were developed to ensure the integrity of the wiring after installation in the spacecraft, during equipment installation and checkout, and during the mission. The complexity of the crew compartment wire harness is shown in figure 4.

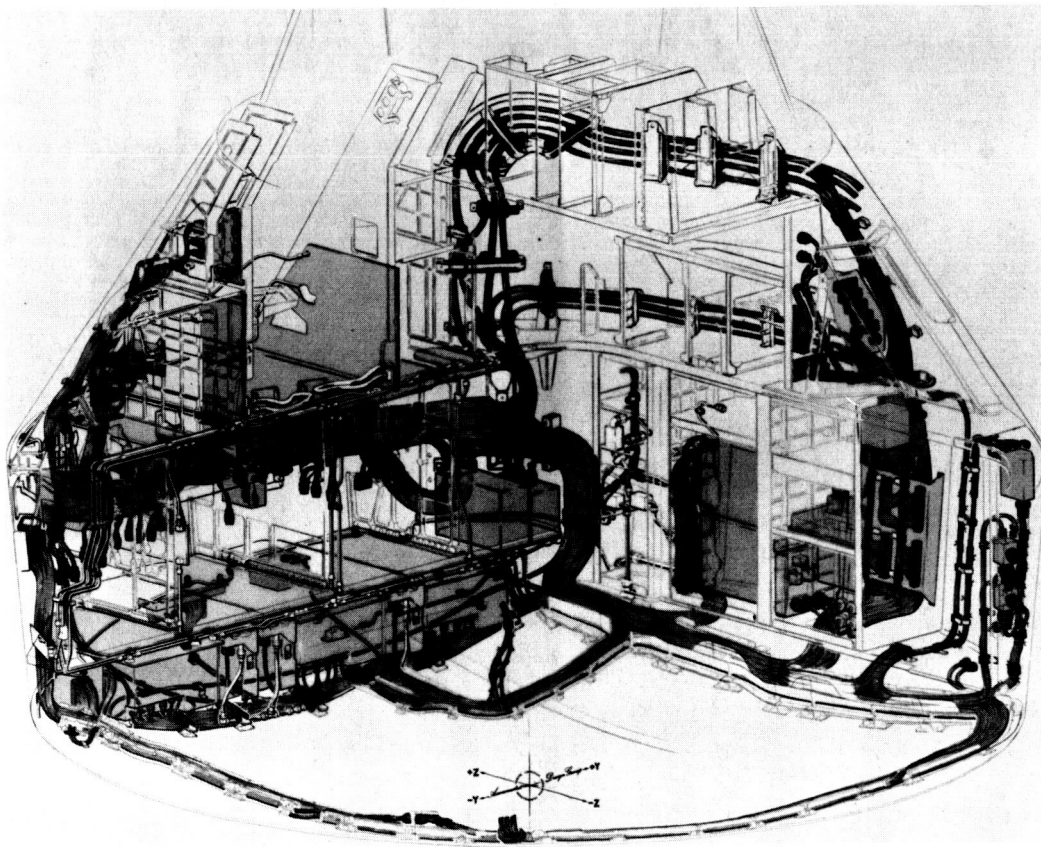


Figure 4. - Crew compartment electrical harness.

Background - harness assembly and installation. - Because of the small size of the crew compartment and the limited number of technicians who can work in the crew compartment at the same time, it was impractical to try to do the spacecraft wiring (measuring, cutting, and other operations) within the compartment.

Experience. - A special assembly fixture (fig. 5) was developed to assist in the assembly of the crew compartment harness. All fabrication operations were performed on the fixture, including installation of connectors. On completion of the harness assembly operations, an inspection was performed by the contractor, after which the harness was submitted to the Government inspectors for visual inspection. The final operation consisted of an automated air dielectric test while the harness was still in the assembly fixture. After completion of the harness checkout, the entire assembly was moved to the spacecraft assembly area for installation of the harness in the command module.

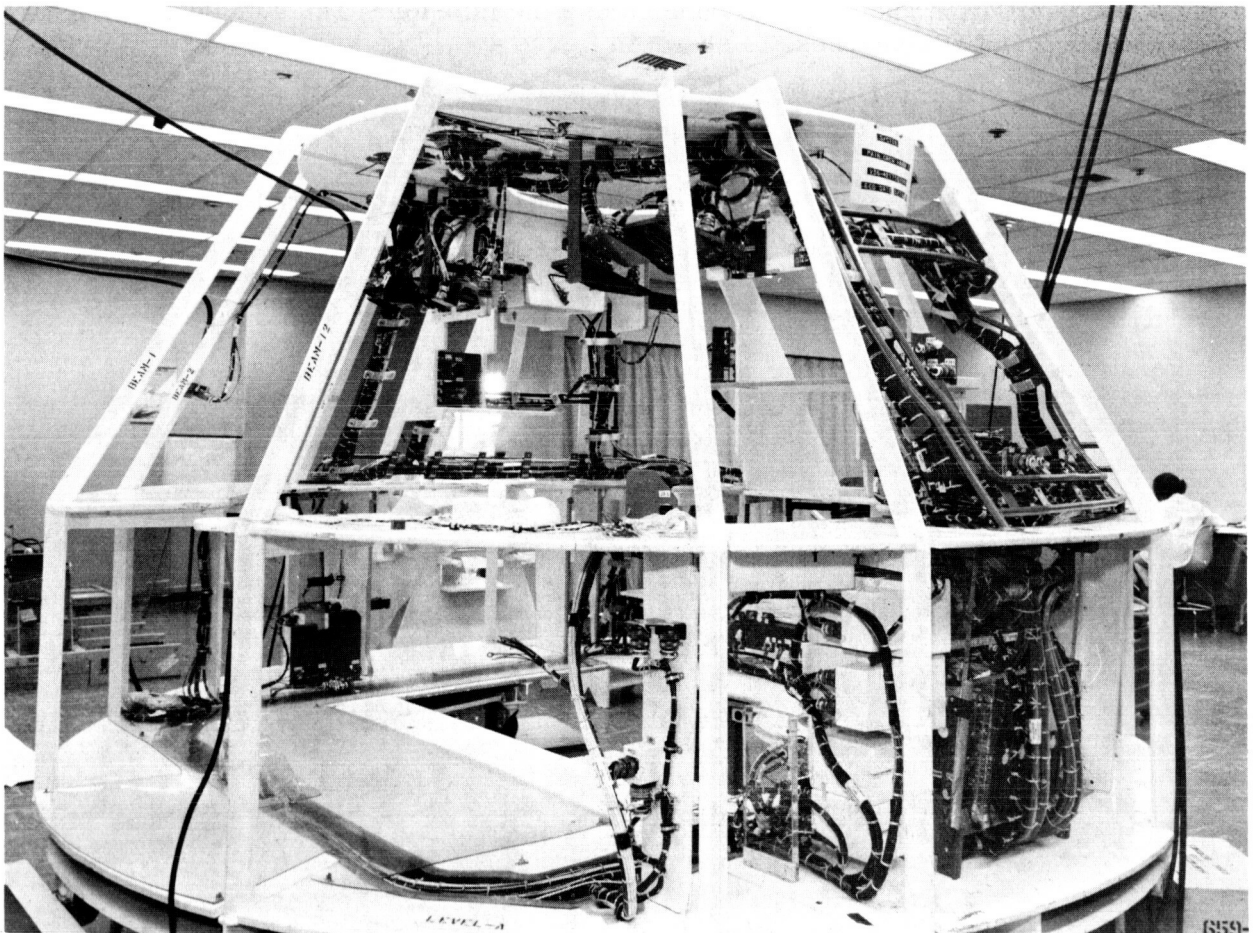


Figure 5. - Special fixture for assembly of the Apollo command module crew compartment wire harness.

Installation of the crew compartment harness was a complex operation and required considerable care to prevent damage to the harness. The completed harness, wrapped in a plastic material for protection, weighed more than 600 pounds and was extremely difficult to handle because of the many wire breakouts and connectors. The contractor devised a Teflon-coated trough (fig. 6) that fits through the command module hatch and allows the harness to be fed into the cabin. As the harness is fed into the command module, technicians position the wire bundle breakouts and clamp them into position. An example of wire routing and clamping is shown in figure 7.

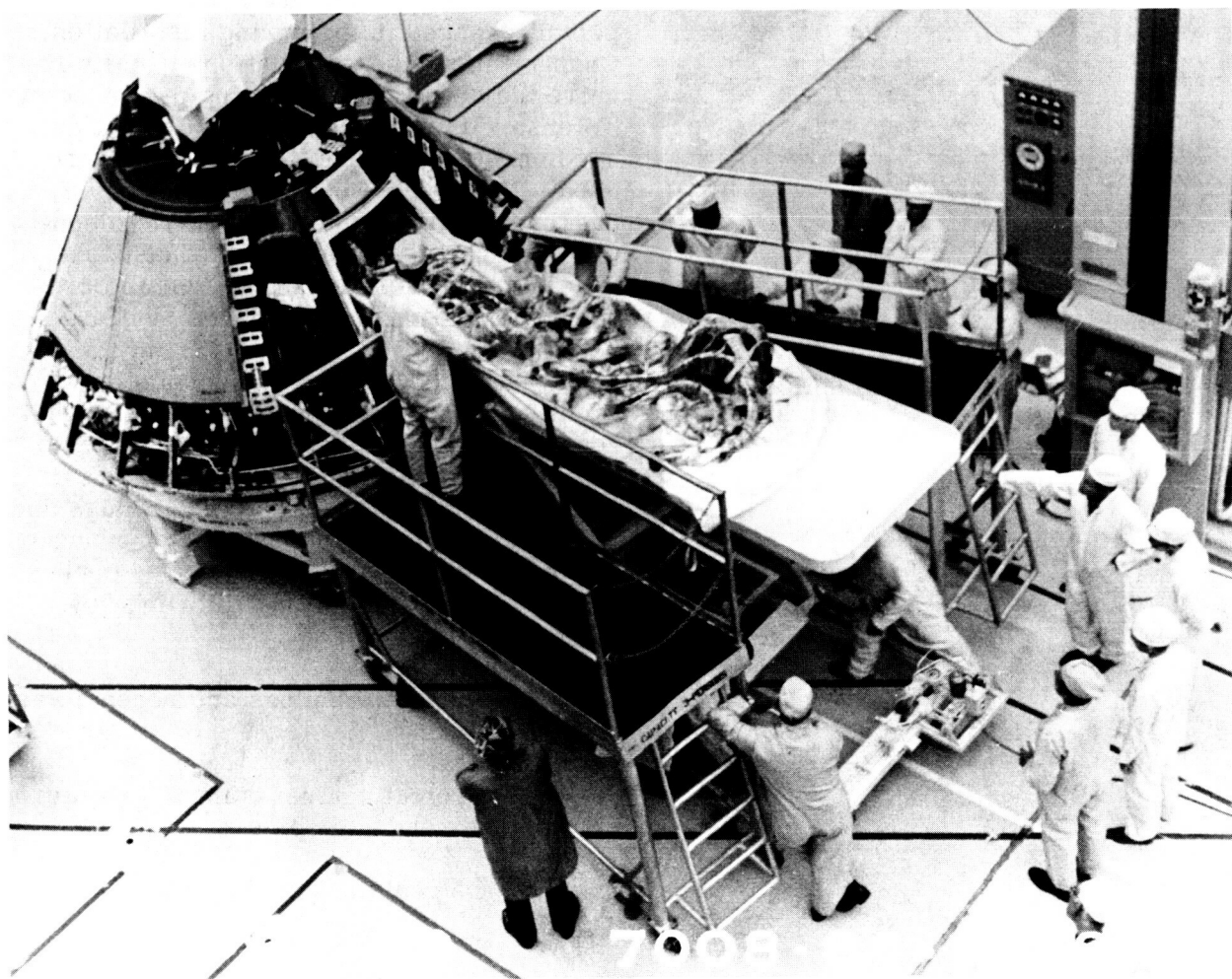


Figure 6. - Special Teflon-lined trough for installation of the Apollo crew compartment wire harness.

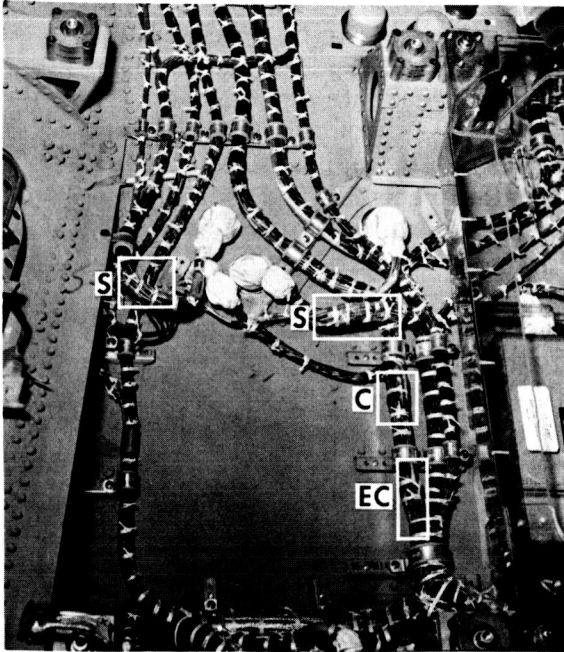


Figure 7.- Lunar module cabin wiring crimp (C) and solder (S) splices and end caps (EC).

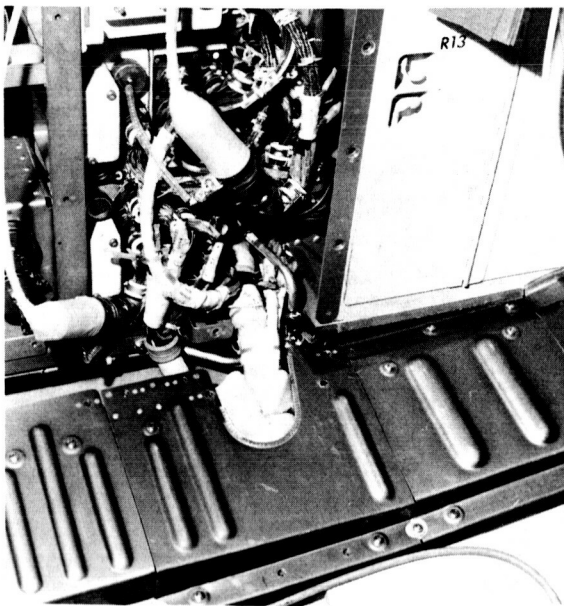


Figure 8.- Command module cable trays.

Background - protection of wiring installation. - Initially, the wiring in the crew compartment was exposed and subject to possible damage during ground-based operations as well as during flight.

Experience. - To protect the cables from physical damage and to reduce the risk of flame propagation, special protective trays were designed (fig. 8). In addition, these trays also are removable to permit changes in the wiring installation. Changes in wiring installations usually require the mating and demating of connectors. To ensure that the connectors are not damaged, protective covers were needed and used. Metal screwcaps were used first, but thread galling and metal particle contamination caused considerable concern. As a result, the following design and procedural standard was prepared by JSC.

Electrical plugs and receptacles of flight equipment and ground equipment that connect with flight equipment must be protected at all times. Protective covers or caps are required over electrical plugs and receptacles whenever they are not connected to the mating part. The protective covers or caps must perform the following functions.

1. Protect the plugs and receptacles from moisture
2. Protect against damage to sealing surfaces, threads, or pins
3. Be resistant to abrasion, chipping, or flaking
4. Be brightly colored so as to be easily discernible and command attention
5. Be maintained at a level of cleanliness equivalent to the plugs or receptacles on which they are used
6. Be made of material that is compatible with the connector material

## Electrical Connectors

Background. - Many electrical connectors are used in the spacecraft. Many of these connectors have a large number of closely spaced, small-diameter pins. Problems encountered included crimping of small connector pins, moisture proofing the connectors, bent pins, and verification that connectors were mated properly. As these problems occurred, solutions were found and techniques and procedures were implemented to prevent recurrence. In some instances, design and procedural standards were developed and contractually imposed on contractors; such was the case regarding moisture proofing of connectors. The standard required that electrical connectors and wiring junctions to connectors be sealed from moisture to prevent open and short circuits and that the composition and quality of the seal depend on the environment to which the seal will be subjected.

Background - crimping. - The large incidence of crimp failures in the early days of Apollo manufacturing precipitated an intensive review of the crimping tools and the crimping techniques. One type of crimping tool then in use, even though properly calibrated, frequently produced overcrimped pins, with the result that the wire would fail the pull test at the point of overcrimp. In other cases, wires were pulled from crimped pins because of improper calibration of the tool.

Experience. - The crimping operations must be controlled rigidly to ensure that the proper tools, properly calibrated, are used by trained personnel. The following controls were established by the contractors.

1. Each crimp tool was serialized.
2. A calibration recall date was established for each tool.
3. Each tool was preset and sealed for each crimp size.

Despite these controls, a problem developed where 24-gage wires pulled out of connectors. Investigation disclosed that the crimps were made with the wrong tools. This condition occurred because the technician had several crimp tools at hand and selected the wrong one. The tool control procedures were changed to permit technicians to check out only one tool at a time. To verify that a crimp had been made properly, test samples were made before and after each crimping operation and subjected to pull tests to verify that the proper tool was used and that the operator performed the crimping properly.

Background - bent connector pins. - In many cases, the use of high-density connectors resulted in bent pins. Added to the basic problem of extremely delicate and easily bent pins was the frequent demating and mating or reconnection of connectors for equipment removal or installation.

Experience. - The problem of bent connector pins became so severe that special training was provided for selected personnel, and, thereafter, all connector handling was performed by these trained personnel. Procedures for straightening pins were prepared, and requirements were established for recording all instances of bent pins. Experience indicates that constant vigilance must be maintained to ensure that connector handling is a closely controlled function at all locations.

A technique used on the Apollo spacecraft to provide the capability of connector integrity control is to apply paint stripes on connectors that have been properly mated and verified to provide an indication when unauthorized demating of the connectors occurs. Special paint was required to ensure that the paint did not chip or flake and become a contaminant in the crew compartment.

Radiographic inspection of electrical connectors. - Radiographic inspection was used to validate the integrity of certain connectors and terminal boards. While wire harnesses were still in the assembly fixture, electrical connectors were examined by X-ray photography. This procedure proved effective in detecting internal defects such as improper component seating, broken wires, bent pins, birdcaging, open joints, and conductive inclusions. Radiographic inspection of connectors and terminal boards also was used for troubleshooting after the wire harnesses were installed in the spacecraft. Small portable X-ray equipment made this procedure entirely practicable. In this manner, the connectors that could be X-rayed without having to remove other equipment could be inspected for bent pins and other defects. Experience with X-ray photography of electric connectors indicates that this practice should be used more extensively. The procedure was relatively inexpensive, and many defects that could not otherwise be detected were found with this method.

## Contamination Control

Background. - The advent of manned space flight introduced stringent requirements for cleanliness in the spacecraft, spacecraft subsystems, and ground support equipment. In the zero-g environment of space, loose objects in the spacecraft (nuts, bolts, washers) can be a nuisance and, in some cases, a hazard because they float freely about the interior of the spacecraft and can provide an unwanted conducting path in electrical circuitry or impede mechanical actuation of equipment. Experience with glass-column manometers and droplights used in the crew compartment indicated that breakage of these glass devices would constitute a threat to the safety of the crew if glass dust were left in the cabin and eventually inhaled by a crewmember. The use of all glass items in the spacecraft is restricted severely and controlled to prevent this hazard. Other forms of contamination included the spillage and leakage of fluids used in the spacecraft system.

Experience - contaminants in fluid systems. - The fabrication and assembly of fluid systems and the associated components required precision cleaning techniques and controlled environments. Many of the experiences from the space programs are presented in references 7 and 8. Many cases of fluid system contamination were caused by the introduction of contaminants during welding, soldering, brazing, or mechanical coupling of fluid system lines during installation of equipment. This experience led to the establishment of special procedures to minimize the chances of contaminating the systems during these operations.

Experience - spacecraft cleanliness. - The following special controls were implemented to minimize the problem of loose materials in the crew compartment.

1. The spacecraft was "tumbled" or rotated several times to recover loose articles that otherwise were inaccessible.

2. The crew compartment was vacuum cleaned frequently.
3. Ultraviolet light inspection was used for detection of residual solvents and other potential contaminants.
4. Filtered air was supplied to the crew compartment when the compartment was open.
5. Hatch monitors were used to control entry into the crew compartment. Tools, materials, and equipment were recorded in a logbook during ingress and egress.
6. Materials (cleaning fluids and so forth) that were used to service the spacecraft were controlled and had to be approved before they could be near or in the spacecraft.

Experience - fluid spillage. - Several incidences of fluid spillage occurred in the early phases of spacecraft assembly and test. For example, mercury was found in the crew compartment after a glass-column manometer shattered. The toxic effects of mercury on the crew or to spacecraft metals caused concern and resulted in the establishment of design and procedural standards to preclude the use of mercury in or around the spacecraft. Another example of fluid spillage was the spillage of the coolant solution (water/glycol) used in the environmental control system. Spillage of this material on spacecraft equipment and wire harnesses frequently necessitated removal and replacement of the equipment and costly and time-consuming cleanup operations. Rework of the removed equipment to render it usable is also expensive.

Tests were conducted to determine the effects of water/glycol solution on electrical wiring because the chemical reaction between the water/glycol and the silver-coated wire with broken insulation can provide a conductive path. Special procedures were developed to assure that water/glycol spills were cleaned properly with chemical tests to prove the adequacy of each cleaning.

## COMPONENT TESTS

### Background

"The single most important factor leading to the high degree of reliability of the Apollo spacecraft was the tremendous depth and breadth of the test activity." The preceding quotation is from reference 9.

Testing of the Apollo spacecraft equipment represents a substantial portion of the program resources and consists of two basic categories: certification testing and acceptance testing. These test activities are discussed in the following paragraphs.

Experience indicates that unless a comprehensive and well-integrated test plan is prepared, much unnecessary testing can be performed and some may be missed. Of greater importance from a reliability standpoint is the fact that testing may be performed at the wrong assembly level. This experience led to the development of special ground rules for testing Apollo spacecraft and equipment. These ground rules are discussed in references 10 and 11.



## Certification of Space-Flight Equipment

**Background.** - The Apollo spacecraft equipment design is certified by test, by analysis, or by similarity to other certified equipment. This certification method minimizes the amount of hardware required for test purposes and shows the capability of the equipment to withstand mission environments and durations. More than 700 tests were required before the first manned Apollo flight.

**Experience.** - The certification testing activity was guided by the following rules.

1. Use production equipment for test.
2. Test at highest practicable level of assembly.
3. Test all redundant paths.
4. Test at or above maximum expected natural and induced environments.
5. Perform acceptance test before certification test.
6. Analyze to supplement testing.
7. Understand and resolve all failures thoroughly.

The distribution of failures detected during certification tests, acceptance tests, and flight is shown in figure 9. Reference 12 contains additional information about the JSC certification test program.

Many design deficiencies were detected and corrected as a result of the certification test activities. A distribution of certification test failures by test environment is shown in figure 10. The dynamic environments yielded a substantial number of the total failures experienced.

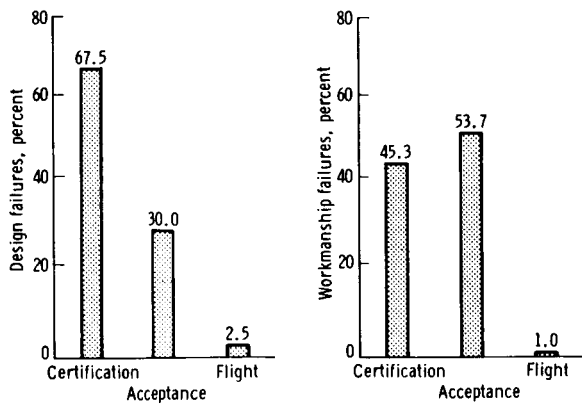


Figure 9. - Apollo spacecraft failures.

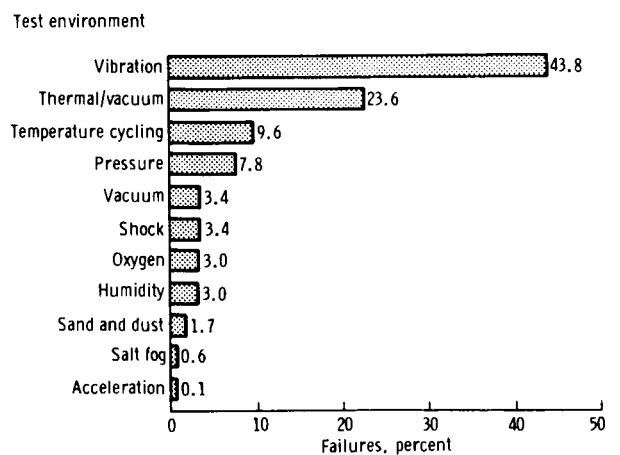


Figure 10. - Distribution of Apollo spacecraft certification failures by environment.

## Acceptance Test

Acceptance tests were conducted on completed equipment and were intended to detect manufacturing defects. The acceptance test requirements for Apollo spacecraft equipment included thermal and vibration tests for those equipment items that were susceptible to failure caused by temperature or vibration. Electronic equipment containing soldered connections is one example of this category. Defective solder connections can be detected during thermal and vibration testing, especially if instrumentation is used to monitor the circuitry for intermittency during the test.

Many manufacturing and design deficiencies can be detected during acceptance tests. A summary of acceptance test failures that occurred during vibration and thermal testing is contained in table I. The testing of spacecraft equipment is described in reference 11.

TABLE I. - SUMMARY OF ACCEPTANCE TEST FAILURES FOR THE LM AND CSM BY INDIVIDUAL SUBSYSTEM

Subsystem	Construction type, percent		Vibration tests				Thermal tests			
	Electronic	Electro-mechanical	Component types	Units tested	Number of failures	Failures, percent	Component types	Units tested	Number of failures	Failures, percent
Sequencers	90	10	10	169	11	6.5	8	159	13	6.2
Environmental	10	90	14	339	32	9.4	13	197	22	11.2
Electrical	80	20	53	847	103	12.2	30	449	28	6.2
Stabilization	80	20	11	184	28	15.2	11	388	71	18.3
Communication	90	10	23	441	105	23.8	21	273	73	26.0
Instrumentation	90	10	7	118	30	25.4	5	469	26	5.6
Reaction control	20	80	1	543	7	1.3	3	757	71	9.3
Propulsion	15	85	9	235	16	6.8	3	22	1	4.5
Abort guidance	80	20	9	257	17	30.0	5	88	100	114.0
Mechanical	0	100	1	74	7	10.6	1	51	6	11.7
Radar	80	20	4	52	32	6.2	0	0	0	0
Display components	90	10	32	7 928	353	4.5	18	848	177	21.0
Display panels	90	10	0	0	0	0	11	106	77	7.3
Total	--	--	174	11 187	741	6.7	129	3807	665	17.4

## Nondestructive Tests

**Background.** - The conventional nondestructive methods (radiography, ultrasonics, dye penetrant, magnetic particle, and so forth) of testing equipment were used on Apollo spacecraft equipment. In some cases, combinations of these methods were used because of the limitations of a particular method in a particular application.

Experience. - Multiple inspections using nondestructive test methods can be used effectively if there is doubt regarding the reliability of the equipment. For example, LM descent stage gaseous-oxygen tanks that had been proof pressure tested were recalled and subjected to additional nondestructive testing. These tanks were reinspected by using X-ray photography, ultrasonic pulse-echo, and dye-penetrant nondestructive methods and were found to be acceptable for flight use. Neutron radiography provided good results in detecting hydrogen embrittlement in weldments and for inspection of pyrotechnic devices.

One innovation in radiographic inspection was very effective. Polaroid film was used with conventional portable X-ray equipment to "rough in" shots of items or objects in difficult areas. The use of this film saves much time because of the short development time compared to that of conventional X-ray film.

Background - receiving inspection at KSC. - When the spacecraft arrived at KSC, an inspection was performed by the vehicle contractor and NASA, primarily as a check for damage in transit. Many deficiencies were found, some of which were not recorded at the time of vehicle shipment and others which had been recorded and accepted "as is." Thus, it was found that the inspectors at the two sites, at KSC and at the contractor facility, were inspecting without benefit of written acceptance instructions or criteria that were compatible with each other.

Experience. - Inspection procedures were prepared, and a set of deficiency diagrams was shipped with each vehicle to indicate where deficiencies had been noted and recorded at time of shipment. This condition is unusual because the spacecraft is shipped with many installations and operations that can be performed only at KSC. Experience indicates that much unnecessary effort and paperwork can be averted by a coordinated planning activity of the inspection operations regardless of where they are performed.

## CONCLUDING REMARKS

To be effective, reliability and quality assurance requirements and functions must be planned, monitored continually, and adjusted as the program develops and advances. The reliability and quality assurance activities are, in reality, disciplines that, if properly implemented, will enhance the probability of producing and delivering reliable equipment. These disciplines have to be selected or tailored for each procurement. Some experiences related to the disciplines that were monitored and adjusted as the program developed are as follows.

1. Specifying in contracts the scope, format, and content of reliability and quality assurance plans
2. Establishment of customer/contractor reliability and quality assurance management review meetings of reliability and quality assurance program status

3. Development of incremental data and documentation reviews associated with program milestone reviews for assessment of space-flight equipment

4. Application of broad specifications for soldering, welding, painting, and similar processes, instead of detailed step-by-step requirements

Effective contributions to product integrity are made by engineering personnel who select parts and materials, establish tolerances, consider environments involved, and prepare the documentation from which the product is purchased, fabricated, and handled. Some experiences encountered in association with engineering functions that contributed to this product integrity are as follows.

1. Documentation of failure mode and effects analysis and single failure point information to an established format

2. Development of contractor electrical, electronic, and electromechanical parts program including requirements that parts be appropriately derated and screened before use and that burn-in procedures and techniques be used

3. Controlling use of nonmetallic materials in spacecraft and for controlling cleanliness of equipment and fluid system

The fabrication, assembly, and testing operations of spacecraft equipment during the manufacturing phase required that adjustment and changes be made to those operations and that new techniques be adopted to preserve the reliability of the product. Experiences related to this phase of the program include the following.

1. Development of a special crew compartment harness fixture

2. Development of design and procedural standards for the protection of electric connectors

3. Establishment of controls for wire crimping operations

4. Development of procedures and controls for the cleanliness of spacecraft

5. Development and establishment of a comprehensive and well-integrated testing program

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National Aeronautics and Space Administration  
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