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APOLLO EXPERIENCE REPORT - GUIDANCE AND CONTROL SYSTEMS: COMMAND AND SERVICE MODULE ENTRY MONITOR SUBSYSTEM

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16. Abstract
The conceptual aspects of the command and service module entry monitor subsystem, together with an interpretation of the displays and their associated relationship to entry trajectory control, are presented in this document. The entry monitor subsystem is described, and the problems encountered during the developmental phase and the first five manned Apollo flights are discussed in conjunction with the design improvements implemented.

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GUIDANCE AND CONTROL SYSTEMS:

COMMAND AND SERVICE MODULE ENTRY MONITOR SUBSYSTEM

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SUMMARY

The design and development of the command and service module entry monitor subsystem resulted in a conceptual component that appeared to be capable of performing functionally and of meeting mission requirements. However, the conversion of the component from design to hardware that would perform as designed was a frustrating task. From the beginning of the entry monitor subsystem qualification test program, hardware problems appeared that continued throughout all manned Apollo flights. Although some of these problems were due to poor workmanship, most were caused by various component parts not performing as designed. Even though modifications to the hardware were made throughout the Apollo Program, component part deficiencies were never eliminated completely.

INTRODUCTION

The entry monitor subsystem (EMS) was incorporated into the Apollo command module (CM) to provide a backup means of monitoring guidance and navigation (G&N) controlled change in velocity (delta-V) and of providing thrust termination to the stabilization and control system (SCS) controlled delta-V, as well as to provide a visual means whereby G&N entry trajectories could be monitored and compared with predicted trajectory curves. This report includes a discussion of EMS development problems, as well as EMS problems encountered during the first five manned Apollo flights, and a review of the major modifications performed to resolve those problems.

SYSTEM DESCRIPTION AND DESIGN CONCEPT

Design Concept

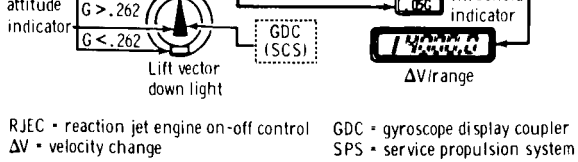The command and service module (CSM) EMS design concept evolved from the single requirement for providing a redundant, manual capability to evaluate and control the entry trajectory (ref. 1) by means of visual entry-corridor-verification displays. The evaluation aspects were primarily concerned with monitoring the path of entry according to a set of prescribed entry curves to determine whether the ensuing

trajectory would produce conditions jeopardizing the safety of the crewmen. The control aspects provided the knowledge required to assume manual control at any time and to complete a safe entry. The concept was further expanded to achieve maximum trajectory design flexibility in the primary guidance, navigation, and control system (PGNCS) (normally automatic) and to achieve mechanization and use simplicity in EMS design.

The design concept factors necessitated the definition of all system limits that could affect crew safety in terms of entry performance constraints. The systems having critical interfaces with the entry trajectory are primarily the thermal protection system (heat shield), the operating time-limited systems, and the flight crew. The limits were defined by entry range (time) and acceleration constraints. These constraints, the vehicle aerodynamic configuration, and the EMS response-time characteristics dictated the trajectory-shaping limit patterns on the flight-monitor scroll. To share sensors and electronics, the EMS display was mechanized to perform powered-flight functions in addition to the required entry functions.

System description and components. - The EMS (fig. 1) provides information to the flight crew for monitoring the PGNCS-controlled entry performance and the PGNCS-controlled delta-V, for providing thrust termination signals through the SCS-controlled delta-V, and for manually controlling entry after a PGNCS failure. The EMS also displays to the flight crew very high frequency (vhf) ranging information between the CM and the lunar module. The system consists of both hardware and software. The software aspects of the EMS refer to the flight-pattern limit-line generation and to developmental techniques and procedures. The EMS hardware includes the components and electronics required to drive the major displays. The hardware consists of the scroll (entry acceleration load factor G and inertial velocity V plotter), a roll attitude indicator (RAI), and a delta-V/range-to-go digital display counter.

Physically, the EMS (fig. 2) consists of two basic assemblies: the entry monitor control assembly (EMCA) and the entry monitor scroll assembly (EMSA). The EMCA contains the electronic components and is composed of integrated circuits; circuit boards; a range integrator; an accelerometer; a delta-V/range-to-go counter logic; a pulse scaler; power supplies, relays, and switches; and all associated wiring. The EMSA or G-V plotter assembly consists of a scroll of Mylar tape or film imprinted with rays called G-onset, G-offset, and range-potential lines. The stepper motors, servomotors, gear trains, and electronic components necessary to drive the scroll are enclosed within the EMSA.

The EMS display is composed of five functional components essential to entry trajectory monitoring and flight control. The five components are the RAI, the entry threshold indicator (0.05G), the corridor verification indicator, the delta-V/range-to-go counter, and the flight monitor or scroll.
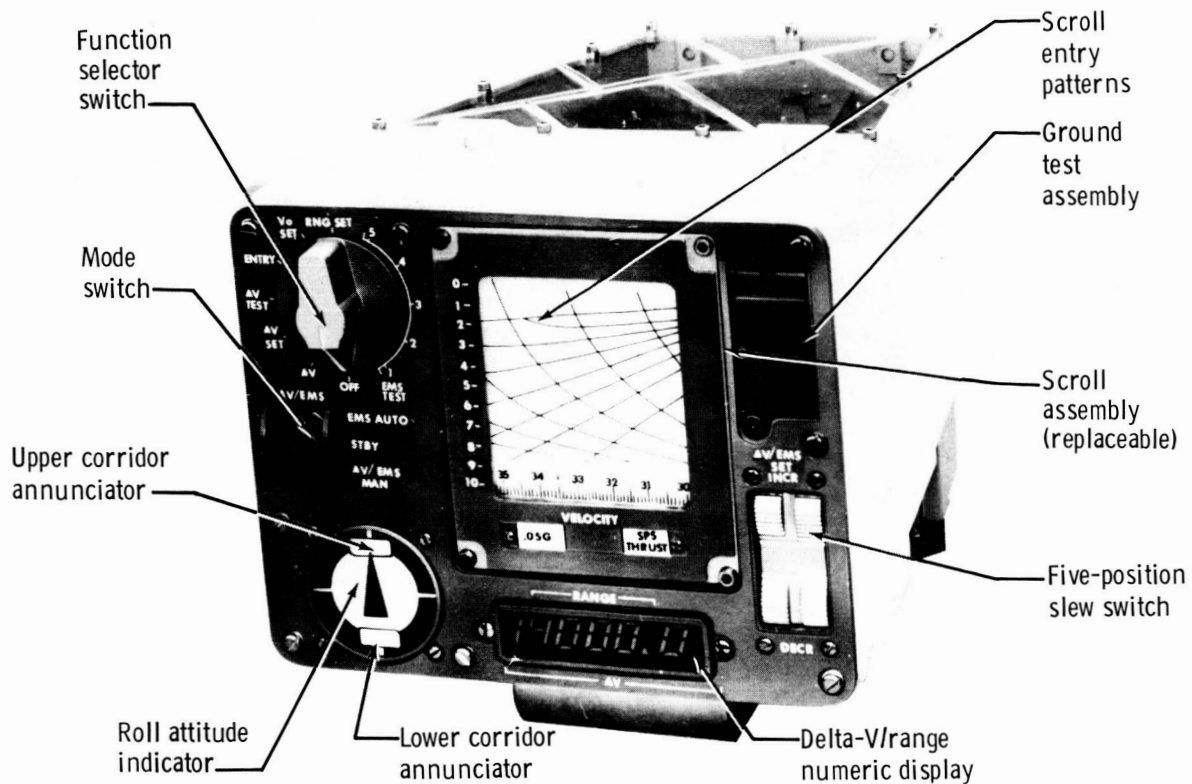

RJEC · reaction jet engine on-off control   GDC · gyroscope display coupler
ΔV · velocity change   SPS · service propulsion system

Figure 1. - Entry monitor subsystem
block diagram.

Figure 2.- Entry monitor subsystem.

The RAI is an instrument used to display the angular position of the lift vector about the relative wind vector of the vehicle. The indicator displays continuous rotation in either direction.

The entry threshold indicator is a lamp that is illuminated when the vehicle encounters a threshold aerodynamic acceleration level, normally 0.05G. This display provides a visual indication that the atmosphere of the Earth has been encountered and indicates the initiation of entry. The threshold lamp is extinguished at any time during entry when the acceleration load factor falls below the prescribed level of 0.02G.

The corridor verification indicator consists of two lamps, one of which is illuminated at a prescribed time (normally 10 seconds) after the entry threshold is reached. The lamp illuminated depends on the measured acceleration level. The two lamps are identified with the required lift orientation during the initial atmospheric penetration and are used to verify and, if necessary, correct the orientation.

The delta-V/range-to-go counter is a digital display that indicates the predicted velocity of the spacecraft. The counter is located directly below the flight monitor.

The flight monitor or scroll is the major component of the system. The scroll provides a rectilinear presentation of G as a function of V. The display is created

with a Mylar tape that has a monitoring pattern printed on the front of 90-millimeter film and a dye-encapsulated emulsion bonded on the back. The tape is contained in the scroll assembly and is driven at a speed horizontally proportional to velocity change. The vertical axis is driven to a position proportional to the acceleration load factor. The scribe removes the emulsion and creates the entry trajectory G-V trace as the tape translates horizontally and the scribe moves vertically. The trajectory trace is compared by the pilot to the permanently displayed monitoring pattern that defines the limiting G-onset and G-offset rates throughout entry.

Hardware requirements. - In implementing the hardware requirements for EMS velocity and range-to-go functions, which are the two most important calculations performed, a computing technique called the digital-operational method was used. This method combines some of the characteristics of both digital and analog methods. The overall computational concepts are those of analog operational systems, in which information flows continuously from one circuit to another as received. Each circuit entity performs a mathematical operation (such as multiplication, integration, and addition) on the input data. The digital characteristics of the EMS result from the fact that the system variables (i.e., velocity and distance) are represented in discrete or pulse form. The discrete nature of these variables allows the use of a hardware mechanization with integrated circuitry and thus reduces size, weight, and power consumption.

Software Concept

Description and concept. - The EMS provides a rectilinear display of the total aerodynamic acceleration load factor as a function of the inertial velocity magnitude during the entry flight phase. The display mechanization provides a trace of actual G and V and families of predetermined G-V profiles that are used by the pilot to assess the character of the entry trajectory on the basis of the criteria used to develop the predetermined G-V profiles. The G-V profiles are not trajectories nor are the profiles intended to represent trajectories, even though it may be possible in some instances to maneuver the vehicle so that the actual G-V conditions correspond to those of a given profile. The profiles actually represent the limiting rate at which the value of G may be increasing or decreasing at a particular velocity and the G condition for which the pilot may maneuver the vehicle and avoid violating the criteria used to develop the slope of the profile. A family of profiles is used to present the limiting slopes because the profiles can be conveniently and meaningfully interpreted by the pilot. Therefore, the required information can be presented with two easily obtained variables, G and V, without resorting to the generation of acceleration rates.

Flight-pattern limit-line generation and developmental criteria. - The procedures are outlined for the three types of flight limits incorporated into the EMS software. The flight limits and the associated procedures for their development may be generated to any criterion that can be defined as a function of velocity and acceleration variables. The procedures presented herein pertain only to criteria that have been specifically defined for the Apollo lunar missions. The EMS scroll patterns for Apollo lunar-return entries are shown in figures 3(a) and 3(b).

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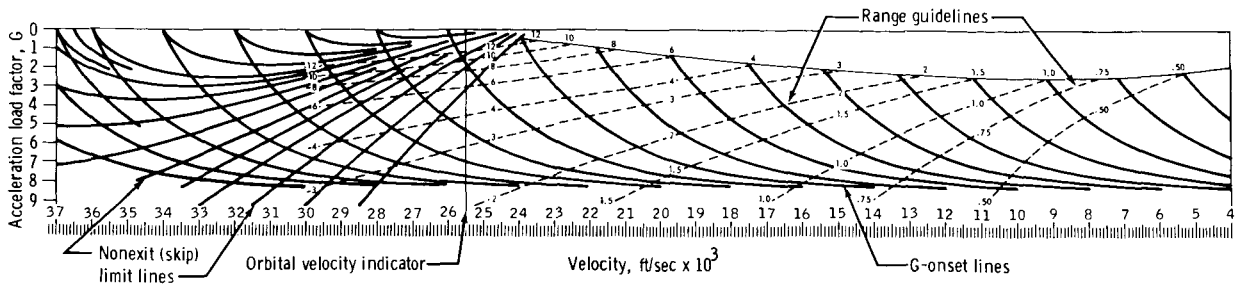
(a) Lunar 3500-nautical-mile range limit pattern.
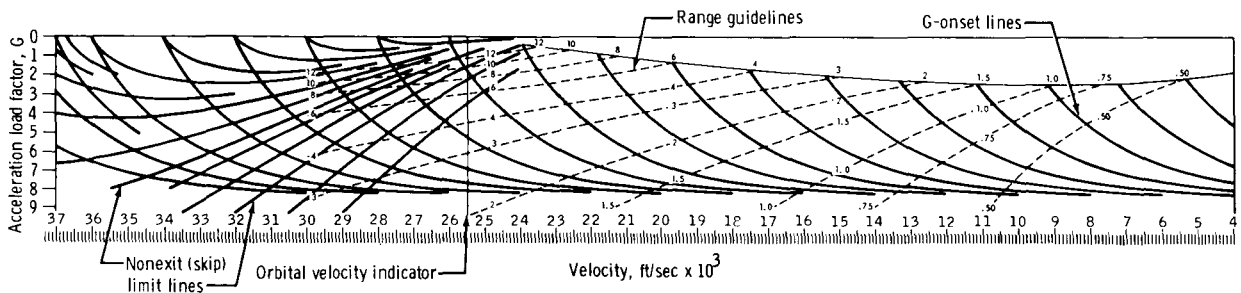
(b) Lunar nonexit range limit pattern.

Figure 3. - Entry monitor subsystem scroll patterns for lunar-return entries.

G-onset limits: The criterion for the G-onset flight limits is to not exceed a specified maximum G-level. Specifically, the dG/dV limits must be determined as a function of G and V at the most adverse vehicle lift attitude (full negative lift, where lift $\phi = 180°$) so that, when this condition is reached, the pilot can delay for 2 seconds and then initiate a maneuver to the best vehicle lift attitude (full positive lift, $\phi = 0°$). The ensuing trajectory then will result in a peak G of 10. It is not necessary to complete the maneuver to the best lift attitude when the pullout at 10G is achieved. Because 10G does not represent a rigid limit (i.e., deviations of 10 to 15 percent above 10G are tolerable), the analysis model considers only off-nominal (not acceptable) deviations in the most sensitive parameters. The parameters are the vehicle lift-to-drag ratio, initial attitude, and maneuver response. All other parameters are designated as acceptable and are a zero-inclination conic (latitude = $0°$, azimuth = $90°$) and the 1962 U.S. Standard Atmosphere. In general, the procedure used to arrive at the limiting flight conditions is to work backward from the known terminal criteria (in this case, 10G) to determine the acceptable initial conditions that are the flight limits.

Nonexit G-offset limits: The criterion for the nonexit G-offset limits is to maintain trajectory conditions that do not result in exiting from the atmosphere, as defined by a selected minimum G-level (G = 0.20), or do not exceed a specified maximum range. The requirements for meeting this criterion are similar to those needed for the G-onset limits in that the limiting dG/dV ratio as a function of G and V must be

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determined. In this case, the most adverse vehicle lift attitude is full positive lift ($\phi = 0°$), and the maneuver is made to the best lift attitude ($\phi = 180°$; full negative lift) incorporating the same pilot-response and vehicle-response requirements. However, for the nonexit G-offset limit, the criteria are more critical, and the analysis model must be constructed so that a worst-case model results.

The procedure for obtaining the flight limits for the G-offset limits is to work backward from the defined terminal conditions to determine acceptable initial conditions. The specified minimum G-level is used to define a terminal condition in the same manner as the maximum G-limit was used to define an initial condition. However, the criteria include a range limit, and this limit does not provide a defined terminal condition. To include the range criteria, a limiting G-V profile that is compatible with the limit criteria and with other flight safety criteria is generated.

Maximum range G-offset limits: The criterion for the maximum range G-offset limits is to maintain trajectory conditions that do not exceed a specified maximum entry range. Unlike the nonexit limits, this criterion will allow an atmospheric exit following initial entry. The flight limits must be determined as a function of G and V such that ranges up to the specified maximum can be obtained consistently and such that no ranges in excess of this value can be achieved. This set of flight limits incorporates the limiting G-V profile as defined by steps 1 to 4 of the nonexit pattern and, in fact, may be the same profile as long as the range limit, the analysis model, and the flight mode are the same as those of the nonexit pattern. In addition, all flight limits generated from the limiting profile are determined in exactly the same manner as those generated from the nonexit limits. This generation includes flight limits that occur at G-levels less than those of the limiting profile.

The only difference between the methods used to obtain the G-offset limits and those used to obtain the nonexit limits occurs in defining the acceptable terminal conditions at $G = 0.20$ for velocities less than the velocity at which the limiting profile becomes tangent to $G = 0.20$. For the nonexit limits, $G = 0.20$ was the lowest allowable load; consequently, the terminal conditions could be obtained directly. For the maximum range G-offset limits, the range must be constrained to a maximum magnitude; consequently, the allowable conditions at $G = 0.20$ must be compatible with this range.

To determine the allowable conditions, the manner in which the trajectory is to be shaped throughout the entry flight must be specified. The exact trajectory shaping, or flight mode selected, is part of the design model. The flight mode selected is based on a constant G-level during the supercircular flight region to a velocity at which full positive lift ($G = 0.20$) is implemented and maintained to exit. Following exit, a zero-lift attitude ($\phi = 90°$) is maintained to an altitude of 25 000 feet.

The trajectory data to define acceptable terminal conditions are separated into four groups as follows.

1. The limiting trajectory profile

2. The maximum trajectory

3. Full positive lift, constant-G trajectories

4. Limiting profile, constant-G trajectories

The maximum trajectory defines (1) the minimum exit velocity from which the range limit can be achieved and (2) the corresponding maximum G-level that can be encountered and the range limit that can still be achieved. The maximum trajectory sets the lower velocity limit for which terminal conditions must be defined. The lower velocity and the velocity at which the limiting trajectory becomes tangent to G = 0.20 set the two extremes in exit conditions.

Verification and simulation of the flight limit lines and range guidelines. - Procedural and simulation examinations designed to verify and evaluate the adequacy of the EMS flight limit lines and the range guidelines have been performed. The purpose of the procedural examination was to verify the procedures and data that related to the derivation of the EMS flight limit lines and range guidelines for the two types of lunar scroll patterns (3500-nautical-mile range limit pattern and nonexit range limit pattern). All derivation procedures conformed to all other existing procedures. Data were checked to ensure consistency throughout the development of each set of lines. One error was found in the development of the 75-nautical-mile range guideline. The error caused this guideline to represent a range that was incorrect by 2 to 4 nautical miles for G-levels between 2.5 and 3.0 and between 7.0 and 8.0. However, in an actual entry, the error developed at the 75-nautical-mile range guideline would be eliminated as the G-V trace approached the 50-nautical-mile range guideline; thus, the error actually would not represent a serious compromise with the EMS backup ranging capability. No other errors or inconsistencies were found. The flight limit lines and the range guidelines, with the one exception noted, were correctly developed and were valid for all applicable flight conditions for Apollo entries.

Two independent manned simulations were performed to verify and evaluate the flight limit lines and the range guidelines on the two lunar scroll patterns. The purpose of the first simulation was to evaluate the G-level and the range attained on the scroll patterns of the design models after a violation of the scroll pattern had occurred. The primary intent was to evaluate the human aspects, as opposed to exact numerical results that could be handled digitally.

The results of the first simulation indicated that the G-onset and G-offset lines on both scroll patterns are valid for all cases in which the pilot delay time in recognizing a violation is less than the design value of 2 seconds. Simulation results also indicated that the EMS monitoring task of judging the slopes of two lines (one of which is dynamic) within 2 seconds of the actual tangency is a feasible pilot task but requires close attention and a critical pilot attitude.

The second simulation was performed to evaluate the range guidelines and various backup ranging techniques that could be used in the event of a PGNCS malfunction. Results of the study indicated that use of the EMS range guidelines provides the best method for backup ranging.

The results of the EMS flight limit line and range guideline verification and simulation studies are summarized as follows.

1. The EMS G-onset limit lines, the EMS 3500-nautical-mile range limit lines, and the EMS skip limit lines were correctly developed. Therefore, the scroll patterns investigated can be used to monitor PGNCS performance during all Apollo entries.

2. The EMS range guidelines, with one exception, were correctly developed. The one exception can be accounted for during manual ranging so that, in the event of a PGNCS malfunction during entry, the range guidelines can be used in backup ranging.

3. The EMS criterion for manual takeover is based on the pilot's evaluation of a tangency condition between the G-V trace and the flight limit lines.

DEVELOPMENT AND QUALIFICATION

Prototype Hardware Development

Complete system development and compatibility testing was accomplished on a prototype EMS breadboard assembled on two chassis with an independently mounted scroll assembly. The testing enabled evaluation of component compatibility and closed-loop system performance in terms of magnitude of unwanted signals and in terms of EMS susceptibility to externally generated signals and to internally radiated signals in the immediate environment for a wide range of operating conditions. The principal benefits of the testing were confirmation of filter design optimization and demonstration of acceptable electrical noise and transient suppression.

Qualification History

Qualification test program. - Much difficulty occurred with the EMS during the first attempt at qualification testing. The original qualification test was aborted because of repeated failures encountered during the vibration and temperature tests. The test unit was modified and the tests repeated. The modifications were directed at what were considered the primary causes of failures: intermittences in the electronic components package and scroll assembly electroluminescent short circuits to ground.

After the minor modification period, the qualification tests were attempted; however, EMS failures continued. The failures recorded during the performance of the test fell mainly into four categories.

1. Problems with the scroll assembly

2. Susceptibility to humidity

3. Intermittent connections on the terminal boards because of vibration

4. Repeated problems with the electroluminescent lighting panels

The most severe problems were associated with the scroll assembly and the RAI electroluminescent lighting. Much redesign was required for solution of these problems. For example, elimination of the electroluminescent lights on the scroll assembly and on the RAI required the addition of incandescent lamps.

Delta-qualification design and proof test program. - One production EMS (qualification test unit 2) was subjected to the full series of qualification tests to certify the flightworthiness of EMS design improvement changes that had been incorporated after the original EMS qualification tests. Only two of the changes were significant: (1) the use of incandescent lighting for the scroll and for the RAI and (2) the improved (more flexible) initialization of the range-to-go integrator. Numerous failures were encountered during the delta-qualification design and proof tests; however, the only environment that adversely affected the EMS was the salt-fog and combined oxygen-humidity portions of tests with corrosive contaminants, oxygen, and humidity (CCOH).

Problems of minor significance, such as electrical overstressing of some EMS components during the insulation resistance tests performed after the environment tests, were resolved by modifying test equipment and procedures. Such conditions as failure to scribe and a V-axis failure during thermal vacuum testing were corrected by verifying the correct stylus spring force and by checking the film spool interference between the roll of film and the housing.

Several problem areas were encountered that were the direct result of CCOH. The qualification tests revealed moisture problems around the hermetically sealed delta-V/range-to-go indicator (causing dimming and flickering of the electroluminescent segments) and around the potting material enclosing the wire header to the hermetically sealed function switch. These situations were corrected by a design change in which the delta-V/range-to-go display assembly was epoxy-bonded to the front panel and by improvements in manufacturing process controls and in inspection to ensure compatibility with humidity. No other significant problems were discovered in tests on the remainder of the EMS components.

Flammability tests. - Flammability tests were performed on a mockup unit containing EMS components made of material generically similar to that used in the actual spacecraft configuration. The purpose of the tests was to determine the structural flammability characteristics of the EMS in 6.2- and 16.5-psia oxygen environments. The tests were to determine whether, in the event of an internal fire, the EMS component units would rupture and thus permit the scattering of flaming contents and would emit flames through vents and thereby propagate the flames to nearby nonmetallic materials.

The flammability tests demonstrated that the EMS would not propagate flames as a result of an internal fire. However, minor material changes were required to meet new Apollo flight material selection criteria. A potting compound on one of the EMS cables was covered with an aluminum shield. A silicone heat-shrink sleeve was removed from a cable. The nylon sleeving on a dust cover was removed. Polyamide spot-ties were replaced with Beta cloth spot-ties. The function selector switch knob made of tenite was replaced with a knob made of aluminum.

Centrifuge tests. - Throughout the original qualification test program and early production phases, one design deficiency was found that required major redesign: The scroll assembly and the RAI electroluminescent lights did not provide sufficient illumination to observe the scroll. In addition, the electroluminescent tabs around the scroll and the RAI were susceptible to moisture, and this susceptibility caused numerous electroluminescent failures.

To implement a new design for the scroll and RAI lighting, a centrifuge test was performed at the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)) to establish the exact lighting requirements. The EMS used was a modified engineering prototype with incandescent lights for scroll and RAI illumination. The scroll patterns used with the EMS were approved for Apollo mission orbital and lunar profiles. The subjects included three engineers from MSC, two astronauts, and three test pilots employed by the contractor. Each test subject observed the EMS scroll and functions throughout the G-profile.

The test results were determined from the comments of the subjects during and after the test runs and from the subjects' abilities to detect trajectory violations during the runs. The maximum G-level reached in these tests was 9.5G.

In all cases, the subjects found that immediately after shifting their eyes from the entry trace to another part of the instrument panel, it was difficult to visually reacquire the trace. Each subject recommended use of a colored trace. The corridor verification indicator was sufficiently bright that no problem existed under any of the acceleration conditions. The 0.05G light was found to be too bright when viewed without the filter. All subjects recommended that a filter be used. The subjects recommended that the numbers on the range-potential lines be placed in a vertical column instead of in a staggered arrangement on the scroll pattern. The G-scale on the left side of the display was also found to be too wide; it was obstructing too much of the useful trace.

The principal benefits of the centrifuge testing were the confirmation of a day-glow orange background to improve identification of the trace, a narrower G-scale, an optical filter design for the 0.05G and service propulsion system (SPS) thrust lights, and the vertical placement of the range-potential guideline numbers. In general, the changes made as a result of the centrifuge test program provided an improved flight-worthy scroll assembly.

Delta-vibration qualification tests. - The EMS was subjected to a total of 10 minutes of random vibration at 0.067 g^2/Hz with no anomalies occurring during or after the delta-vibration test. System performance during prefunctional and postfunctional testing was normal except for an identical failure occurring in both functional tests. The stylus tip penetrated the Mylar film to the extent that the G- and V-axis driver became inoperative. Analysis indicated that the stylus penetration resulted from excessive retracing of the scribe line, with other factors contributing to the penetration. Because there were no indications of penetration during the vibration cycle, the anomaly was not considered to be environmentally induced. The completion of the delta-vibration test provided additional confidence that the acceptance vibration test level of 0.04 g^2/Hz does not degrade the flight hardware.

Design and proof tests for vhf ranging. - Design and proof tests were also performed to certify the flightworthiness of the EMS unit modified to incorporate vhf ranging within the EMCA, and of the improved header seal within the EMSA. The modified elements successfully completed all tests. Some failures were encountered in areas not associated with the modifications. However, no problem was attributed to the environments imposed.

A hardware failure was detected before the random vibration; the G-axis servomotor (stylus drive) hesitated approximately 30 to 60 seconds before responding and driving from the 9G level to 0.22G. Subsequent analysis of the failure established that it was caused by a fractured solder joint that had apparently been damaged during the modification of the EMS qualification test unit.

During the combined high-temperature and vacuum environment, the EMSA scroll drive failed. Disassembly of the EMSA revealed that the internal front plate had not been relief-milled (as specified) to provide space for the orange tape that was added to produce a "colored" G-V trace. The clearance between the internal front plate and the enclosure was insufficient, and the buildup of scribe-coat residue caused frictional forces beyond the capabilities of the V-axis stepper motor.

Several failures caused by an error in the qualification test procedure and by noise pickup of a wire within test-equipment cabling were encountered. Test procedure changes were implemented to prevent the problem from recurring. After the noise-sensitive wire was rerouted within the test-equipment cable, proper operation of the EMS was verified. No failures were encountered either in the new header seal or in any of the circuits that were added or modified by incorporation of the vhf-ranging mode.

Microencapsulated-dye-coated scroll engineering development tests. - Engineering development tests were performed to evaluate a microencapsulated-dye-coated EMS scroll. One of the most significant failures encountered with the previous scroll assembly occurred during the Apollo 9 and Apollo 10 flights. The G-stylus failed to penetrate the emulsion backing of the scroll pattern and thus failed to produce a visible trace.

Several failures were encountered with the originally used scribe coat throughout the qualification test phases. Some of the failures were attributed to the scribe-coat formula, to the scribe-coat application technique, to defective stylus springs, and to improper stylus tips. For each failure, some form of corrective action was implemented such as using sharper tips, increasing the spring force, improving the formula with the elimination of urea from the scribe coat, and using different purging procedures. Although these minor corrections seemed to indicate a tentative solution to the scribe-coat problems, the contractor was directed to investigate the scribe coat thoroughly. Areas investigated included, but were not necessarily limited to, the following.

1. Basic process changes of the scribe coat

2. Length of bake and number of bake cycles

3. Exposure time to air during handling and installation

4. Effect and control of ambient humidity in the handling areas

5. Measure or indication of scribe-coat hardness

6. Time limits on exposure to vacuum, heat, and humidity

The scribe-coat investigation was terminated prematurely by the contractor because he thought that no greater improvement could be achieved with the existing scribe coat.

Concurrently with the scribe-coat investigation, a search for an alternate scribing concept was begun. A survey of the industry was performed, and a statement of work was awarded to develop a more functional and reliable type of recording assembly. The study was designed to integrate and evaluate available technology that was related to the scroll recorder tape requirements and that could be introduced into the existing flight scroll assembly with minimum hardware modifications. The studies were performed sequentially: dye selection and evaluation, encapsulation of selected dyes, formulation of emulsion coatings, development of coating techniques, and environmental testing of coated Mylar tapes.

In the beginning of the EMS scroll program, contractor conferences provided information and dye materials that enabled proceeding to the encapsulation study immediately. Encapsulation studies were performed on each of six dyes. Because some of the dyes were used in contractor-furnished paper and had been extensively investigated, encapsulation presented no problems.

The capsule coatings are self-contained capsule systems; that is, the encapsulated dye is first applied to the Mylar substrate and then overcoated with a phenolic resin dispersion. On pressure activation of the dry coating, the encapsulated dye is released and immediately reacts with the acidic phenolic resin to develop a colored print.

A production EMS scroll assembly was powered by bench test equipment that permitted evaluation under laboratory conditions, lighted and unlighted, of various scroll traces using a coated scroll. The existing scribing method was compared to the contractor method. The contractor method did provide a usable trace under the conditions demonstrated; however, the trace was pale red and did not contrast well. A darker color of dye was used to improve the contrast. The new trace was also slightly narrower: 0.020 to 0.025 inch compared to 0.030 inch. A slightly wider scribe was developed as a result of this test.

On June 5, 1969, two contractor pilots and two astronauts participated in a centrifuge evaluation of a scroll incorporating the previously discussed changes. Each pilot made two runs in the centrifuge, the first at 5.8 G and the second at 9.4 G; the latter was a maximum G-profile. The dark-red dye used in the new scroll improved the trace/background contrast, and a reshaped stylus tip that was used produced a

slightly wider trace. Based on the successful tests, it was concluded that the contractor-developed method provided a visible and readable trace under normal-G and high-G entry conditions.

After the centrifuge tests, engineering development tests were performed by the contractor during June and July of 1969. Both the EMSA and individual segments of the microencapsulated-dye-coated scrolls were subjected to environments that might adversely affect them, and the EMSA and scroll segments performed successfully in all the environments to which they were exposed. A few anomalies occurred during the testing; however, the anomalies either could not be attributed to the environments imposed or were encountered only in off-limit conditions. The successful completion of the design verification test program demonstrated that the coated scrolls were compatible with the selected Apollo environments. No failures or anomalies were encountered that would prevent the coated scrolls from producing an acceptable entry trace.

FLIGHT HISTORY

In each of the first five manned Apollo flights, several malfunctions of the EMS occurred. Many of the anomalies recorded were hardware failures, whereas others were classified as operational procedures or equipment-operation peculiarities. The significant fact about these failures is that none of them occurred during the qualification tests. A combination of marginal design conditions and poor workmanship accounted for the majority of the failures.

A critical design review of the EMS was conducted after the malfunctions had been encountered. Several major design improvements were implemented to improve EMS operation and to increase EMS reliability. In addition to making hardware improvements, extra care during the modification cycle was requested of quality control and manufacturing personnel. Despite the extra precaution taken to ensure trouble-free hardware, additional minor problems were encountered with the redelivered units. Table I is a summary of the overall problems encountered during the Apollo 7 to 11 missions.

TABLE I. - ENTRY MONITOR SUBSYSTEM MISSION PROBLEMS

Mission	Problem
Apollo 7 (CSM 101)	An improper scribe drive unit (EMCA) was replaced.
	The replacement unit had ground and flight problems.
	1. Range-to-go function
	2. Delta-V/range-to-go counter jumps of the "90 000" digit
Apollo 8 (CSM 103)	The delta-V/range-to-go counter jumped 100.4 ft/sec at Saturn IVB separation.
	The midcourse correction (MCC) 5 velocity was not measured properly by the EMS.
	The delta-V/range-to-go counter jumped during post-MCC-5 troubleshooting.
	Scroll scribe perturbations occurred during entry.
Apollo 9 (CSM 104)	No G-V trace scribing was obtained during entry.
Apollo 10 (CSM 106)	Intermittent scribing was obtained during preentry tests.
Apollo 11 (CSM 107)	Electroluminescent segment failure occurred in the delta-V/range-to-go numeric display counter.

Apollo 7 Mission

Performance. - Both the delta-V and the range-to-go counter circuits in the EMS malfunctioned before lift-off of the Apollo 7 CSM. The first failure involved the range counter during a self-test. In this test, the counter is preset, then counts down in response to a known stimulus for a specified time, and finally reaches a value near 0 miles. The system repeatedly failed the self-test, both before flight and in flight.

A delta-V/range-to-go counter malfunction, totally independent of the range counter failure, was noted during the prelaunch setup of the delta-V/range-to-go counter just before lift-off. A "9" appeared in the most significant digit of the counter when a crewman switched the function selector to the "delta-V set" position; however, the operation was normal during a repeat of the procedure. The malfunction

occurred several times during flight and, in all but one instance, coincided with a switching operation.

Postflight testing and analysis indicated that the most probable cause of the "90 000" digit-jump anomaly was a high-resistance crimp joint on wire 18 of the delta-V/range-to-go display. The high resistance caused a voltage drop of approximately 0.7 volt direct current (dc) in the 4-volt dc input line. The voltage-drop level is near the operational threshold of the circuit.

During postflight testing, the range integrator malfunction was verified and repeated. However, during temperature testing in the investigation of the "90 000" digit-jump anomaly, the range integrator began functioning properly, and the malfunction could not be induced again.

The most probable cause of the range integrator anomaly was the short circuiting of welded leads in the range integrator submodule. The short circuiting caused the velocity register to be latched at 37 000 ft/sec and, thereby, induced a 2.2-nautical-mile error in the entry monitor self-test and a gross error in ranging during entry.

Postmission modification. - The postmission corrective action implemented required soldering of all wire crimp joints in the delta-V/range-to-go counter and performing of low-voltage margin tests of the counter-integrated circuit module. A thermal cycling screening test was also instituted as part of acceptance testing.

Entry postflight results. - Postflight assessment disclosed that the anomalies encountered prevented accomplishment of some of the detailed flight test objectives. The ranging accuracy could not be assessed because the range-to-go display did not operate correctly as had been anticipated. The G-V was displayed by the entry monitor properly. The EMS G-V flight scroll trace correlated well with the PGNCS trace flown during the entry trajectory. The velocity error of 286 ft/sec at 11 500 ft/sec after 0.05G was within both the hardware and the total delta-V error budget of 300 ft/sec. The total velocity error of 52 ft/sec at 4000 ft/sec was again less than the 97-ft/sec budgeted delta-V error. Despite the range integrator anomalies, the EMS demonstrated proper scroll operation and delta-V control during powered flight and entry.

Apollo 8 Mission

Performance. - The following performance anomalies in CSM 103 were observed by the Apollo 8 flight crew during the mission.

1. A -100.4-ft/sec jump occurred in the delta-V/range-to-go counter display at the time of CSM separation from the Saturn IVB. (Postflight crew debriefing confirmed that the jump actually was -100.4 ft/sec.)

2. A -6.2-ft/sec error occurred in the delta-V measured during midcourse correction (MCC) 5. The actual MCC-5 delta-V was -5.0 ft/sec, and the EMCA error should have been 0.7 ft/sec maximum, as stated in the specification requirements.

3. A higher than normal EMCA acceleration drift rate occurred immediately following completion of MCC-5. A counter display change from -6.2 to -6.9 ft/sec was observed by the flight crew immediately following MCC-5, just before the EMS was turned off.

4. Erroneous fast counts as high as -20 ft/sec occurred when the EMS mode switch was cycled from "standby" to "auto." The counts occurred during post-MCC-5 troubleshooting performed by the flight crew. The magnitude of the count increased when attempts were made to go through the switch-closure points slowly during actuation.

5. Two negative acceleration pulses occurred on the EMSA scroll pattern during entry.

Postflight testing.- After flight, the EMSA passed a visual inspection and a complete functional test, and no anomalies were noted. During functional testing of the EMS, including the EMCA, erratic accelerometer operation was noted. The accelerometer null output was unstable for a period after the EMCA acceleration input axis was placed on the horizontal.

Transient signals on the accelerometer analog dc output were also observed. The transients occurred only during the time following a repositioning of the accelerometer input axis between zero-g and approximately one-g conditions. Occurrence of the transients depended on allowing sufficient stabilization time before repositioning the accelerometer input axis.

The linear acceleration measurement unit (LAMU) was physically removed from the EMCA, and the same transient behavior was produced by physically moving only the LAMU. During these tests, the LAMU output signals were disconnected from the EMCA electronic components and monitored to ensure that the anomalies were the result of an LAMU malfunction rather than a problem within the EMCA electronic components. This EMCA disconnection isolated the problem to the LAMU, and the LAMU was subsequently returned to the vendor for further analysis and test. During vendor testing, the LAMU continued to exhibit extraneous outputs, which were thought to be caused by an air bubble in the accelerometer sensor. Before the LAMU was opened, the validity of the hermetic seal was verified by leak test. When the unit was opened, oil was found around the sensor/electronic unit dust cover. The leak path was traced to the O-ring seals under the two oil fill/seal screws on the sensor cover. The sensor was drained of oil, refilled, resealed with new O-rings and seals, and retested. The mass of oil removed indicated that approximately 1 cubic centimeter of oil had leaked from the unit. Retest verified proper accelerometer operation and confirmed the hypothesis that the air bubble caused the extraneous acceleration outputs.

Postflight ground testing correlated the spurious accelerometer output to the delta-V/range-to-go counter in the delta-V mode and to the G-V trace in the entry mode. The spikes on the G-V trace were not of the same magnitude as the spikes encountered during the mission; however, ground testing indicated that the air bubble had varying magnitudes of effect, primarily as a function of the history of rotational motion and acceleration inputs.

Extensive diagnostic testing was performed in an effort to duplicate and isolate the spurious -100.4-ft/sec velocity that appeared in the delta-V/range-to-go display during Saturn IVB separation, as well as the spurious counting that occurred during slow cycling of the mode switch. With a positive acceleration, the delta-V/range-to-go display counts down if an acceleration reversal (negative acceleration) occurs as the display reaches 0.0 ft/sec and if the display jumps to -99.2 ft/sec. This phenomenon was repeated by using both the sine torque and the tilt table for acceleration reversals. This test was also run on prototype unit 1, and display jumps to -9.2 ft/sec as well as to -99.2 ft/sec were encountered. The display jump was caused by a logic race that is inherent to the design of the delta-V/range-to-go display.

The postflight testing and analysis resulted in the identification of two specific problems within the Apollo 8 EMS. The first, air bubbles in the accelerometer, is considered an isolated case; the second, the logic race, is inherent to the EMS design but may or may not exist in all units, depending on component characteristics of individual units. The manner in which these problems were reflected in the EMS performance during the mission is specified as follows for each flight anomaly.

1. A -100.4-ft/sec jump in the delta-V/range-to-go counter display occurred at the time of CSM separation from the Saturn IVB. This anomaly was never exactly duplicated; however, the logic race, which was at least the major contributor to the error, was repeated many times during testing. During these tests, the display consistently jumped to -99.2 ft/sec; however, the tests were performed with the Apollo 7 (CSM 101) accelerometer rather than with the Apollo 8 (CSM 103) accelerometer. In addition, circuit analysis indicated that the logic race would just as likely cause a display jump to -100.2 ft/sec (the difference of 0.2 ft/sec being likely to have mission segments). This jump, coupled with the normal accelerations during Saturn IVB separation, could create the -100.4-ft/sec display. An alternative and equally probable cause of this anomaly would be the combination of the two system problems. Whereas the logic race caused the display to jump from 0.0 to -99.2 ft/sec, the difference of 1.2 ft/sec was the result of both natural accelerations associated with the separation and spurious counts caused by the air bubbles.

2. A -6.2-ft/sec error occurred in the delta-V measured during MCC-5. This anomaly can be directly attributed to the accelerometer air bubble.

3. A higher than normal EMS acceleration drift rate occurred immediately following MCC-5.

4. Erroneous fast counts as high as -20 ft/sec were observed when the mode switch was cycled from "standby" to "auto." The counts occurred during post-MCC-5 troubleshooting performed by the flight crew.

5. Two negative acceleration (+G) pulses on the EMS G-V trace occurred during entry.

Items 3, 4, and 5 can be directly attributed to the accelerometer air bubble. The spurious counting was caused by the residual effect of MCC-5 on the accelerometer. The air bubbles were distorted as a function of acceleration and accelerometer

internal geometry; following acceleration, return of the bubble to its minimized pressure shape damped fluid motion and resulted in spurious accelerometer outputs. The accelerometer air bubble is considered to be the total cause; slow cycling of the mode switch simply inhibited the display in the standby mode and allowed the display of spurious counts when in "auto."

The foregoing conclusions were based on extensive testing and analytical effort after the Apollo 8 mission. The problems that were found resulted in positive corrective action to preclude a recurrence on subsequent missions.

Postmission modification. - After flight, the following corrective action was implemented for the Apollo 9 (CSM 106) mission and subsequent missions.

1. An accelerometer stabilization test was added to the EMCA acceptance test program to verify the absence of air bubbles in the accelerometer damping fluid.

2. A verification test was added to prove the integrity of the plug-type O-ring seals.

3. The EMCA acceptance vibration tests were revised to include three-axis tests.

4. For the Apollo 9 (CSM 104) mission and subsequent missions, an Apollo Operations Handbook (AOH) change, dated February 4, 1969, was implemented to correct the erroneous display of 100 ft/sec. The AOH change moves the setting of the display from 0.0 to -100.0 ft/sec, moves the mode switch to "standby," and specifies when it is necessary to bias the counter.

Entry postflight results. - Even though the EMS encountered intermittent transients contributing approximately 100 ft/sec to the velocity error during the Apollo 8 flight, the EMS operation at the end of the entry trace was within the error budget specified in the CSM Operational Data Book (Part I, Constraints and Performance). Postflight assessment indicated that the general operation of the EMS during entry was satisfactory, except for the two intermittent transients caused by the air bubbles. The transients affected both G and V channels. In addition, an entry pattern misalinement amounted to a constant 0.44G error throughout the entry trace, which, in itself, did not degrade the usefulness of the EMS. This type of discrepancy in the initial setting of the scroll should have been corrected before the entry phase.

By comparison to the G-time and V-time derived from onboard pulse-integrating pendulous accelerometer data, overall scroll operation (G-V trace) was within the 0.12G limit, except at the two points at which transient positive-G pulses occurred. The EMS ranging performance was satisfactory. The EMS ranging accuracy for a lunar-return entry is ±23.04 nautical miles. The EMS range-to-go at the end of the entry trace (V = 4000 ft/sec) was 17.4 nautical miles. The range-to-go counter counts approximately 25 nautical miles from the end of the entry trace to the drogue deployment altitude. At drogue deployment, the range was -7.6 nautical miles, which is much more accurate than the ±23.04-nautical-mile lunar-return ranging accuracy specified. A further substantiation of the accuracy of the EMS was reported when the crew verified that the range-to-go display read 50 nautical miles just as the

50-nautical-mile potential-range guideline was reached on the scroll. Comparison of the delta-V at 11 500 ft/sec after 0.05G (V = 24 700 ft/sec) to the hardware delta-V budget of 100 ft/sec indicated that the Apollo 8 EMS delta-V of 130 ft/sec with the two transients was not within the hardware error budget but was within the total delta-V budget of 300 ft/sec.

Apollo 9 Mission

Performance. - On the Apollo 9 (CSM 104) mission, the entry monitor failed to scribe during entry. Postflight testing of the scroll assembly revealed a leak around the base of one of the four scribe-glass-adjustment-screw cups. The neon leak rate was approximately 1.0 cm^3/sec. The leaking screw cup showed evidence of physical damage, an indication of possible unit mishandling after the last leak test.

Analysis of the scroll after it was removed from the scroll assembly disclosed that the scroll scribed properly for the first flight test pattern. The scroll failed to scribe at the start of the preentry flight test pattern and began scribing again during the last half of the pattern. Scribing of the film was proper down to the initial set position of the first entry pattern, but scribing failed from that point to entry until just before drogue deployment.

Photographs of the scroll made through the use of special lighting and photographic techniques revealed that the acceleration and velocity drive assembly that holds the stylus for scribing the film functioned properly and would have indicated the proper entry pattern had scribing occurred. Hardening of the scribe coat during flight prevented scribing by the stylus.

The scroll is susceptible to moisture, and subsequent slow drying of the moisture causes a hardening of the film coat. The scroll was probably moisturized when ambient air leaked into the unit before lift-off. During flight, reduction of cabin pressure to 5 psia provided a slow vacuum dry as the moist air was expelled from the unit. After being soaked for 10 days at 5 psia, the scribe coat hardened and prevented scribing. Postflight analysis also revealed contamination to the stylus holder and bushing; the contamination caused a 2- to 3-second lag in the stylus response.

Postmission modification. - After flight, the following corrective action was implemented for the Apollo 10 (CSM 106) mission and subsequent missions.

1. The stylus spring load was increased to $11^{+1}_{-0.5}$ ounces.

2. The dimensions of the stylus holder and bushing were verified.

3. Acceptance tests were performed to verify repeated scribing.

Entry postflight results. - Postflight assessment disclosed that, because of the scribing anomaly encountered during entry, the scroll reproduction was not sufficient for an accurate reading of the G-V trace. However, the scribe did track the load factor and velocity of the trajectory accurately during entry. The G-V impression

left on the actual entry pattern was photographed using special filters and lighting in an attempt to obtain a faint trace and to reconstruct G-time and V-time histories.

Postflight entry trajectory simulations were generated using the latest state-vector information to determine whether the EMS scribe impression followed the actual trajectory load factor and velocity. By comparison of the G-V data to the qualitative data reduced from the scroll photographs, the scribe was shown to be driven according to the trajectory flown. No entry error budget checks were made on this flight because the trace impression was not of sufficient quality to provide good engineering G-V data. The delta-V performance was satisfactory during the eight SPS burns and was well within the accuracy of 1.3 percent of the burn delta-V specified in the Apollo CSM Operational Data Book.

Apollo 10 Mission

Performance. - Following successful completion of the preentry self-tests on the EMS for the Apollo 10 (CSM 106) mission, the stylus of the entry monitor failed to scribe while the scroll was driven to the entry pattern. The scroll was slewed back and forth once, and the stylus then penetrated the emulsion on the scroll. The trace of acceleration as a function of velocity was normal throughout entry.

The emulsion used on the scroll film had a latex rubber and detergent base. The formulation of the detergent, which was commercially procured, had been changed by the addition of uric acid. Uric acid tends to increase the hardness of the emulsion by a chemical reaction with the gelatinous film on the Mylar scroll.

Postmission modification. - After flight, no major change was made to the emulsion formula for either the Apollo 11 or the Apollo 12 scroll. Instead, a decision was made that use of the original formulated detergent for the scroll emulsion base would be continued with better application and formulation controls or tnat a new technique incorporating a flight-qualified pressure-sensitive scroll coating would be used for the scroll on subsequent vehicles.

Entry postflight results. - Postflight assessment revealed that the overall operation of the EMS was demonstrated on the Apollo 10 mission, despite the small scribing anomaly that was encountered in the self-tests before entry. The EMS parameters were within the budget limits for both the range-to-go and the delta-V functions.

Apollo 11 Mission

Performance. - An electroluminescent segment on the EMS delta-V/range-to-go numeric display was reported inoperative by the flight crew during the Apollo 11 (CSM 107) mission. Because the EMCA that houses the numeric display was not removed from the spacecraft for failure analysis, a circuit analysis was performed to identify the most probable cause. The possible problem areas were investigated and isolated to the electroluminescent segments, the blanking circuits, and the segment drivers and interconnecting wiring.

The electrical circuit analysis was performed basically to determine whether the problem was generic and applicable to all the numeric displays. Each digit in the numeric display contains seven individual electroluminescent segments; each segment is controlled by separate but identical logic. Any of the individual components such as resistors, silicon-controlled rectifiers, and integrated circuits could have caused the failure.

Each electroluminescent segment making up the digits is independently switched through a logic network that activates a silicon-controlled rectifier to bypass the light when it is not illuminated. The power source is 115 volts at 800 hertz.

A reliability review revealed four cases of malfunctions similar to that reported. One malfunction involved a constantly illuminated segment. In each case, the cause was identified as misrouting of logic wires in the circuitry controlling the silicon-controlled rectifiers. The misrouting bent the wires across terminal strips containing sharp wire ends that punctured the insulation and caused either short circuits to ground or a 4-volt activation or deactivation, respectively, of the segment.

The affected circuitry was reworked in the process of soldering crimp joints that were involved in the Apollo 7 anomaly. An inspection to detect misrouting was performed; however, because of restricted access, the inspection was limited.

Although several other failure mechanisms existed in circuit elements and leads, there was no associated failure history. A generic or design problem was considered unlikely because of the number of satisfactory activations demonstrated by units in the field.

During qualification testing, several display segments failed because of CCOH penetration of the moisture seal. However, in no case was a single segment blanked while the remaining segments were in full brilliance. An improved moisture seal was installed to resolve the moisture problems.

Postmission modification. - No major postmission design change was required, because the past history of the numeric display problems encountered during qualification testing revealed that the most probable cause for the electroluminescent segment failure was either a faulty component controlling that particular segment or a workmanship problem associated with wiring or soldering. The recommendation for this particular failure was to rely on existing acceptance screen tests and an additional spacecraft test for verifying illumination and uniform intensity of all segments.

Entry postflight results. - Postflight assessment indicated satisfactory overall operation of the EMS. All the test objectives were accomplished. Because the on-board data storage equipment was not turned on during entry, the accuracy of the EMS load factor, velocity, and range data by comparison with the integrated pulse-integrating pendulous accelerometer data was not verified.

CONCLUDING REMARKS

The operational characteristics of the entry monitor subsystem were greatly improved with two design modifications: the changing of the crimp-joint terminal connections of the delta-velocity/range-to-go counter to solder connections and the replacing of the original scribe coat with a new microencapsulated-dye process. The lesson learned from experience with the entry monitor subsystem was to be wary of a design that is relatively straightforward in itself but that is very difficult to implement.

Lyndon B. Johnson Space Center
    National Aeronautics and Space Administration
        Houston, Texas, September 4, 1974
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