application of a dynamic sampling concept appears to reduce data requirements significantly, with the obvious benefits relative to system complexity and requirements to advance the state-of-the-art. Finally, the scenario method of organizing the many events involved in the total system helped to develop the concept of the system and suggested the way to sequence the various sensors and other elements of the operational system.

References

[1] Summers, R. A., Smolensky, S. M., and Muir, A. H., "Forecasting the Economic Impact of Future Space Operations," AIAA Paper 67-962, Anaheim, Calif., 1967.

[2] Muir, A. H. and Sattinger, I. J., "Methods of Feasibility and Economic Analysis of Remote Sensing Applications," *Proceedings of the Fifth Symposium on Remote Sensing of Environment*, Univ. of Michigan, Ann Arbor, Mich., April 16–18, 1968.

[3] Muir, A. H. and Summers, R. A., "The Use of Economic Benefit Analysis in Earth Resources Satellite System Planning," AIAA Paper 68-1077, Philadelphia, Pa., 1968.

[4] Summers, R. A., "System Analysis Techniques in Earth Resource Satellite Systems Planning," *Sixth International Symposium on Remote Sensing of Environment*, Univ. of Michigan, Ann Arbor, Mich., Oct. 14, 1969.

[5] Muir, A. H., "A Water Management Model Using Earth Resource Satellites," to be printed in *Proceedings of the Princeton University Conference 97, Aerospace Methods for Revealing and Evaluating Earth's Resources.*

Apollo Spacecraft Certification Test Program

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TESTING played a vital role in the development and maturity of the Apollo spacecraft hardware. The four elements paramount to achieving the present high degree of reliability demonstrated in flight by that hardware were adequate design redundancies, exhaustive testing, control of configuration changes, and a thorough understanding of all discrepancies. These elements played a significant part during preflight ground tests in demonstrating the capability of the Apollo spacecraft hardware to withstand the rigors of lunar flight and the return to Earth.

The role of the certification test program can be clarified by considering its relationship to other aspects of the total Apollo spacecraft test program. The purpose of this test series was to ensure that the hardware design was adequate for the performance of specified functions for the time and under the spectrum of environments that were expected for a like piece of hardware during the combined ground and flight life of the hardware. The hardware was used solely for testing and, as such, was not used for flight.

The certification concept selected for the Apollo Spacecraft Program was an integrated test and analysis program in which, nominally, two production units of hardware were used; one unit for design-limit testing, and the second unit for mission-life testing. This program was designed to not require an excessive amount of hardware and to demonstrate the capability of the hardware to withstand the spectrum of environmental magnitudes and durations with margins of safety greater than those expected in flight. This test program permitted more test articles for testing of certain critical items such as those in the propulsion system and for testing of high-usage hardware such as switches and relays. Although a statistical demonstration of the reliability of the hardware would not be obtained, this approach would provide a significant degree of confidence in the design.

A total of 712 certification tests for the command and service module (CSM) and 505 certification tests for the lunar module (LM) were required to be completed successfully before flight. Complete subsystem and vehicle-level tests were included in the program to demonstrate the design capability of the interfaces between hardware elements (125 tests for the CSM and 175 tests for the LM).

Although certification hardware was required to be tested for the equivalent of one complete ground-operating cycle and two complete flight-duration cycles, most of the certification hardware was exposed to considerably more testing than this ground rule indicates. Additional testing occurred, in part, because significant design changes were incorporated into the certification units, and the complete test or major parts of the test were repeated. In addition, some hardware, such as switches, were used in a hybrid test program that resulted in the accumulation of additional test hours.

The multitude of certification tests to be conducted, the numerous locations across the country at which the testing was done, and the large number of persons involved necessitated a thorough management control system. Although the successful development of spacecraft hardware cannot be reduced to a specific formula, a series of specific requirements was used to manage the certification test program.

Testing was the primary method for the demonstration of hardware capability under environmental stress and was undoubtedly the key to the success of the certification test program. The "show me by test" attitude was dominant in the organization that managed the test program.

The use of production hardware, whereby the test article was produced under the same design manufacturing processes and controls as the flight hardware, ensured that the minor, and sometimes subtle, design or process changes (from which new failure modes can be introduced) were adequately tested.

Units were tested at the highest practical level of assembly to ensure that as many of the interface problems as possible would be uncovered. Although this procedure was often

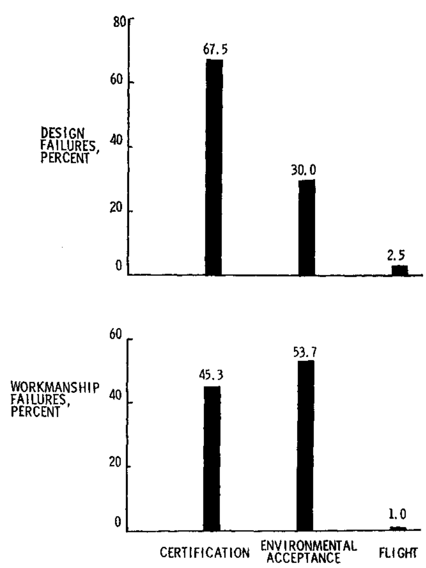

Fig. 1 Distribution of Apollo design and workmanship failures to three test categories.

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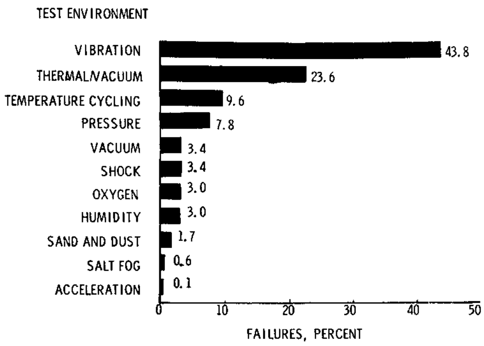

Fig. 2 Representative distribution by environment of design failures that occurred during certification testing.

dictated by the level of assembly at which a particular manufacturer produced hardware, additional higher-level-of-assembly tests were conducted. For example, the display and control panels and the consoles in the spacecraft cabin were tested environmentally as complete built-up assemblies, even though similar individual instruments and control devices on the panels previously had been subjected to separate certification tests.

A minimum of two test articles gave the assurance of an adequate margin of safety for environmental exposures as well as for operating time and operating cycles.

The certification program required that all redundant paths be operationally and functionally tested. This was an extremely important consideration for equipment necessary for crew safety and mission success.

Testing for both natural and induced environments assured that all possible environmental factors were considered and imposed on the hardware. For example, the corrosive contaminants, oxygen, and humidity (CCOH) tests imposed on hardware located in the cabin combined requirements that simulated the manned crew compartment atmosphere.

Where practical, combined environmental exposures were used. The CCOH testing and the combination of thermal cycling and vacuum testing are examples of environments that were combined most frequently.

Acceptance tests were performed on the certification hardware before certification testing was begun. This testing sequence provided assurance that the test hardware was free of manufacturing defects. It also was ensured that the certification test hardware was subjected to the same total envelope of environmental exposure to which the actual flight articles would be subjected.

Although the use of certification by similarity was allowed by the guidelines, the most common application was to eliminate duplication of testing. For hardware common to the LM and the CSM, tests were conducted to the levels at which the environments were the most severe (in the LM or in the CSM). As a result, cost savings were realized with no loss of demonstration capability.

The use of analysis to supplement testing was common; however, the use of analysis in place of testing was permitted only when it was impractical or impossible to perform an adequate test. For example, numerous tests were conducted on the LM landing gear to demonstrate adequate structural design margins. These tests included 16 drop tests of a structural test article and 5 drop tests of a flight-configured LM to simulate the more critical loading conditions on the total vehicle. However, because of the infinite number of combinations of landing velocities, attitudes, and angular rates, all of which result in different sets of landing stability dynamics and load inputs to the structure, it was necessary to perform the primary certification for these two factors by analysis and to obtain point confirmation by testing.

Tests at the higher-level-of-assembly and vehicle-level phases of the certification test program were likewise exhaustive for the demonstration of the interfaces and the interacting effects of the hardware of a given module. The vibroacoustic testing of entire LM and CSM ground-test spacecraft, the land and water impact tests on the command module, the LM drop tests, the thermal vacuum tests of the full-scale LM and CSM vehicles, and the full-scale launch escape system tests conducted at the White Sands Test Facility added thousands of ground-test hours to flight-configured hardware.

A thorough understanding and corrections of all anomalies was another enforced ground rule. The concept of a random failure was unacceptable to management. It was acknowledged that hardware failures were caused by discrete flaws in design, manufacturing, or procedures, and the function of the personnel responsible for the hardware was to ensure that the particular problem did not recur in flight.

Summary and Conclusions

The use of failure mode and effect analyses was helpful in the understanding of the criticality of the hardware being tested (whether failure could involve crew safety, affect mission success, or just be a nuisance in flight). This knowledge also was important to the decision-making process during corrective action procedures after the occurrence of a hardware failure. This analysis technique was not limited to certification testing but was equally useful for the evaluation of the entire ground-test program.

Certification testing at the highest level of assembly practicable did not eliminate the need to qualify and conduct screening and burn-in tests on electrical, electronic, and electromechanical (EEE) piece parts. Controlled EEE piece parts were necessary if the certification test results were to be applicable to identical flight hardware.

Teardown inspection after test completion provided the capability for the determination of incipient failures that were not detected with the test instrumentation.

Because of the inherent lag in the preparation of test reports, on-site review of raw test data by Government and prime contractor personnel was required when successful test completion was a constraint to an imminent flight.

The certification test program, although accomplishing the demonstration of the design capability under environmental exposure, was not 100% effective in uncovering all design-type deficiencies. The environmental acceptance tests that were conducted on certified flight hardware for the primary purpose of detecting manufacturing flaws also resulted in the detection of some design problems, particularly in the designs that were difficult to manufacture.

Certification by similarity required exhaustive review for acceptability. Certification testing, environmental acceptance testing, and actual flight were considered the three major areas in which Apollo hardware is exposed to environments. Although the amount of hardware tested for certification was relatively small (in equivalent spacecraft), 67.5% of all design problems and 45.3% of all workmanship-type failures were found during certification testing (Fig. 1). Environmental acceptance testing (vibration and thermal cycling), which was conducted primarily to ensure that the hardware was free of workmanship flaws, uncovered 30% of all design problems (primarily produceability design problems). However, the combination of certification and environmental acceptance testing and the consequent implementation of corrective actions and controls, thus precluding failure recurrence, kept the number of design problems to a minimum during flight. Figure 2 shows a representative distribution by environment of the design failures that occurred during certification testing.

In summary, the spacecraft certification test program did accomplish its objective of verifying the design suitability of Apollo spacecraft flight hardware and provided additional confidence that the lunar mission could be safely and successfully conducted.