A Survey of Spacecraft Testing as Applied to Long-Duration Space Missions

W. H. Douglas*
NASA Manned Spacecraft Center, Houston, Texas

AND

G. W. Hewett†
General Electric Company, Houston, Texas

The Apollo Applications Program (AAP), the next manned space-research mission to be undertaken and the longest in duration to date, has generated great interest in the proper balance between testing, analysis, and design. A survey and evaluation of existing and planned tests was conducted to satisfy the needs for an orbital mission lasting 10 or more months. The investigation included the Gemini test program, the Apollo certification/qualification program, accelerated-life testing, dynamic mission-equivalent testing, and a failure-flow-analysis technique. Results of this study have been used as guidelines for the AAP command and service module test-program requirements and may be helpful in planning of future test programs in support of space research.

Introduction

A MANNED space vehicle with a useful orbital life of up to 10 months is planned in the Apollo Applications Program (AAP). Future plans include such programs as a space station with a planned orbital life of up to 10 yr and a space base with an indefinite orbital life. The challenge for the aerospace community is to apply the knowledge gained during the Apollo era to longer duration missions in a manner that will result in a more cost-effective test approach.

Design, development, and qualification tests confirm the capability of the design to meet the mission requirements. Life tests confirm the absence of wear problems that would jeopardize the mission. In Project Mercury and the Gemini Program, the time scheduled for such testing was much longer than the actual mission duration. All primary systems were exposed to the anticipated environmental stress and to at least one simulated-mission duty cycle. Critical systems subsequently were exposed to "search for critical weakness" or "overstress" tests. In the Apollo Program, the risks were increased, the national goals were acute, and program schedules were just as demanding. Critical systems were exposed to a flight mission duty cycle with the maximum environmental stresses expected in flight and to a mission simulation equivalent to 1) a flight mission duty cycle and 2) a ground-operational cycle at nominal environmental stresses.

Final manufacturing acceptance tests and associated inspections were necessary to insure that the product met the design and manufacturing requirements and specifications physically and functionally. Environmental exposures employed in acceptance tests were tolerated in the beginning of Project Mercury, were expected as the test results appeared promising in the Gemini Program, and eventually were required for all critical Apollo systems for which conventional inspection and test methods could not insure isolation of potential flight failures associated with the quality of the product.

Presented as Paper 70-378 at the AIAA Test Effectiveness in the 70's Conference, Palo Alto, Calif., April 1–3, 1970; submitted April 27, 1970; revision received July 13, 1970.

* Manager, Manufacturing and Test Office, Apollo Applications Program Office.

† Systems Test Engineer, Apollo Applications Program Operations Engineering, Apollo Systems Department.

Apollo Applications Program (AAP) Concepts

The AAP involves the conduct of longer duration manned orbital missions under two concepts. The first concept is to use the Apollo-developed spacecraft in conjunction with a newly designed orbital workshop. The workshop will consist of crew living space and laboratories to further scientific research in the fields of medicine, biology, astronomy, earth resources, communications, and meteorology. The concept involves providing sufficient expendables to sustain individual long-duration missions in order that flights can continue for predetermined durations or as long as no major flight-hardware problems arise. This concept is possible because of the availability of the Apollo spacecraft for emergency exit of the crew from the workshop during the mission. The second concept is that of revisitation and reuse of the workshop after it has been left in a dormant, unmanned mode in orbit.

The development and testing of spacecraft hardware in support of these concepts are influenced by the desire to exploit the long-duration operational potential of this Apollo and Gemini hardware as rapidly and economically as present technology will permit. Design changes to existing equipment have been held to a minimum.

The ground-test program that will be required to modify the Apollo command and service module (CSM) for a manned space-research mission of longer duration will be simpler because of the wealth of test and mission data available from the Apollo Program. Postflight analysis and testing of all flight failures added significantly to the intrinsic value of this Apollo information.

A Manufacturing and Test Office has been established within the AAP Office at the Manned Spacecraft Center (MSC). This office will establish criteria and will implement plans for AAP activities related to the formulation and implementation of test requirements for system qualification and acceptance, material selection, manufacturing, government-supplied equipment, facilities activation, logistic support, quality-assurance programs, reliability programs, and activities required to insure flight safety. It will provide the support necessary to determine the verification requirements for MSC interfaces with other AAP hardware. The office provides the primary AAP interface with John F. Kennedy Space Center for AAP launch-site activities. Support is obtained from the Engineering and Development Directorate for system design and use of MSC test facilities; from the Flight Crew Operations Directorate for crew participation in spacecraft acceptance testing; and from the MSC Reliability, Quality Assurance, and Safety Offices for the respective disciplines of each.

Several approaches to testing have been investigated. One approach was test condensation by accelerated-life testing of components and by dynamic mission-equivalent testing, a novel technique for time compression of subsystems, systems, and spacecraft tests. Another approach investigated was a study method used to "look back" at a completed program and analyze the effectiveness of each test and inspection using the "failure flow analysis" method. Finally, a detailed investigation of the Apollo certification guidelines and test program was undertaken, and the AAP verification program evolved from it, with increased emphasis on test planning in the preliminary design phase.

Accelerated-Life Testing

Accelerated-life testing (ALT) was investigated by a survey of published literature. An ALT "is a test run (usually on a part) at operating/environmental conditions, which provides a reduction in test costs over normal operating/environmental conditions and which provides an algorithm for extrapolating the reliability observed at the accelerated conditions to the reliability which will be obtained under normal life conditions."

The basic problem of any ALT is that the extrapolation algorithm is valid only if the mode of failure in the ALT is identical with the normal failure modes found in actual use. Acceleration is performed by increasing one or more of the stresses, applied singly or in combination, to force the failure mode. The allowable upper limit of the increased stress is normally that stress level that will change the failure mode. For example, in testing semiconductor devices, the temperature may be increased in one of three temperature profiles to cause failure of the device while under operating conditions. If the temperature is increased above the phase change or the melting temperature of the semiconductor chip, the failure mode has been changed and the test results are invalid. The most difficult part of ALT is the correlation of the failure data with the expected performance under actual use and environment. A considerable effort is required to obtain a statistically valid algorithm. It is difficult within reasonable budgets and time schedules to obtain an extrapolation that will meet statistical-rigor requirements. For example, exposing a solid-propellant motor to 125° F for 3 months is not necessarily equivalent to an exposure for 3 or 5 yr at 80° F. Most attempts at this type of chemical extrapolation make the simplifying assumption that the speed of any chemical reaction or degradation is an exponential function of the absolute temperature. (This is one form of the familiar Arrhenius equation often used to seek environmental exposure equivalence.) When considering "black boxes" or complex systems that have more than one failure mode, performing a valid ALT is difficult at best.

The Department of Mathematics of Princeton University, under a U.S. Army ordnance research and development contract, attempted to design a complex mathematical model for items with many modes of fa lure.[1] The theory proposed was that, even though there might be many failure modes, on'y one would be dominant during certa n periods. If each of these modes could be predicted for each input stress/history/environmental level, a complex mathematical analysis could be developed.

At this time, it is difficult to see any practical application of ALT to complex systems. The use of the ALT has contributed to many improvements in design and more uniform production of simple high-reliability electrical and electronic parts and components; applications at this level of complexity are practical.

Dynamic Mission-Equivalent Testing

In 1966, General Electric Company began an effort to achieve increased test effectiveness and improved life demonstration of unmanned spacecraft. From this activity, the dynamic mission-equivalent (DME) technique evolved. The DME concept compresses test time in a manner somewhat analogous to the ALT. Studies of the test and flight failures compared with the state of the equipment at the time of failure show that more failures occur when either the function or the environment is dynamic. Specifically, the number of failures during power or mode switching, or when a temperature is changing rapidly, exceeds the number of failures that occur when the equipment is in a static state by a ratio of greater than 5 to 1.

Thus, the basic premise of the DME testing is that the efficiency of the simulation portion of the test program can be increased by shortening or eliminating the static or steady-state periods of the mission-life test. Additional severity is obtained by increasing the rate of change of one or more parameters. In the DME profiles, test-time compressions of 9:1 to 24:1, compared with mission time, were obtained. Extending this technique to the spacecraft system level becomes complex. Although individual parameters for single components can be constructed into a profile rather simply, the task of interrelating 100 or more components becomes more difficult. The approach used is to key the DME profile to each mission-critical function (MCF) of the flight. An MCF is any event or action that is necessary during the flight to execute the mission. These functions then are matched to the environmental profile. A practical DME test program was developed for the Mariner MV-67 spacecraft after the flight. It consisted of the following simulation tests: 1) acoustic noise test—ambient, specimen hard mounted, under launch acoustic profile; 2) standard vibration test—ambient, exposed to all three orthogonal axes and torsional vibration around the roll axis; and 3) space simulator test—specimen in thermal vacuum chamber, exposed to induced and natural environments, hard mounted with solar simulation.

The time-compression results of test 3 were 86:1. The complete test report is contained in Ref. 2. This series of tests showed that, for unmanned spacecraft, a reasonable degree of test effectiveness could be achieved using time-compression techniques.

Failure-Flow-Analysis Method

Failure-flow analysis is a method being explored by NASA and the aerospace industry. The analysis assesses the effectiveness of a completed test program and its execution by investigating the defects that escaped each successive screening procedure during component, system, spacecraft, and flight tests.

In the failure-flow method, these "defects" (i.e., conditions of not meeting the characteristics) are considered as the elements by which the screening-procedure effectiveness is measured. Each significant test or flight anomaly (failure) is diagnosed, and it is determined at which level of hardware testing the defect should have been detected if the screening procedure had been perfect. An analysis is conducted of that step in the manufacturing, testing, and flight cycle in which the defect was generated and in which it finally was detected. This activity can be considered as a logical extension of an ideal or well-performed failure-analysis system. The analysis method forces a review at all levels of the screening procedure; the reasons for the failure to detect the defect are analyzed. This method is one of the devices that are available to organize and summarize the test results on any program. Intelligent use of this device is a way of passing the results onto subsequent spacecraft programs. Reliability in succeeding programs can be improved by intelligent application of this information. Four previous spacecraft programs have been studied by the General Electric Company in Philadelphia using this failure-flow analysis.[3]

Apollo Certification Guidelines

The Apollo certification program[4] consisted of qualification tests on components and higher level assemblies and analysis in situations in which complete certification could not be achieved by ground testing. The qualification tests were performed in the following two phases on different sets of equipment.

1) Design proof tests were performed on one set of equipment. These tests were designed to demonstrate the strength characteristics and usually are referred to in connection with the Apollo Program as the design limit tests. These tests consisted of singly applied environments, applied sequentially at 1.5 times the maximum design-limit stress conditions.

2) Mission-simulation tests were performed on another set of equipment. These tests were designed to demonstrate the endurance characteristics and are referred to as mission-life tests and as endurance tests. These tests consisted of a nominal operational cycle and one additional flight mission duty cycle at anticipated extreme environments. (An operational cycle consists of all acceptance tests through transportation, handling, all checkouts, the actual mission, and one additional flight mission.)

Two other types of tests were included, but generally were not required formally: 1) overstress tests were used to determine design margins for certain identified failure modes; and 2) certain components were cycled to failure under appropriate environments.

Complete reporting, investigation, and analysis of failures were required in the Apollo tests. Comprehensive failure-tracking, analytic, and closeout activities were initiated to manage, implement, and retain this information. These data have been of great value in the establishment of the AAP test program.

Beginning with the detailed design requirements, the certification test specifications (CTS) were prepared for each piece of equipment. These CTS's were summarized for each component or system in the certification test requirement document. Every CTS was certified either by testing, by analysis, or by similarity to other test programs of like equipment. The program was accomplished in a step-by-step manner. Every major assembly (such as engines, attitude and guidance systems, ordnance, and parachutes) and most minor assemblies were qualified before the actual mission. For example, engines were tested extensively by firing in vacuum chambers at White Sands Test Facility. Also, fire safety in the crew cabin was tested by scores of flammability tests in boilerplates, mockups, and test vehicles. Extensive launch-environment tests were conducted under vibration and acoustic conditions. A more complete description of the certification program is given in Ref. 5.

Verification Requirements for AAP

The requirements for CSM systems verification in AAP were based upon the history and success of the Apollo spacecraft. For the first time in manned space programs, it became neither practical nor necessary to requalify the modules and related equipment by the conventional method of duplicating the total mission duration in a complete test program. The AAP verification program has been formulated to provide adequate confidence through a cost-effective test program while minimizing full-time mission simulations. To accomplish this program effectively has required the extensive use of systems-engineering analyses of previous test data available from the Apollo Program.

The inherent performance capabilities of the systems as determined by careful examination of system design, by failure-mode and effect analyses, by inflight-maintenance capability, and by demonstrated performance (Apollo test and flight data) were compared with AAP operational requirements and environments. Testing was concentrated on resolving the uncertainties that systems-design analyses and previous test data could not suitably resolve. As an example, special attention was focused on possible "wear out" problems. This wear-out review has encompassed both obvious situations of wear and the more subtle types of wear (e.g., high-level radiation exposure of electrical components). Based on this review, a supplemental testing and assessment program has been established to assure appropriate levels of confidence in achieving primary mission objectives and preserving crew safety for longer duration missions.

One of the definitions employed to establish the performance requirements and subsequent verification of each piece of equipment was the criticality of its function with respect to the objectives of the mission. Each piece of equipment was placed in one of the following criticality categories.

Category 1 Equipment

Failure could adversely affect crew safety.

1) Test to the specified ground- and orbital-operations environmental design-limit extremes to verify that the equipment will survive and perform as intended when exposed to both natural and induced environments.

2) Test for the nominal stresses expected in one ground operational cycle and two simulated-mission duty cycles to demonstrate life capability and to establish a factor of safety.

3) Use analysis to supplement testing when it is neither practical nor feasible to simulate flight environments in ground testing or when it can be shown that specific environments and lifetime duration do not contribute to the failure mechanism.

Category 2 Equipment

Failure could result in not achieving primary mission objective.

1) Test to the specified ground- and orbital-operations environmental design-limit extremes to verify that the equipment will survive and perform as intended when exposed to both natural and induced environments.

2) Use analysis supplemented by tests to confirm that the life of the equipment is adequate and that the equipment is capable of functioning through one ground duty cycle and one mission duty cycle at nominal-mission environmental stresses.

a) Analysis shall be used for equipment or components with no identifiable wear-out features or when it can be shown that specific environments and lifetime duration do not contribute to the failure mechanism.

b) Tests shall be conducted to the nominal stresses found in one ground-operations cycle and one simulated-mission duty cycle for components with identifiable wear-out features or life-limiting features or which constitute a crew hazard.

Category 3 Equipment

Failure could result in not achieving a secondary mission objective.

1) Test to the specified environmental design-limit extremes to verify that the equipment will survive and perform as intended when exposed to both natural and induced environments.

2) Use analysis to confirm the capability of the equipment to function adequately through one ground-duty cycle and one mission-duty cycle.

Verification Methods for AAP

A brief summary of the methods used to define and plan the tests considered necessary to verify the 56-day AAP Earth-orbital mission capability of the modified CSM may provide some suggestions that could be helpful in subsequent space research programs.

It was first necessary to identify, assemble, and collate all the test data accumulated on each subsystem. Valid test data from all portions of the Apollo test program were used. Simultaneously with the test-data gathering, estimated mission-level environmental stresses and mission duty-cycle time lines were published. A comparison of the anticipated environmental stresses to the previously test-demonstrated capability was displayed on matrices in such a way that mission requirements that needed additional verification could be identified readily. Failure histories, postflight analyses, and test results were reviewed with respect to associated corrective actions taken to resolve the deficiencies. Based on this information, evaluations were made to determine the capability of each system to support the longer duration mission requirements. As a result, no test plan for existing systems was approved without an understanding to the component level of all previous failures. New systems were reviewed rigorously to determine the total testing (development through qualification) that would be required to verify these designs for AAP applications.

Extensive tests were not approved until it was determined that adverse conditions could not be reduced, revised, or eliminated. As an example, exposure of the service propulsion system components to lower temperatures than encountered previously during the Apollo Program was corrected by the addition of heating devices. This modification permitted raising the anticipated low-temperature limits to those for which equipment had been qualified previously in Apollo testing. Tests could be optimized because trade studies were conducted early, when design alternatives could be considered before design "freeze." Figure 1 is a graphic representation of the system engineering approach used to determine the appropriate mix of analyses and tests required to verify the AAP-mission performance capability of the CSM and to identify possible areas of redesign.

Figure 2 is a portion of an actual verification comparison matrix (VCM). The environments, previous tests, and verification method are summarized in the VCM along with the failure history of the item and recommended verification testing.

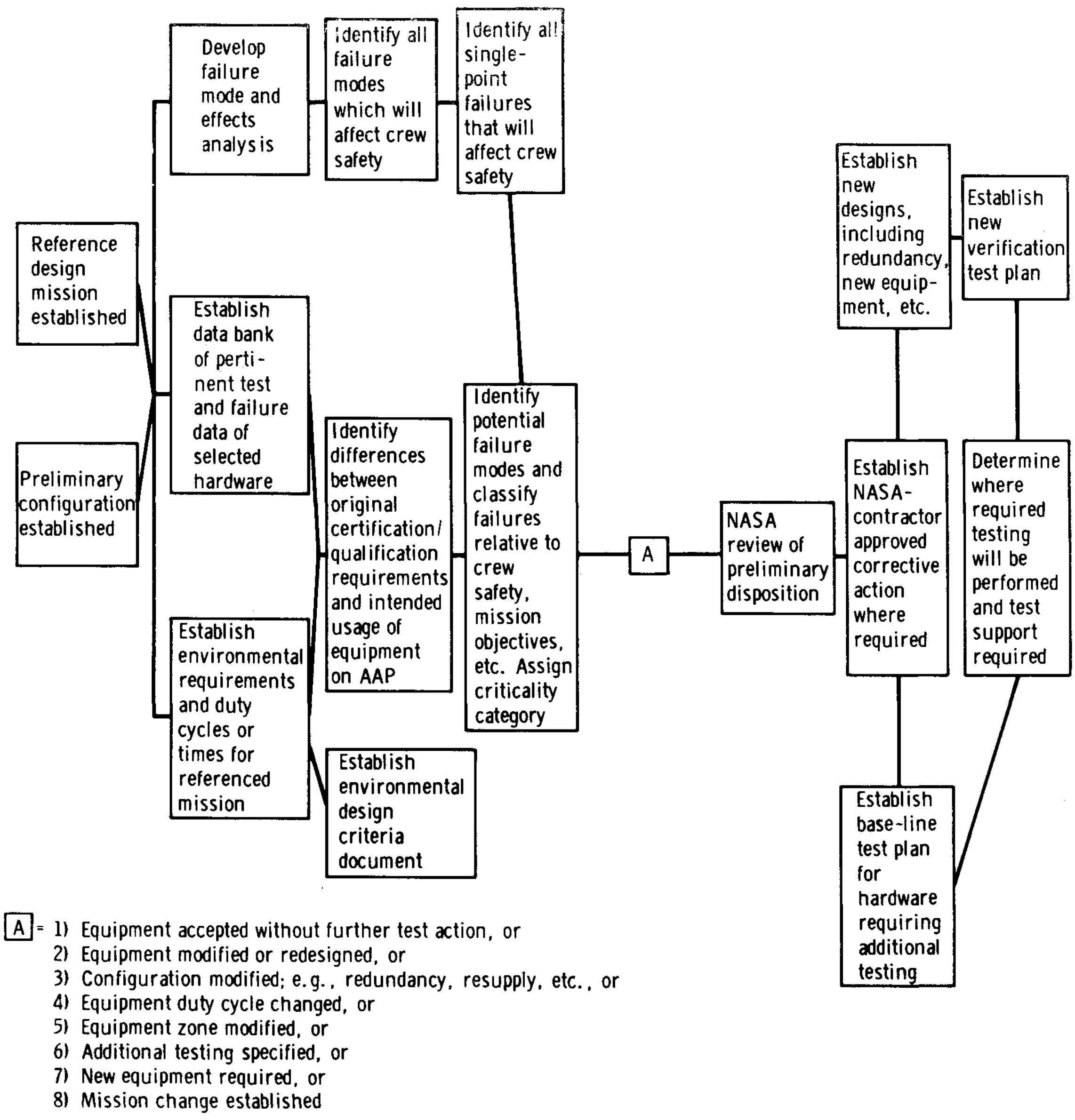

Fig. 1 Verification methodology.

AAP CSM VERIFICATION COMPARISON MATRIX

AAP SUBSYSTEM/END ITEM: ELECTRICAL POWER
EQUIPMENT NUMBER: V37-440030
EQUIPMENT NAME: SPS ELECTRICAL CONTROL BOX
ORIGINAL PROGRAM: APOLLO
SC FLOWN ON: Spacecraft 101 and 103

VERIFICATION CONTROL NO: 22-37A
DATE: 12-12-68
REVISED: 3-28-69

SUMMARY OF SIMILARITY:

AAP component identical to Block II

REFERENCED DOCUMENTS USED IN EVALUATION:

1. SD 68-551, CSM Mission/System Requirements
2. SD 68-552, AAP Environmental/Design Criteria
3. SD 68-553, AAP CSM Verification Program Guidelines
4. Block II System Capability Summary
5. AAP CSM Verification Comparison Matrix 22-31 and 22-38
6. Apollo Nonconformance Report U156-02-003
7. Apollo CRT(s) 25492029, 25492056, 25492073, TAR(s) SID 67-190, SID 67-384, SD 68-138

1. ENVIRONMENT	2. PREVIOUS TEST LIMITS	3. VERIFICATION REQUIREMENTS
TEMPERATURE	Low temperature: -50 F, functional test; D = 24 hours High temperature: +150 F, functional test; D = 24 hours Vacuum temperature cycling: 1×10^{-6} psi, +150 F to -50F: +150 F, D = 10 hours; cycle to -50 F, D = 10 hours; -50 F, D = 10 hours; cycle to +150 F, D = 10 hours; repeated above environment 8 times, D = 335.4 hours: test performed twice for total D = 670.8 hours.	Thermal-vacuum test at 1×10^{-6} Torr: 1. Room ambient to 200 F in 30 minutes 2. Constant at 200 F for 648 hours 3. Linear decrease to zero degrees F in 4 hours 4. Constant at zero degrees F for 40 hours 4.1 Operate at 10 times (cycle switches and relays) during last 4 hours. 5. Linear increase to 200 F in 4 hours. 6. Constant at 200 F for 648 hours. 6.1 Operate at least 10 times (cycle switches and relay) during last 6 hours. Performance test after temp/vac test (Refer to Column 11.)
PRESSURE (INCLUDING VACUUM)	1×10^{-6} psi, functional test; D = 24 hours	
HUMIDITY (INCLUDING SALT ATMOSPHERE)	95 percent RH, at 95 F, 3 micrograms per CM^2 accumulation per day; functional test every 24 hours; D = 72 hours.	Environmental level same as Apollo Block II. No further verification required.

4. FAILURE REPORT SUMMARY	5. ESTIMATED MISSION DUTY CYCLE: PRE-LAUNCH TIME	5. 28 DAYS	5. 56 DAYS	6. PREVIOUS DESIGN LIFE REQUIREMENT (OPERATIONAL CYCLE)	7. AAP LIFE REQUIREMENTS (MISSION CYCLES)	8. DEMONSTRATED LIFE	9. MOST PROBABLE FAILURE MODE/CAUSE	10. FAILURE EFFECT
11 failures reported 1. (1) Failure: During vacuum test overload sensor dropped out in 3.1 sec. It should have dropped out in 45-80 sec. Cause: Test error Corrective Action: None required. Repetition of anomaly nonrecurrent on similar subsequent tests. 2. (10) Failures were manufacturing problems Cause: Procedures, workmanship, material, installation Corrective Action: None. Not true failures. Handled by MRB action.	256 hours		1344 hours	Not defined for control box. Life requirements were established for the various elements contained in the control box.	Prelaunch: 20 minutes Flight: Operative three times during mission for approximately two minutes.	Life tests not conducted at control box level of assembly. Life tests conducted on the elements within the control box. (Refer to VCM 22-31 and VCM 22-38).	Failure mode: open closed, short to ground. Failure causes: Shock, vibration temperature	Category II Failure effect: Lose one of two control circuits

11. NR RECOMMENDED ACTION	12. NASA PRELIMINARY REVIEW RESULTS	13. NR VERIFICATION REVIEW DISPOSITION	14. FINAL DOCUMENTATION SUBMITTAL DATE	15. NASA REVIEW ACTION
Conduct thermal vacuum test. (Parameters as stated in Column 3 under temperature.)				

Fig. 2 Sample portion of VCM.

Recommendations for Future Programs

Several recommendations have been formulated based upon review of past manned-spacecraft test programs, the formulation of the AAP certification program, and studies into some unmanned programs. These recommendations may be useful to those who plan tests for future long-duration missions.

1) A unified test planning and management organization should be considered for future hardware programs. These groups should be responsible for the overall test program, including such phases as feasibility development, certification/

verification, qualification, factory acceptance, integrated systems, and prelaunch and postlaunch tests. The planning goal should be to insure that all hardware is qualified for all environments encountered throughout the duration of the mission with the minimum expenditure of program funds, time, and manpower.

2) To be cost effective, the test-program planning must be initiated early in the design-requirements phase to permit sufficient time to conduct tradeoffs for alternate designs against later requirements for testing. Long life in the equipment must be considered as a design function, supported by inflight maintenance when practical, rather than as the purpose of the test program. An excellent paper presented by R. W. Lanzkron to the AIAA covers this subject.[6]

3) A broad trade-off study should be employed to reach a balance between testing, analysis, and design. This study should make full use of the test data and the results of past programs. Life and failure histories of systems and components proposed for use in the current program should be included in the total tradeoff study.

4) The utilization of interface-simulation devices should be considered in the development of test programs for long-duration orbital missions. This recommendation is made based upon the increased size and complexity of the flight modules as well as upon the absence for ground checkout of actual flight-module interfaces after the modules are in orbit. Associated with this recommendation is the need for a high level of configuration-control management of the flight interfaces and the corresponding simulators to insure proper mating during the mission.

References

[1] Allen, W. R., "Accelerated Life Tests of Items with Many Modes of Failure," TR 44 (U.S. Army Contract DA-034-ORD-2297), Feb. 1962, Princeton Univ., Princeton, N. J.

[2] "Dynamic Mission Equivalent Test Analysis of the Mariner Venus '67 Spacecraft," Doc. 68SD4297, Aug. 1968, General Electric Co., Valley Forge, Pa.

[3] Charp, S., "Test and Evaluation Aspects of the Nimbus II Program Useful to Other Long Life Space Programs," *Proceedings of the Canaveral Council of Technical Societies 5th Space Congress*, Vol. 2, Mar. 1968, pp. 17.1–1–17.1–16.

[4] "Apollo Spacecraft Test Engineering Certification Test Program Guidelines," MSC Doc. MSC-ASPO-RQA-11A, Jan. 1967, NASA; supersedes ASPO-RQA-11, May 1965.

[5] Westerheid, R. J., "The Apollo Spacecraft Qualification Program," *Annals of Assurance Sciences; Proceedings of the AIAA/ASME 8th Reliability and Maintainability Conference*, July 1969, pp. 153–159.

[6] Lanzkron, R. W., "Maintenance of Future Spacecraft in Orbit," AIAA Paper 68-1060, Philadelphia, Pa., 1968.

DECEMBER 1970 J. SPACECRAFT VOL. 7, NO. 12

Ablative Material Response to CO_2 Laser Radiation

WILLIAM D. BREWER*
NASA Langley Research Center, Hampton, Va.

Results are presented from an experimental study to evaluate the performance of various ablative materials subjected to radiative heat fluxes in the range 36–47 Mw/m². The radiative environment was produced by a 9-kw, continuous-wave CO_2 laser. Carbon-phenolic, phenolic-nylon, a filled epoxy material in honeycomb (Apollo material), and graphite were tested in air, nitrogen, and helium at pressures of 1.0, 0.3, and 0.1 atm. A silicone elastomer and a polybenzimidazole (PBI) were tested in air and nitrogen at 0.1 atm. The behavior of the ablative materials was relatively insensitive to changes in test gas, pressure, and heat flux. The PBI and phenolic-nylon withstood the severe environment reasonably well, whereas the elastomer and the epoxy material showed large surface recession, and the carbon-phenolic was subject to considerable spallation, apparently due to thermal stresses within the material. The graphite, tested primarily for reference purposes, showed improvement in performance with increasing heat flux and showed little effect of changes in environmental pressure over the range considered.

Introduction

THE performance of ablative materials subjected to environments such as those encountered in Earth re-entry at orbital and escape velocity has been extensively investigated, and analyses have been developed with which the behavior of materials in such environments can be satisfactorily predicted (see, e.g., Ref. 1). For proposed interplanetary missions, however, the heating will be much more severe. Because of the high entry velocities, atmospheric entry in such missions is characterized by large radiative heat inputs to an entry vehicle, typically in the range 30–50 Mw/m².[2] There is a need for a better understanding of the interaction of the high-radiative heating environments with thermal protection systems.

An experimental program was undertaken to obtain information about the behavior of the ablative materials subjected to large radiative heat fluxes. The only facilities presently available which are capable of producing the required level of radiant heating continuously are gas lasers. For this investigation a CO_2 laser capable of a maximum power output of about 9 kw was used.[3] This facility produces continuous radiation at 10.6 μm wavelength for run times up to several minutes.

The materials tested are representative of those commonly considered as candidate materials for re-entry vehicle thermal protection systems. They were tested in air, nitrogen, and

Presented as Paper 70-864 at the AIAA 5th Thermophysics Conference, Los Angeles, Calif., June 29–July 1, 1970; submitted August 3, 1970; revision received September 18, 1970.

* Aerospace Engineer, Thermal Analysis Section, Structures Research Division.