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APOLLO EXPERIENCE REPORT - FLIGHT ANOMALY RESOLUTION

John D. Lobb

Lyndon B. Johnson Space Center
Houston, Texas 77058

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16. Abstract

The identification of flight anomalies, the determination of their causes, and the approaches taken for corrective action are described. Interrelationships of the broad range of disciplines involved with the complex systems and the team concept employed to ensure timely and accurate resolution of anomalies are discussed. The dynamic nature of the program required a rigorous effort in documenting all procedures for the use of program management, flight control, engineering design, and scientific investigation personnel. · The documentation techniques and the techniques for management of anomaly resolution are included. Examples of specific anomalies are presented in the original form of their progressive documentation. Flight anomaly resolution functioned as a part of the real-time mission support and post-flight testing, and results were included in the postflight documentation. However, this report refers to these activities only insofar as they affect, or are affected by, the progressive activities of flight anomaly resolution. The details of real-time mission support, postflight testing, and postflight documentation are discussed under these headings in separate reports.

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APOLLO EXPERIENCE REPORT

FLIGHT ANOMALY RESOLUTION

By John D. Lobb
Lyndon B. Johnson Space Center

SUMMARY

The frequency of the Apollo missions demanded that flight anomalies be quickly identified and resolved so that prompt corrective action could be taken. Analyses of the data for problems and anomalies had to be compressed into a relatively short time frame.

Timely resolution of flight anomalies was achieved during the Apollo Program so that corrective actions necessary for crew safety, mission success, and program success were completed during each mission and between missions. This success was largely due to a team of engineers who understood the details of hardware design, test history, and operational characteristics of their respective systems. A working relationship that ensured quick responses and concurrence of this team with program management and flight operations personnel contributed equally to program success. The analysis team had access to the support of any other specialists or facilities needed to the extent justified by the nature of the particular problem. Team understanding of the mechanism associated with the cause of the problem was required for resolving each anomaly. Complete understanding of an anomaly often required postflight data analysis, crew debriefings, and testing of spacecraft hardware.

The efficient documentation system established a definite point on which to focus direction and continuity of effort for more effective anomaly resolution. The flexibility of some of the documentation provided continuous updating by the analysts and ensured a common understanding of the current status of each system problem by the analysis team and by program management and flight control personnel.

Of course, the complexity of the spacecraft configuration and of the complement of experiments taken on the lunar-landing missions increased the probability of a wide variety of anomalies. The same general procedure was used to properly identify and understand each problem, analyze the cause, and determine the proper course of action. Examples of actual flight anomalies illustrate the general types of causes identified, the levels of analysis required, and differences in the nature and extent of the corrective actions justified.

INTRODUCTION

Flight anomaly resolution was the mission evaluation task that covered space-craft and experiment problems and deviations from expected or predicted performance. This task included not only the resolution of true failures and malfunctions, but also the resolution of items that appeared to be problems or discrepancies at first but that, on further investigation, proved to be incorrectly identified as anomalies. Thus, the term "resolution," as used in this report, includes the proper identification of the anomaly as well as the determination of the cause and the proper course of action to be taken both during the mission in progress at the time and before subsequent missions.

The flight anomaly resolution system used during the Apollo Program was an out-growth and further development of the mission evaluation procedures used on the pre-vious manned space flights of Project Mercury and the Gemini Program. Mission evaluation ensured that maximum information was obtained from each Apollo flight for use in managing and planning later flights and future programs. The information was also provided to the scientific community and to the public so that they could be well informed on the activities of U.S. space exploration.

It was necessary that anomaly resolution be completed in a timely manner for the interim in-flight course of action. Just as important was the need for a time frame that would enable completing the proper corrective action for subsequent missions with-out requiring changes in the scheduled launch dates for lunar-landing missions, which were limited to specific lift-off times and calendar dates for each lunar exploration site.

This report contains a discussion of the primary characteristics of the success-ful resolution of Apollo flight anomalies. Typical experiences have been used to illustrate how the system was actually implemented. In addition to the examples of flight anomalies discussed in the body of the report, extracts from actual anomaly resolution reports for four problems are presented in the appendix. These extracts have been included to illustrate that changes from issue to issue of the reporting system reflect the progress made in resolving anomalies. The four anomalies selected reflect different combinations of causes, sources of data for analysis, corrective actions, and reporting histories.

PERSONNEL

Essential to the successful performance of anomaly resolution was the makeup and interaction of the mission evaluation team. Each of the many disciplines involved was represented on the team by a group of specialists managed by a NASA team leader who was also a specialist in the same discipline. Each specialist had a thorough under-standing of system characteristics, operations, and limitations gained from experience with his particular systems from initial design through development and testing of the hardware. Team members were selected from NASA and contractor personnel.

Each team leader was the analysis manager for anomaly resolution within his particular range of responsibility. For example, the Apollo 14 team included an

analysis manager for each of the following: telecommunications, crew systems, electronic systems, propulsion and power, guidance and control, structures and mechanics, thermal control, flight crew support, trajectory, and lunar surface experiments.

The responsibilities of each team leader included coordination with the other team leaders to ensure that any solution or recommended course of action would not jeopardize other systems. The team leaders reported to an evaluation team manager who was responsible for the overall operation of the team, reviewed and integrated the inputs from the team leaders, and communicated with the Mission Control Center as the single point of contact. In addition, an anomaly engineer was responsible to the team manager for following through on each anomaly to completion of the resolution. There was an anomaly engineer for command and service module problems, one for lunar module problems, and one for experiments and Government-furnished-equipment problems. Continuity to completion of the activity was enhanced because some team members in each discipline were also responsible for the detailed implementation of hardware changes required for subsequent missions. The mission evaluation team provided direct support to the flight control organization in the Mission Control Center for inflight resolutions and to program management for resolutions requiring action on the ground before subsequent missions.

The premission planning and training of flight operations personnel with the crewmen covered many possible failures and malfunctions of systems and components. These failure modes and corrective contingency procedures were thoroughly exercised during simulations. Nevertheless, it was not surprising that unpredicted problems and discrepancies were encountered with a complex configuration such as the spacecraft and the complement of experiments taken to the Moon. The prime tasks for the mission evaluation team were to properly identify and understand these problems, to perform the investigations and analyses required, to determine the causes, and to recommend the proper courses of action.

In support of the team effort at the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)), the prime contractors maintained similar teams of specialists at their facilities during the mission for analyses, tests, and related activities as they were required. These teams also reported to the mission evaluation team management at MSC.

Many times during Apollo flights, the support team personnel at the prime contractor facility provided test information that was invaluable for understanding a problem and for determining the best course of action. For example, during lift-off of the Apollo 12 spacecraft, a lightning discharge resulted in tumbling of the inertial platform and loss of inertial reference. The support team at the Massachusetts Institute of Technology in Cambridge, Massachusetts, performed a test simulating the condition in an attempt to understand how the potential discharge had caused the platform to tumble. It was important to quickly verify that the platform had not been damaged. A prompt response was received by the evaluation team, and the mechanism that had caused the conditions in flight was determined.

The choice of team personnel for Apollo flight anomaly resolution was a major contribution to the success of the missions. Many of the analysis managers continued

in that capacity for the entire program and, thus, provided continuity to the anomaly resolution and corrective action effort as well as exceptionally good intrateam understanding. The team manager, who was also chief of the MSC Apollo Spacecraft Program Office Test Division, led the mission evaluation and anomaly resolution operation for the Apollo Program, beginning with the Apollo 6 flight.

IDENTIFICATION OF ANOMALIES

The first task of the mission evaluation team was to identify the anomaly. This task required the team's constant awareness of the total system performance as the mission progressed. Individuals monitored telemetry data that were received by the tracking stations, transmitted to and processed by the Mission Control Center, and displayed on closed-circuit television receivers in the Mission Evaluation Room. In addition, the air-ground voice communications and television coverage of crew activities were closely monitored. Selected telemetry data, which were not on the television displays, were provided to team members in the form of computer tabulated printout copies several hours after transmission for analysis of system performance. Identification of flight anomalies continued after completion of the mission through crew debriefings and additional individual conferences between specialists and the crewmen, results of the analyses of in-flight photography, and results of the analyses of reduced data from the mission.

Identification of anomalies for the lunar surface equipment operating at the five Apollo science stations will continue for the remaining data-gathering lifetime of each installation. When indications of a problem appear in the telemetry data, various troubleshooting command sequences are transmitted to the affected station to help identify the possible anomaly. Initial indications sometimes are evident in the real-time data; at other times, the anomaly may not be evident until the more detailed data processed by the principal investigator have been analyzed several months later.

Insufficient Ground Test Data

System performance was usually determined by comparing the flight data with performance predictions and with data from ground tests and from other flights. Data comparison was also a prime method of detecting anomalies. However, in the most difficult identification problems, the available data were not sufficient for complete understanding of all normal operating characteristics of the system.

A typical example of this condition occurred on the Apollo 7 mission. The command module entry battery recharging characteristics were below predicted levels throughout the flight, and the planned charge levels could not be maintained. Available ground test data were insufficient to explain the condition. The condition was duplicated during postflight tests, and a detailed analysis was made. Results of the analysis showed that the charger to battery line impedances, which were not evaluated previously, were large enough to cause a significant reduction in the charge voltage applied at the battery. Results of the system analysis also showed that the charger output voltage was within specifications, but on the low side, and that the characteristics of an experimental plate-divider material used in the batteries could result in a condition, at zero g, that could limit the recharge capacity of the battery.

As a result of the anomaly investigation, chargers with the highest voltage output were selected for subsequent missions, and integrated systems tests were performed to establish the overall system characteristics of each installation and, thereby, to ensure adequate recharge capability. In addition, for Apollo 11 and subsequent missions, the charger was modified for a higher output voltage setting, and conventional plate-divider material was used in the batteries. Performance on subsequent missions was satisfactory. Additional detail on this anomaly is contained in reference 1.

Insufficient Flight Data

Sometimes, the flight data were insufficient for immediate identification of a specific problem. For example, during the Apollo 15 mission, the service propulsion system thrust light, located on the entry monitor system panel, was illuminated shortly after transposition and docking at a time when no engine-firing command was present. Because the problem could not be accurately identified by using available data, the crewmen were provided with special troubleshooting procedures to better pinpoint the problem. Application of the fault isolation procedures resulted in isolation of the malfunction to a short circuit in bank A of the service propulsion system ignition circuitry. The results of the next special procedure - to manually initiate ignition for the first midcourse correction thrust firing by closing the pilot-valve main A circuit breaker - further verified that the short circuit existed on the negative side of the service propulsion system pilot-valve solenoids, and also indicated that subsequent maneuvers could be controlled by manual control of bank A. Results of postflight tests and examination of the returned hardware showed that the intermittent short circuit was caused by a freefloating strand of contaminating wire inside the system A differential-velocity thrust switch. All switches of this type were subjected to additional screening procedures for subsequent missions.

Obvious Component Failure

Many anomalies were recognized simply because a specific component was obviously not functioning. For example, during the initial deployment of the Apollo 12 color television camera on the lunar surface, the picture was lost because the camera was inadvertently pointed at the Sun. The direct sunlight had caused a light overstress, which damaged the image sensor to the extent that a usable picture could no longer be attained. For further details, see the appendix and reference 2.

Crew Observation

Sometimes, the initial indication of an anomaly resulted from observation of an off-nominal condition by a team member or by a crewman, reported either at the time the problem occurred or later if the problem was not critical. An example was the postflight report by the crewmen concerning the failure of the primary floodlights in the command module lower equipment bay during the Apollo 7 mission. Subsequent investigation revealed that the lamps had been operated excessively in the dimmed mode before flight. For additional information, see the appendix.

ANALYSIS

Two basic techniques were used to determine the cause of a problem and the required corrective action. The first technique was the experimental testing of the actual or identical hardware under actual or simulated flight conditions or under laboratory ambient conditions. The use of breadboard systems when required was another type of experimental testing available to the mission evaluation team. The second technique was analytical, generally in the classical sense. The analytical technique included the use of computerized mathematical models, the application of physical laws, and the use of established engineering formulas.

The choice of technique depended on the nature of the problem. The most expedient approach was sought; however, attention to detail was also of prime importance because the analysis had to be sufficiently rigorous to establish the cause and, then, to develop and prove the necessary corrective action to prevent future occurrences. Of course, corrective action sometimes was unnecessary.

Extensive Analysis

The extent of the analysis varied considerably and depended on the significance and nature of the problem. Extensive analysis sometimes was required. For example, on the Apollo 6 mission, a structural failure occurred in the adapter that housed the lunar module during launch and provided the structural connection between the service module and the launch vehicle. This adapter had the largest honeycomb structure designed and developed for any application to that time. Photographs from mission support aircraft and ground-based long-range cameras showed that much of the honeycomb sandwich facesheet had separated abruptly from one of the four circumferential sections of the adapter during launch. The effects of the separation were indicated on many measurements in the command and service module, the lunar module, and the launch vehicle. The adapter continued to sustain the required loads, however.

The seriousness of the problem because of its possible effect on the integrity of the space vehicle and impact on the Apollo Program required an extensive analysis. The investigation of this anomaly included testing full-scale hardware under dynamic and static conditions, performing many experimental tests on smaller test articles, and performing extensive structural analyses at various NASA centers and contractor facilities. To determine the cause of this anomaly, analyses were made of the structural dynamics of the launch vehicle, the dynamic loads of the lunar module, the dynamic modes of the adapter itself, the effect of thermal and pressure environments during launch, and the assembly techniques and quality control procedures used in the manufacture of the adapter structure.

The investigation was focused first on an understanding of the coupled vibration modes and vibration characteristics of the launch vehicle, the spacecraft, and the adapter. Results of extensive vibration tests showed that the failures had not been caused by vibration. Investigations of the thermal and pressure conditions, which included full-scale simulations, revealed that the pressure buildup within the honeycomb

sandwich, because of the effect of aerodynamic heating on air and moisture trapped in the panel, could have caused the anomaly wherever a weak bond existed in the panel structure.

Analysis of the original ultrasonic inspection scan records of the Apollo 6 adapter assembly showed an abnormal condition extending several feet along a panel internal structural splice in the center of the region where the adapter failed in flight. Normally, when a suspect condition was detected during the manufacturing process, the area was X-rayed. If the X-rays confirmed a weak joint or bond, a void, or a misalined component, the fault was repaired. Nevertheless, the anomalous indication at this location had been overlooked on the ultrasonic inspection scan record during manufacturing. The void and misalined splice indicated by the observed abnormality caused a weakness of sufficient size that the facesheet was blown off by internal pressure buildup during launch.

As a result of the anomaly investigation by the mission evaluation team, the following was accomplished.

1. The probable cause was identified.

2. Similar conditions found on other adapters were repaired.

3. Vent holes were drilled through the inner facesheet, and cork insulation was added on the outer facesheet to reduce the temperature and pressure buildup in the honeycomb panels.

4. Manufacturing assembly techniques and quality control applications were modified to avoid repeating the condition on future assemblies.

5. The fact that the failure was not the result of a basic design deficiency was established.

6. The structural integrity of the adapters for subsequent missions was verified.

Limited Analysis

An example of the other extreme in the extent of analysis required was the type of anomaly for which no corrective action was taken because of the nature of the failure. For example, on the Apollo 11 entry monitor system, an electroluminescent segment of the velocity counter would not illuminate. A generic or design problem was considered highly unlikely because of the number of satisfactory activations experienced previously. A circuit analysis produced a number of failure mechanisms; however, there was no failure history in any of the circuits. This anomaly was typical of random failures that could occur. The basic design concept of the spacecraft provided for alternate procedures or redundant equipment to perform the function; consequently, no corrective action was taken for this and similar problems.

Returned Flight Hardware

Sometimes, the analysis and resolution could not be completed until the returned hardware had been examined in detail. Examples of dependence on flight hardware for anomaly resolution were the failure of the Apollo 12 color television camera on the lunar surface and the failure of the primary lower equipment bay floodlights on the Apollo 7 mission (ref. 2 and appendix). The floodlights were returned because they were part of the command module equipment. However, the television camera was returned because of the anomaly resolution requirement. The camera had not originally been listed for return stowage. For details of the Apollo postflight testing program, see reference 3.

Unreturned Flight Hardware

In general, two types of malfunctioning equipment were not returned. One type was hardware that had been deployed and was operating as part of a lunar surface science station, such as the Apollo 14 active seismic experiment geophone that was producing erratic data (appendix). Testing to resolve the problem was accomplished by using breadboard equipment in the laboratory and by transmitting commands to the science station on the lunar surface.

The other type of problem equipment that could not be returned was equipment located in the lunar module or in the service module. Oscillation of fuel cell condenser exit temperatures during the Apollo 10 and 11 missions was a good example. See reference 4 and the appendix. The fuel cell condenser was mounted in the service module, which separates from the command module at the time of entry and is not recoverable. Extensive review and analysis of the flight data for all previous missions were necessary because the condition had been observed on several missions.

TYPICAL CAUSES OF ANOMALIES

The causes of most anomalies were related to manufacturing quality, hardware design, or operational procedures or to a combination of these.

Manufacturing Quality

The structural failure of the Apollo 6 adapter was primarily a manufacturing quality problem because of the failure to adequately interpret the ultrasonic scan record. If the record had been interpreted properly and the fault confirmed by X-ray, the correct structural repair would have been implemented. In addition, there had been manufacturing process difficulty in properly alining all structural parts when the assembly was prepared for bonding in the autoclave. Manufacturing quality anomalies also included irregularities such as improperly torqued screws, incorrectly soldered joints, and improperly potted components which resulted from deficient manufacturing procedures.

Hardware Design

System anomalies caused by hardware design deficiencies sometimes occurred because all factors that would influence the performance of the system were not included in the design criteria or specifications. Because component and system testing was based on these criteria or specifications, the deficiency could go unnoticed during development and qualification tests and not be detected until actual flight conditions were encountered. A typical illustration was fogging between the panes of the Apollo 7 command module windows caused by deposits from the outgassing products of the room-temperature-vulcanizing sealing material around the windows. The design of the assembly had not required that the sealing material be cured at the operating temperature and pressure. Such a curing process would have reduced the amount of outgassing during flight. For further discussion of this problem, see reference 5.

Other types of design deficiency anomalies were those in which the state of the art had advanced or additional knowledge and experience in space had been acquired following the design and manufacture of the component or assembly. An example of this type was the cracking solder phenomenon that occurred on electronic hardware designed and manufactured before 1967. An investigation, performed at that time because of problems with spacecraft and launch vehicle electronics, revealed that existing design practices for printed circuit board assemblies did not allow for occurrence of thermal expansion of the assemblies during normal operations. Differences in the thermal expansion properties of the board materials, coating materials, potting materials, and component lead materials caused stress and cracking in the soldered connections. The program also resulted in development and publication of tested, acceptable design configurations and guidelines for printed circuit board assemblies. See references 6 and 7. Many non-mission-critical electronic assemblies had been built before that time. Although the assemblies were subjected to additional testing and screening, some anomalies did occur as a result of this design weakness. For example, during the Apollo 12 mission, a failure occurred in the mission timer tuning fork circuit because of a cracked solder joint in the cordwood construction. Electrical components such as resistors, capacitors, and diodes had been soldered between two circuit boards, and the void between the boards had been filled with potting compound. The thermal expansion differential between the potting compound and the component leads resulted in solder joint cracks at a board-to-lead connection. Design of a new clock, developed for subsequent missions, did not include the cordwood construction.

Operational Procedures

Procedural problems in operating the various systems and equipment were usually easy to correct. An example of a procedural problem occurred during the entry and landing sequence on the Apollo 12 mission. A crewman was struck by a 16-millimeter camera that was dislodged from the mounting bracket near the rendezvous window at splashdown. The camera was to have been stowed before landing because design of the mounting bracket did not include retention under landing forces. Designation of the camera for stowage in the flight plan and the crew checklist on subsequent flights precluded recurrence of this incident.

The correction of some procedural problems involved both crew training and hardware design changes. This type of correction was required after the loss of lunar surface television transmission during the Apollo 12 mission (appendix and ref. 2). It was found that high-intensity light inputs were received not only during direct pointing at the Sun, but also during normal pointing as a result of specular reflections from objects in the field of view. This problem hastened completion of the development of new burn-resistant image sensors. The newly developed tubes were used with success on subsequent missions. Operational procedure on later missions was established to avoid pointing the television camera at specified light sources. Also, with the addition of the lunar roving vehicle having a television camera mount on the Apollo 15 mission, remote pointing control from the Mission Control Center freed the flight crew from most of this responsibility.

Another type of procedural problem was illustrated by the short in-flight life of the floodlights in the Apollo 7 command module lower equipment bay (appendix). Here, the preflight procedures were modified to ensure sufficient floodlight lifetime for mission operations.

DOCUMENTATION

Documentation provided, in firm and visible form, definitive information for a better understanding of each anomaly throughout the resolution process. Clearly written explanations, accompanied by illustrations and data when required to clarify or back up a point, ensured a common understanding of the status, findings, and final resolution of anomalies by management, engineering, and operations personnel. The character of the documentation and the scheduling of the documentation also forced analysts to organize the work so that the results and conclusions were concurred upon by the working groups and reported in an understandable format and in a timely manner.

During Flight

During flight, the anomaly resolution activity of the mission evaluation team was documented in several different formats, each serving a specific purpose and each supporting the other. Communications between the Mission Control Center and the Mission Evaluation Room about questions, answers, and specific information concerning the spacecraft and experiments hardware were documented on a spacecraft-analysis/mission-evaluation action request form. This documentation was often the written confirmation of concurrent verbal understandings between the two groups, sometimes containing additional detail backing up the verbal action. The identification of an anomaly was frequently documented for the first time in one of these messages.

The request forms issued by the mission evaluation team, in the form of questions, responses, or information, were signed by the originating specialist, by the analysis manager or managers for the system or systems affected, by the contractor representative to indicate concurrence from the team at the contractor facility, and by the evaluation team manager to indicate that the contents covered all affected systems. Copies of these messages were also forwarded by wire to the contractor, and contractor inputs to the team at MSC were documented on similar forms.

Because the actions covered by these communications were for real-time decisions, response time was kept to a minimum. Sometimes, the answer was almost instantaneous and required close-knit, alert team action. Sometimes, an immediate reply required action to achieve a safe standby condition until the results of expedited, special ground tests and analysis provided a more permanent, longer range procedure. The team handled an average of 325 of these requests for each lunar-landing mission.

In addition, anomalies were noted briefly in the 2-hour status reports prepared by the analysis managers during the mission. In these reports, the status of each spacecraft system and experiment was presented for each 2-hour period during the mission. As a result, a problem would sometimes be described several places in the same report because of its effect on more than one system. This report provided additional assurance that team members were aware of problems and trends in other systems as well as in their own. The daily report was, in essence, a summary of the 2-hour reports for the preceding 24 hours.

As problems were identified, they were documented on a problem-tracking list, which included a statement of the problem as it was understood at the time, identification of the responsible analysis manager or managers, and a brief discussion of the problem, including the action in progress and the schedule status of the resolution. This list, distributed to team members and posted in the Mission Evaluation Room, established a definite point on which to focus direction and continuity of effort so that anomaly resolution would be more efficient and effective. Items that had been incorrectly identified as problems because of insufficient or misinterpreted information were quickly recognized as normal operations, and efforts were directed toward resolving the authentic anomalies.

After Flight

After flight, the documentation was changed to suit the postmission testing and analysis required for anomaly resolution. The problem-tracking list was expanded into the Problem and Discrepancy List reports, which included separate documentation for each anomaly. Examples of the Problem and Discrepancy List format for individual problems are included in the appendix. The extract from the Apollo 14 mission is an example of the final format for the program.

The Problem and Discrepancy List was updated frequently as the fast-moving resolution process progressed. Statements in each issue of the report were subject to change as the analysis continued and were based on indications at the time the list was published. As a result, discussions and conclusions could change significantly from issue to issue until final closeout. The changes reflected the progress in the analysis and resolution. Because of the frequency of the Apollo missions and the need for corrective actions before the next flight, this frequently updated format was a definite advantage.

The Problem and Discrepancy List included problems from the problem-tracking list; problems identified during crew debriefings, particularly those pertaining to crew-operated equipment; and problems identified during the analysis of the in-flight photography and processed data. There was an average of 72 Problem and Discrepancy List items for each lunar-landing mission.

A report was published by MSC 30 days after each flight. In the 30-day report, the anomalies were identified, the analyses discussed, and the corrective actions explained when determined.

The mission report, published by MSC approximately 90 days after each mission, included sections in which each flight anomaly was discussed. Extracts from three mission reports are included in the appendix. An average of 35 anomalies were discussed in each lunar-landing-mission report.

Updating and publishing of the Problem and Discrepancy List was continued after publication of the mission report until all problems could be considered closed. Corrective action was always taken for critical failure modes. When the cause of a critical failure could be isolated to no less than two or more possibilities, corrective action was taken for each possible cause. A closed problem was usually one for which the cause had been determined and the corrective action was being implemented. A separate anomaly report was published for each anomaly that was not resolved and closed before publication of the mission report. Examples of anomaly reports are included in the appendix.

Continuing Documentation

Scientific data-gathering equipment and related communications and power equipment were deployed on the lunar surface by the crewmen on each of the six Apollo lunar-landing missions from July 20, 1969 (Apollo 11), to December 12, 1972 (Apollo 17). The deployed equipment was designed to continue to provide data after return of the crewmen to Earth; therefore, from the standpoint of the experiments hardware specialist, the lifetime of each of these missions extends considerably beyond splashdown.

Transmission of data from the Apollo 11 station ended on December 14, 1969. However, the other five stations were designed for considerably longer lifetimes, and communications with all five stations are continuing. Almost all the experiments that were deployed and activated continue collecting data, and analysis of the scientific data continues.

The spacecraft-analysis/mission-evaluation action request form is being used to provide the documentation of communications between the flight controllers and the hardware engineers and scientists in much the same way as during the flight. Problem identifications, investigative actions and results, resolutions, and corrective actions are documented in this system. The Apollo Program Lunar Surface Equipment Status Report has replaced the Problem and Discrepancy List. This report is issued at approximately 3-month intervals; interim reports are issued if an earlier update is required for a specific purpose.

Anomaly resolution documentation was handled in the same manner for the two particles and fields subsatellites that were launched into lunar orbit from the Apollo 15 and 16 service modules. The Apollo 16 subsatellite mission ended May 29, 1972. The Apollo 15 subsatellite mission ended August 23, 1973.

CONCLUDING REMARKS

The flight anomaly resolution system, developed and implemented during the Apollo Program, was used successfully for identifying and resolving problems and for determining the proper course of action within the relatively short time frame allowed by the Apollo Program schedule of missions. The success of this operation contributed to the overall success of the Apollo Program. The primary reasons for the degree of success achieved in flight anomaly resolution are as follows.

1. The application of the concept of a mission evaluation team that was knowledgeable in all hardware systems serving as an integral part of the mission team while retaining the freedom to pursue problem solution to the extent required for mission and program success

2. The selection of the proper personnel for this team, including the specialists, the team leaders, and the team manager

3. The recognition that this team assignment was the prime activity for each member during the mission anomaly resolution period

4. The establishment of an effective interface level for the evaluation team with other segments of the overall mission team

5. The provision to the evaluation team of displays, data, and communications necessary for maintaining constant awareness of total system performance as the mission progressed

6. The establishment of a definite point on which to focus direction and continuity of effort through a timely documentation system

7. The implementation of a flexible updating system for problem resolution documentation to ensure a common understanding of problem status by members of the overall mission team, including project management

8. The consistent application of the premise that, before any anomaly was considered resolved, it was necessary

    a. That the details of how each affected system, component, or circuit functioned normally, and its purpose, be understood

    b. That the details of the anomalous condition be understood

    c. That the relationship of the affected function with other system functions and with the total mission be understood

d. That the corrective action be proved by test and/or analysis

e. That the responses and documentation be reduced to the most practical and simple terms to ensure clarity and common understanding

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APPENDIX

EXAMPLES OF PROGRESSIVE DOCUMENTATION OF ANOMALY RESOLUTION

Extracts from the anomaly resolution documentation system are included because the changes in the documentation from issue to issue reflect the progress made in the anomaly resolution process. The series of reports also illustrates some of the many conditions that influence the resolution process. The reports included are as follows.

1. Extracts from Problem and Discrepancy List reports

    a. Apollo 12, December 5, 1969, GFE-1

    b. Apollo 12, December 16, 1969, GFE-1

    c. Apollo 14, April 12, 1971, ALSEP-18

    d. Apollo 14, May 14, 1971, ALSEP-18

    e. Apollo 14, July 15, 1971, ALSEP-18

2. Extracts from mission reports

    a. Apollo 12 Mission Report, March 1970, Section 14.3.1

    b. Apollo 14 Mission Report, April 1971, Section 14.4.7

    c. Apollo 7 Mission Report, December 1968, Section 11.21

3. Complete Reports

    a. Apollo 14 Mission Anomaly Report No. 6, December 1972

    b. Apollo 7 Mission Anomaly Report No. 3, February 1969

    c. Apollo 10 and 11 Missions Anomaly Report No. 1, April 1970

The four problems selected were among the less complex examples available. Resolution of the Apollo 12 lunar surface television camera problem involved examination of the flight hardware, which was returned as a result of the problem. It was an obvious component failure and was resolved quickly. The problem hastened completion of the development of an improved image sensor.

Resolution of the Apollo 14 active seismic experiment geophone problem required testing by telemetry uplink commands to the experiment and breadboard bench tests on the ground because the flight hardware had been deployed on the lunar surface. The problem occurred after completion of the flight and was not resolved before publication of the mission report. The progress made in the resolution process, including changes in the conclusions from issue to issue, is apparent in the extracts from the reports.

Resolution of the Apollo 7 command module floodlight problem involved examination of the flight hardware as well as testing to determine expected lamp life and to develop proper preflight procedures. The flight hardware was available since it was part of the returned command module.

As described in the anomaly report, the fuel cell condenser exit-temperature oscillations encountered on the Apollo 11 mission had been observed on several missions. Analysis in greater depth was required to understand the condition. The resolution included a detailed analysis of the flight data.

APOLLO 12 LUNAR SURFACE COLOR TELEVISION CAMERA FAILURE

The loss of the Apollo 12 color television picture occurred when the camera was inadvertently pointed toward the Sun while being transferred to the lunar surface from the modular equipment stowage assembly of the lunar module. The permanent loss resulted from both a crew operational procedure problem and a design weakness because the image sensor was susceptible to almost immediate damage if exposed to high-intensity light. Ground tests performed on similar equipment and on the returned hardware revealed the following.

1. That light overstress from direct sunlight would immediately damage the image sensor

2. That high-intensity light from highly specular reflections, as well as direct sunlight, would damage the image sensor

3. That an image sensor more resistant to damage by high-intensity light was necessary

4. That improved pointing procedures and controls were needed

The cause of the problem was closed out in the documents that follow. The corrective action, which continued after the publication of these documents, produced a satisfactory image sensor and a remote-control camera-pointing system for subsequent missions.

EXTRACT

Apollo 12 Problem and Discrepancy List
December 5, 1969

GFE-1

TIME: During first extravehicular activity at 116 hours

DESCRIPTION: Lunar surface color television camera did not operate after deployment from lunar module.

DISCUSSION: The camera provided satisfactory television coverage for approximately 40 minutes. When moved to a different location, the picture failed when the tube was apparently exposed to direct sunlight or direct reflection from highly specular lunar module surfaces.

IN PROGRESS: Camera is now in Lunar Receiving Laboratory and will be released on December 6, 1969. After release, the following testing will be performed at MSC:

    1. Determine whether the color wheel is rotating; if possible, without removing the camera case.

    2. Disable the automatic light control circuit and evaluate the total video signal to determine the extent of vidicon damage.

    3. Perform a mechanical/visual inspection of the equipment to determine if any other damage was incurred and if extreme heating had been experienced by the camera.

This task will be completed within two weeks after receipt of camera.

COMPLETION: January 21, 1970

ASSIGNED TO: Kingsley

EXTRACT

Apollo 12 Problem and Discrepancy List
December 16, 1969

TIME: During first extravehicular activity at 116 hours

DESCRIPTION: Lunar surface color television camera did not operate after deployment from lunar module.

DISCUSSION: The camera provided satisfactory television coverage for approximately 40 minutes. When moved to a different location, the picture failed when the tube was apparently exposed to direct sunlight or direct reflection from highly specular lunar module surfaces.

After decontamination and cleaning, the camera was inspected and then operated. The picture that resulted was the same as that received at the end of the Apollo 12 transmission. The color wheel could be heard turning within the camera, and when the lens was removed, the turning was viewed directly. The power to the camera was turned on and off several times to see the wheel start and stop. By cutting one wire, the Automatic Light Level control circuit was disabled, and the camera turned back on. A well defined image was visible in the picture in the area which was formerly black. This black represented the undamaged area of the image sensor target. This test proved conclusively that the Apollo 12 failure was due to a damaged image sensor.

In addition, the camera contractor deliberately damaged a similar image sensor by applying bright light levels. The resulting picture was similar to that of the Apollo 12 camera.

Subject to Apollo CCB approval on December 12, 1969, a lens cover will be provided for the Apollo 13 camera. Operational procedures and training will also be improved to reduce probability of exposure. Automatic protective design approaches are also being evaluated.

EXTRACT

Apollo 12 Mission Report
March, 1970

14.3 GOVERNMENT FURNISHED EQUIPMENT

14.3.1 Color Television Failure

The color television camera provided satisfactory television coverage for approximately 40 minutes at the beginning of the first extravehicular activity. Thereafter, the video display showed only white in an irregular pattern in the upper part of the picture and black in the remainder. The camera was turned off after repeated attempts by the crew to restore a satisfactory picture.

Ground tests using an Apollo-type image sensor (secondary electron conducting vidicon tube) exposed the camera system to extreme light levels. The resulting image on a monitor was very similar to that seen after the flight camera failure.

After decontamination and cleaning, the flight camera was inspected and power was applied. The image, as viewed on a monitor, was the same as that last seen from the lunar surface. The automatic light-level control circuit was disabled by cutting one wire. The camera then reproduced good scene detail in that area of the picture which had previously been black, verifying that the black area of the target was undamaged, as shown in figure 14-39. This finding also proved that the combination of normal automatic light control action and a damaged image-tube target caused the loss of picture. In the process of moving the camera on the lunar surface, a portion of the target in the secondary-electron conductivity vidicon must have received a high solar input, either directly from the sun or from some highly reflective surface. That portion of the target was destroyed, as was evidenced by the white appearance of the upper part of the picture.

Training and operational procedures, including the use of a lens cap, are being changed to reduce the possibility of exposing the image sensor to extreme light levels. In addition, design changes are being considered to include automatic protection, such as the use of an image sensor which is less susceptible to damage from intense light levels.

This anomaly is closed.

EXTRACT

Apollo 12 Mission Report
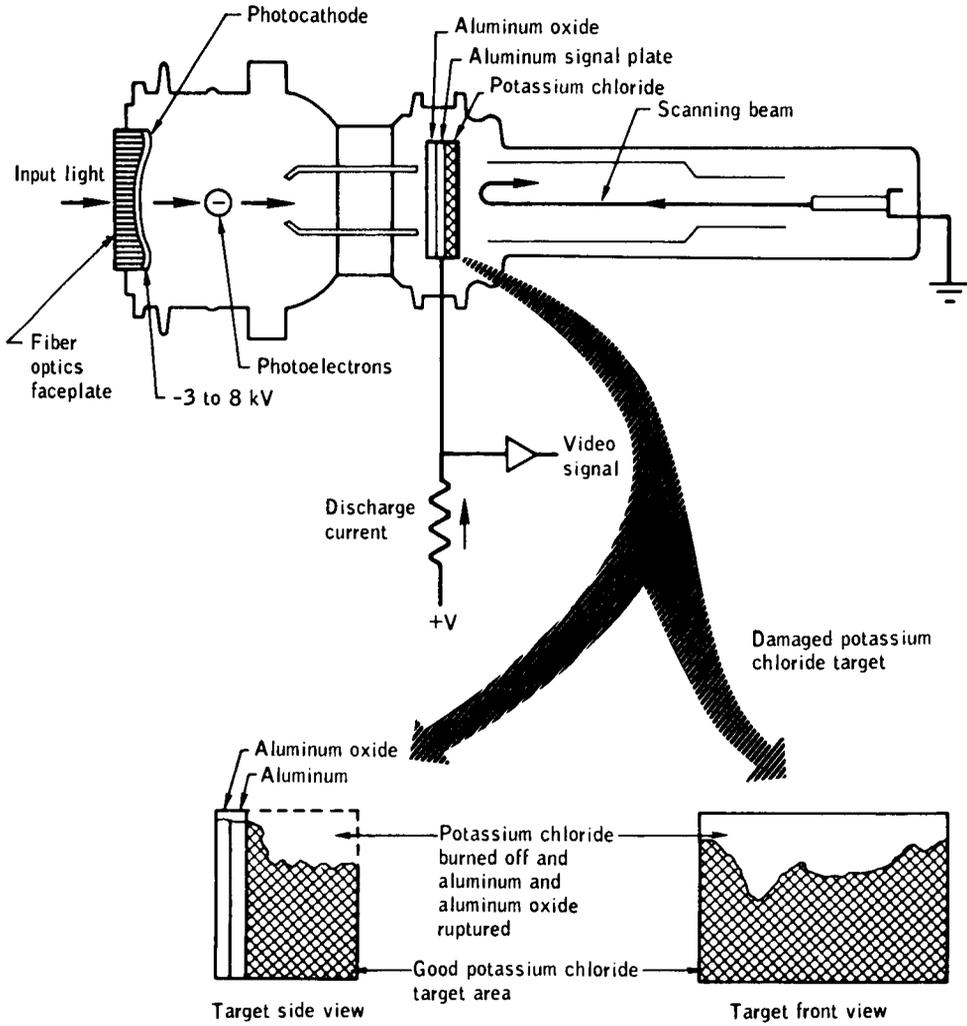### March, 1970

NASA-S-70-1434

Figure 14-39.- Secondary electron conductivity tube in the color television.

APOLLO 14 ACTIVE SEISMIC EXPERIMENT - ERRATIC DATA
FROM NUMBER 3 GEOPHONE

The number 3 geophone data from the Apollo 14 active seismic experiment became erratic. These data had been satisfactory during crew thumper operation on the lunar surface and also during high-bit-rate listening periods during the first 49 days after deployment at the lunar surface site. Tests of the emplaced flight hardware were performed by transmitting selected command sequences to the experiment, and the telemetry data and experiment circuits were analyzed. The problem was duplicated by breadboard bench tests. Components taken from the lot that included the malfunctioning component were tested for a possible generic problem that would require correction before the next mission.

The progressive steps in the analyses are apparent in the documents that follow. They reflect a better understanding of the cause as more results of tests and analyses became available. As indicated in the final anomaly report, the resolution also included an analysis of how the data from the number 3 sensor could be used if required for the analysis of a specific event.

Apollo 14 Problem and Discrepancy List
April 12, 1971

Italics indicate change from previous issue.

PROBLEM AND DISCREPANCY LIST   No. *ALSEP-18*

Statement of Problem:

Active seismic experiment no. 3 geophone data became erratic.

Discussion:

On March 26, the experiment was turned on in the listening mode (high bit rate) and Geophone #3 was spiking to off-scale high. The calibration command was transmitted to all three geophone channels. Geophone #3 channel went off-scale high simultaneous with the application of the calibration pulse and stayed off-scale high for the remainder of the listening period. During the one second period when the calibration pulse was present, Geophone #3 data showed four negative going pulses from off-scale high. Pulse widths were shorter than corresponding oscillations on Geophones 1 and 2 and decreased from the first to the fourth. The characteristics of these pulses indicated that Geophone #3 channel was operating at a higher gain than Geophones 1 and 2 during the calibration period. Circuit analysis indicated that the problem had to be in the logarithmic compressor in the Geophone #3 amplifier chain.

Signals are coupled into the logarithmic compressor through an input coupling capacitor which would block any dc voltage which would have to be present to drive the output voltage off-scale high for long periods (more than 1 or 2 minutes).

The logarithmic compressor is basically an inverting amplifier with exponential negative feedback. Two diode connected transistors between the output

(see continuation sheet)

Schedule:

	April					May	
	1	8	15	22	29		5
Data Review							
Analysis							
Tests (Identify in Note)							
Changes (Identify in Note)							

Notes:
1. *Third lunar day data. 5 to 15 minutes of high bit rate data daily, April 4 - 12*
2. *Preliminary analysis April 1 - 8 - Complete*
3. *Bench checks and analysis.*

Personnel Assigned:

J. Harris, Bendix, Geotech, Gadbois

Conclusions:

Apollo 14 Problem and Discrepancy List
April 12, 1971

Italics indicate change from previous issue.

PROBLEM AND DISCREPANCY LIST
CONTINUATION SHEET

No. *ALSEP-18*

Discussion:

and input of the amplifier supply the feedback. The first diode is used for positive going and the second for negative going input signals. The diodes for all three geophone channels (2 per channel) are physically located in an oven which controls their temperature at 105°C.
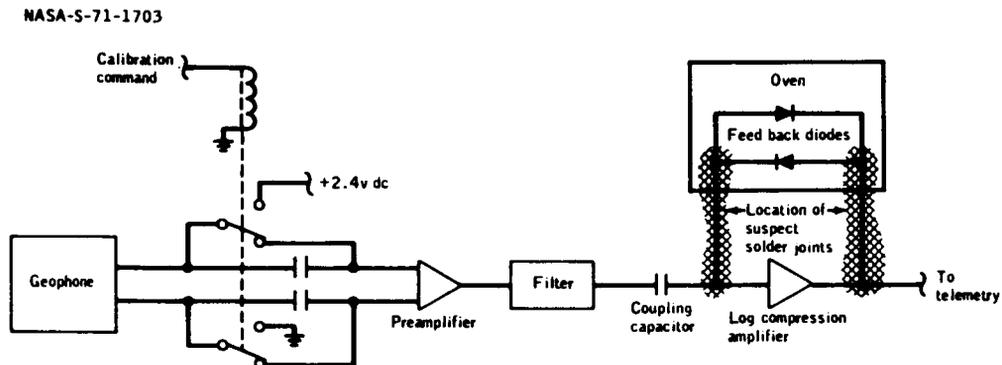
Analysis indicates that the most probable cause of the problem is an intermittent open circuit in the diode feedback path. This would allow the amplifier input transistor to saturate, driving the output off-scale high. When signals large enough to drive the input stage out of saturation were present, the output would then respond and amplifier gain would not be compressed.

Two copper paths conduct the feedback diodes to the logarithmic compressor amplifier. A solder crack in either path would then result in the data characteristics. Since the calibration voltage is applied to the 3 geophones by energizing 3 relays, the relay contact transfer shock could then disturb the solder crack and either open or close the feedback path.

The problem was detected during the lunar night at the experiment location. Under lunar night conditions the thermal gradient between the oven (105°C) and the rest of the electronics (4.4°C) was maximum. Since thermal gradients cause mechanical stresses by differential thermal expansion, the large temperature gradient between the oven and the rest of the experiment electronics probably caused the crack.

A breadboard of the logarithmic compressor will be constructed and the diode feedback loop will be opened to duplicate the experiment data.

EXTRACT

Apollo 14 Mission Report
April 1971

14.4.7 Active Seismic Geophone 3 Electronic Circuit Erratic

The experiment was turned on in the listening mode on March 26, 1971, and geophone 3 data were spiking off-scale high (fig. 14-34). When the geophone channels were calibrated, the geophone 3 channel went off-scale high simultaneously with the start of the calibration pulse and stayed off-scale high for the remainder of the listening period. During the 1-second period when the calibration pulse was present, data from geophones 1 and 2 showed the normal 7-hertz ringing caused by the calibration pulse. However, geophone 3 data showed four negative-going spikes coincident with the first four negative half cycles of the ringing on the other two channels. The spikes decreased in duration from the first to the last, the last having an amplitude of 90 percent of full scale (plus 2.5 volts to minus 2.0 volts). During the time that this pulse was present, the signal on channel 2 changed from minus 2.2 volts to minus 2.35 volts, indicating that channel 3 was operating at an apparent gain of 30 times the channel 2 gain.

As shown in figure 14-35, each geophone channel consists of a geophone, an input preamplifier, a low-pass filter, and a logarithmic compressor amplifier. The output of the logarithmic compressor feeds the instrumentation system. The logarithmic compressor is basically an inverting amplifier with exponential negative feedback. Two diode-connected transistors between the output and input of the amplifier supply the feedback. The first diode is used for positive-going and the second for negative-going input signals. The diodes for all three geophone channels (two per channel) are physically located in an oven which controls their temperature at 105° C.

NASA-S-71-1703

Figure 14-35.- Typical geophone channel.

24

EXTRACT

Apollo 14 Mission Report
April 1971

It is believed that the failure is in the logarithmic compression amplifier because signals are coupled into it through an input coupling capacitor. This capacitor would block any offset voltages from the preceding stages which would be required to drive the output off-scale high. Analysis indicates that the most probable cause of the problem is an intermittent open circuit in the diode feedback path. This would allow the amplifier input transistor to saturate, driving the output off-scale high. When signals large enough to drive the input stage out of saturation were present, the output would then respond and the output signal would not be compressed.

The experiment electronics uses "cordwood" construction of the type which has caused solder cracks in other equipment. Two copper paths conduct the feedback diodes to the logarithmic compressor amplifier. A solder crack in either path would then result in the data characteristics.

There are 10 such solder joints for each geophone (fig. 14-36): four on the oven terminal board, four on the mother board, one on the top board of the log compressor module, and one on the bottom board of the log compressor module. The one most likely to fail first is on the top board of the log compressor module. Continuity at the joint recovers as long as the crack closes during the lunar day.

NASA-S-71-1704
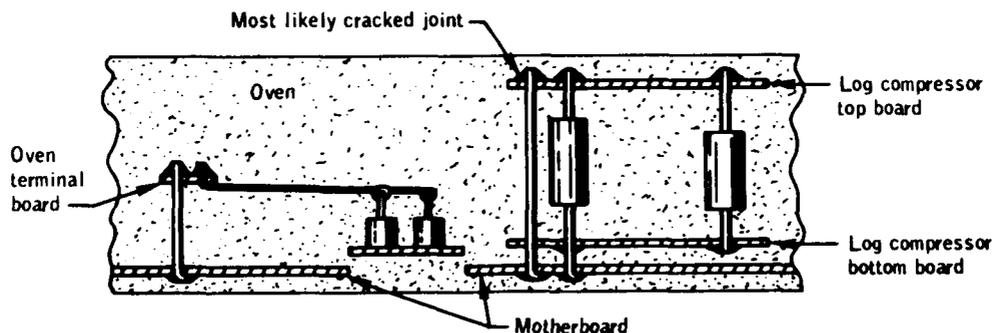
Figure 14-36.- Suspected cracked solder joints in amplifier.

Apollo 14 Mission Report
April 1971
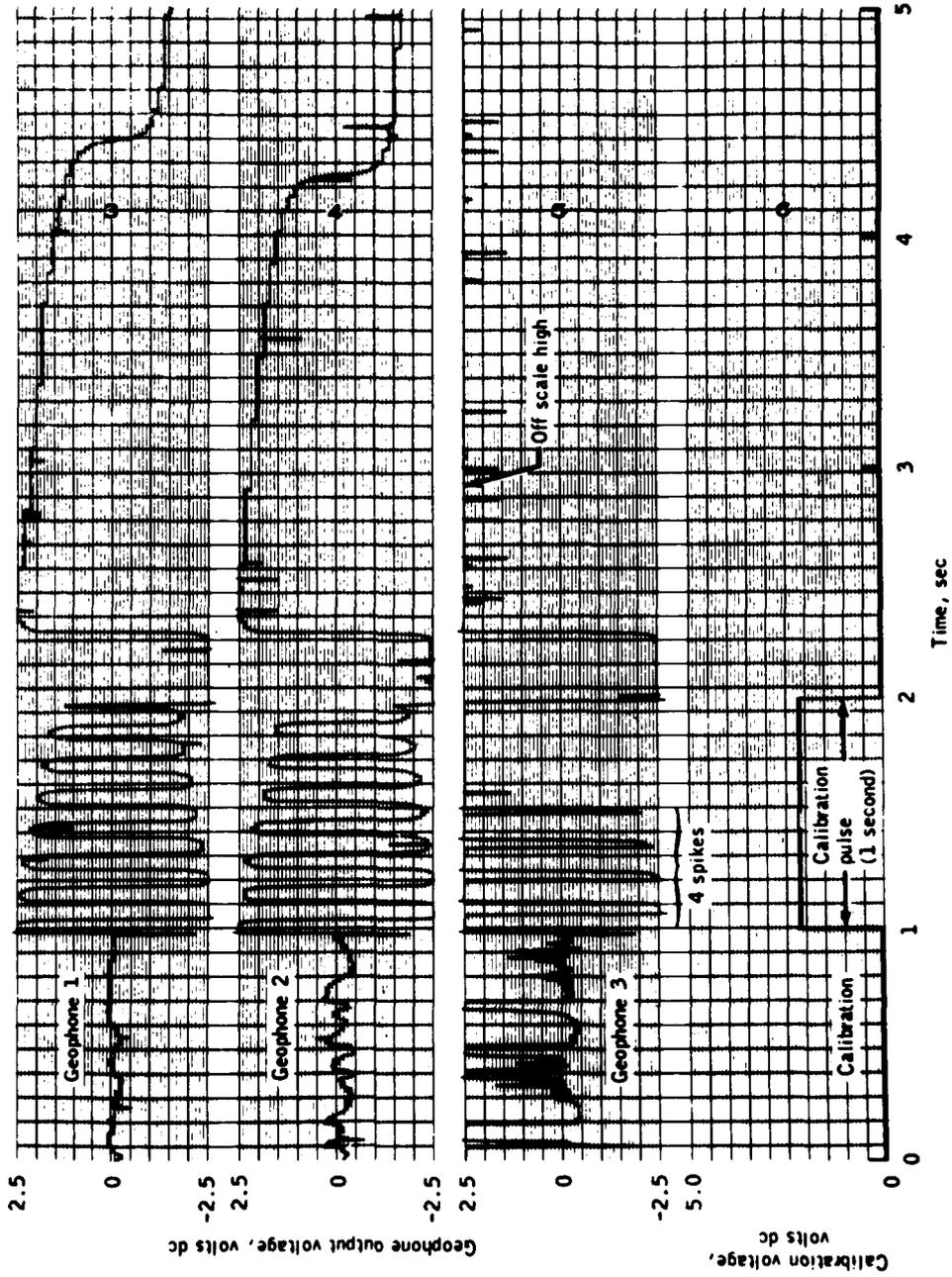
Figure 14-34.- Geophone calibration data.

EXTRACT

Apollo 14 Mission Report
April 1971

The log compressor modules for geophones 1 and 2 are of the same type construction. Since these are located slightly further from the oven than the one for geophone 3, the maximum temperature may not be quite as high. As a result, it may take longer for them to crack, if at all.

Systems testing included operational thermal cycling tests over the temperature range for lunar day and night. However, cracked solder joints are a function of time as well as temperature, and apparently the ground test cycle did not allow enough time for a creep failure. This equipment was designed and built prior to the time when it was found that cordwood construction with soldered joints was unsatisfactory.

A breadboard of the logarithmic compressor has been constructed, and the diode feedback loop will be opened to duplicate the experiment data. The mechanical design of the logarithmic compressor will be reviewed to determine the changes that must be made to prevent solder cracks on Apollo 16. The active seismic experiment is not carried on Apollo 15.

Procedural changes under consideration include operation of the oven to maintain compressor module temperature because the solder joint which is most likely cracked is in compression (stronger) at the higher temperature.

This anomaly is open.

Apollo 14 Problem and Discrepancy List
May 14, 1971

Italics indicate change from previous issue.

PROBLEM AND DISCREPANCY LIST

No. <u>ALSEP-18</u>

Statement of Problem:

Active seismic experiment no. 3 geophone data became erratic.

Discussion:

On March 26, the experiment was turned on in the listening mode (high bit rate) and geophone #3 was spiking to off-scale high. The calibration command was transmitted to all three geophone channels. Geophone #3 channel went off-scale high simultaneous with the application of the calibration pulse and stayed off-scale high for the remainder of the listening period. During the one second period when the calibration pulse was present, geophone #3 data showed four negative going pulses from off-scale high. Pulse widths were shorter than corresponding oscillations on geophones 1 and 2 and decreased from the first to the fourth. The characteristics of these pulses indicated that geophone #3 channel was operating at a higher gain than geophones 1 and 2 during the calibration period. Circuit analysis indicated that the problem had to be in the logarithmic compressor in the geophone #3 amplifier chain.

Signals are coupled into the logarithmic compressor through an input coupling capacitor which would block any dc voltage which would have to be present to drive the output voltage off-scale high for long periods (more than 1 or 2 minutes).

The logarithmic compressor is basically an inverting amplifier with exponential negative feedback. Two diode connected transistors between the output

(see continuation sheet)

Schedule:

		May 1	8	15
Data Review	Complete			
Analysis				
Tests (Identify in Note)				
Changes (Identify in Note)				

Notes:
1. Third lunar day data. 5 to 15 minutes of high bit rate data daily, April 4 - 12
2. Preliminary analysis April 1 - 8 - complete
3. Bench checks and analysis

Personnel Assigned:

J. Harris, Bendix, Geotech, Gadbois

Conclusions:

Apollo 14 Problem and Discrepancy List
May 14, 1971

Italics indicate change from previous issue.

PROBLEM AND DISCREPANCY LIST
CONTINUATION SHEET

No. ALSEP-18

Discussion:

and input of the amplifier supply the feedback. The first diode is used for positive going and the second for negative going input signals. The diodes for all three geophone channels (2 per channel) are physically located in an oven which controls their temperature at 105°C.

Analysis indicates that the most probable cause of the problem is an intermittent open circuit in the diode feedback path. This would allow the amplifier input transistor to saturate, driving the output off-scale high. When signals large enough to drive the input stage out of saturation were present, the output would then respond and amplifier gain would not be compressed.

The experiment electronics used "cordwood" construction of the type which has caused solder cracks in other equipment. Two copper paths conduct the feedback diodes to the logarithmic compressor amplifier. A solder crack in either path would then result in the data characteristics.

There are ten such solder joints for each geophone: four on the oven terminal board, four on the mother board, one on the top board of the log compressor module and one on the bottom board of the log compressor module. The one most likely to fail first is on the top board of the log compressor module. Continuity at the joint recovers as long as the crack closes during the lunar day.

The log compressor modules for geophones 1 and 2 are of the same type construction. Since these are located slightly further from the oven than the one for geophone 3, the maximum temperature may not be quite as high. As a result, it may take longer for them to crack, if at all.

A breadboard of the logarithmic compressor has been constructed and the diode feedback loop will be opened to duplicate the experiment data.

The active seismic experiment is not on Apollo 15.

Apollo 14 Problem and Discrepancy List
July 15, 1971

Italics indicate change from previous issue.

◈ = Closure date.

PROBLEM AND DISCREPANCY LIST

No. __ALSEP-18__

Statement of Problem:

Active seismic experiment no. 3 geophone data became erratic.

CLOSED

Discussion:

On March 26, the experiment was turned on in the listening mode (high bit rate) and geophone no. 3 was spiking to off-scale high. The calibration command was transmitted to all three geophone channels. Geophone no. 3 channel went off-scale high simultaneous with the application of the calibration pulse and stayed off-scale high for the remainder of the listening period. During the one second period when the calibration pulse was present, geophone no. 3 data showed four negative going pulses from off-scale high. Pulse widths were shorter than corresponding oscillations on geophones 1 and 2 and decreased from the first to the fourth. The characteristics of these pulses indicated that geophone no. 3 channel was operating at a higher gain than geophones 1 and 2 during the calibration period. Circuit analysis indicated that the problem had to be in the logarithmic compressor in the geophone no. 3 amplifier chain.

Signals are coupled into the logarithmic compressor through an input coupling capacitor which would block any dc voltage which would have to be present to drive the output voltage off-scale high for long periods (more than 1 or 2 minutes).

(see continuation sheet)

Schedule:

May
1   8   15

Data Review	Complete	
Analysis	Complete	
Tests (Identify in Note)	Complete	
Changes (Identify in Note)	None	◈

Notes:
1. Third lunar day data. 5 to 15 minutes of high bit rate data daily, April 4 - 12
2. *Mathematical analysis, May 11*
3. *Bench checks and analysis. Breadboard tests, May 31*
4. *Review, June 3*

Personnel Assigned:

J. Harris, Bendix, Geotech, Gadbois

Conclusions: *Problem was caused by an intermittent failure (open) in the positive going diode wired transistor in the log compressor for the no. 3 geophone. Transistor failure appears to be an isolated case rather than a generic condition.*

Apollo 14 Problem and Discrepancy List
July 15, 1971

Italics indicate change from previous issue.

PROBLEM AND DISCREPANCY LIST
CONTINUATION SHEET

No. <u>ALSEP-18</u>

Discussion:

The logarithmic compressor is basically an inverting amplifier with exponential negative feedback. Two diode connected transistors between the output and input of the amplifier supply the feedback. The first diode is used for positive going and the second for negative going input signals. The diodes for all three geophone channels (2 per channel) are physically located in an oven which controls their temperature at 105°C.

Mathematical analysis and breadboard tests show that the cause of the problem is an intermittent failure (open) in the positive going diode wired transistor. This allows the amplifier input transistor to saturate, driving the output off-scale high. When signals large enough to drive the input stage out of saturation are present, the output responds, and amplifier gain will not be compressed.

No previous failures of this type have been experienced during the development and test program. The collector of the intermittent transistor (2M2484-2B) is connected directly to the case without a lead. The emitter and base are connected from pin to chip by small aluminum leads which could possibly break and again make contact with temperature changes or by mechanical shock from nearby relay actuation.

The experiment electronics uses "cordwood" construction of the type that has caused solder cracks in other equipment however, a cracked solder joint in the cordwood construction, in this case, will not produce the flight results. Apparently some inadvertent strain relief configuration in the cordwood construction has averted a cracked solder joint, - at least, for the time being.

The next mission scheduled for the active seismic experiment is Apollo 16.

MSC-07638

APOLLO 14 MISSION

Anomaly Report No. 6

ACTIVE SEISMIC EXPERIMENT GEOPHONE 3 DATA ERRATIC

PREPARED BY

Mission Evaluation Team

APPROVED BY

.

Owen G. Morris

Owen G. Morris
Manager, Apollo Spacecraft Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
December 1972

ACTIVE SEISMIC EXPERIMENT GEOPHONE 3 DATA ERRATIC

STATEMENT OF ANOMALY

During the high-bit-rate listening mode period on March 26, 1971, the geophone 3 data showed intermittent spikes going off-scale high. When the calibration signal was applied to all three geophones, the geophone 3 data went off-scale high for the remainder of the listening period. A similar response was observed during the succeeding weekly listening mode periods.

SYSTEM DESCRIPTION

The active seismic experiment consists of an array of three geophones, a thumper with 21 initiators (detonators), a mortar package with four rocket-launched grenades, a central electronics assembly, and connecting cabling. The three geophones are deployed on the lunar surface in a straight line at 150-foot intervals and are used to translate physical surface movement into electrical signals. The thumper initiators, fired at intervals along a path parallel to the geophone line, and the mortar grenades, propelled to distances of 500 to 5000 feet away from the geophone line, artificially produce seismic waves which are detected by the geophones. In addition, the geophones monitor naturally produced lunar seismic activity in the 3 to 250 Hz range.

The construction of a geophone is shown in figure 1. A coil of copper wire (seismic mass) is suspended in a magnetic field by flat cantilever springs which also guide the coil vertically. The magnetic field is produced by a permanent magnet frame. Relative motion between the coil and the frame generates an output voltage across the coil, and this voltage is supplied through contacts of the calibrate relay (fig. 2) to the input of a preamplifier. The preamplifier output is then fed through a low-pass filter to a logarithmic compression circuit. Signals are coupled into this circuit through an input coupling capacitor which would normally block any d-c voltage that must be present to drive the output voltage off-scale high for long periods (more than 1 or 2 minutes). The output signal from the logarithmic compression circuit (the logarithm of the input signal) is supplied to the telemetry system.

The logarithmic compression circuit provides adequate resolution when small signals are present, but also has the capability to respond to the expected 60- to 80-dB signal range. The circuit is basically an inverting amplifier with exponential negative feedback. Two diode-connected transistors, in parallel, between the output and input of the amplifier supply
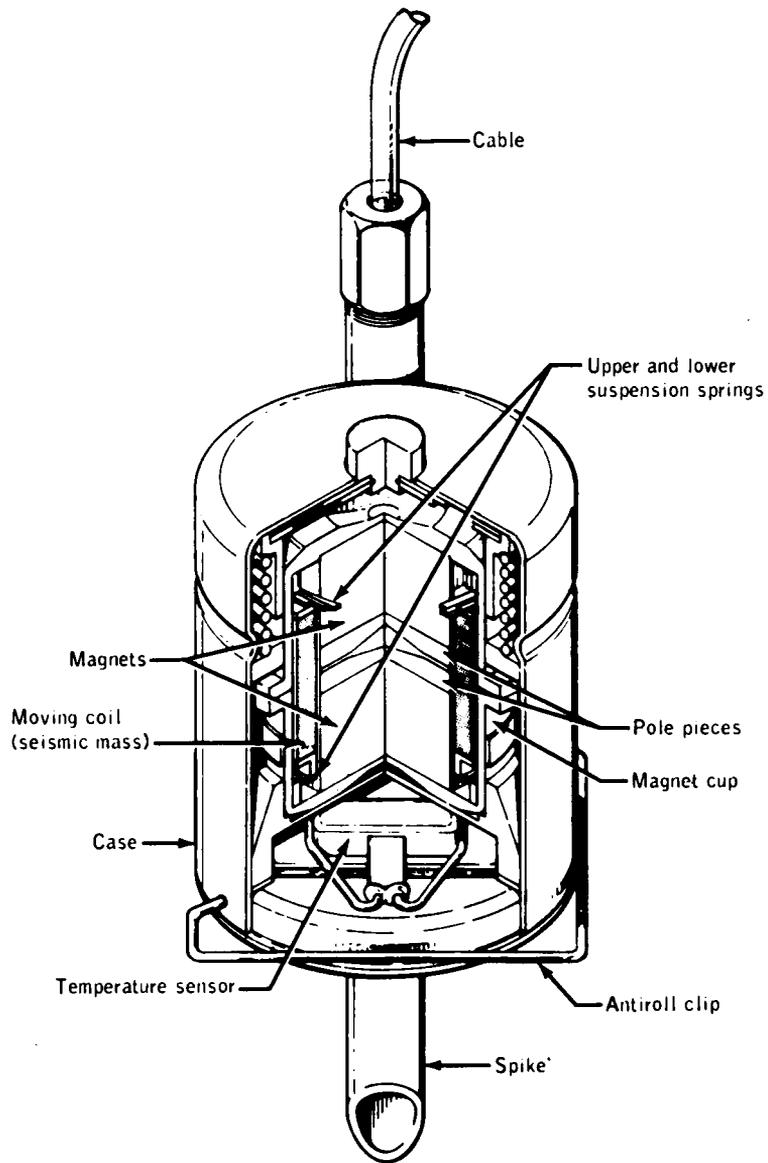
Figure 1.- Cutaway view of geophone.

the feedback signal (fig. 2). One of the transistors is used for the positive-going input signals, and the other is used for the negative-going input signals. The feedback transistors for all three geophone channels (two per channel) are physically located in an oven that maintains their temperature at 105° C.

The geophone is calibrated by applying a fixed-amplitude, 1-second current pulse to the geophone coil. The current forces the coil to move to a new balance position. The coil will oscillate about the new position until the oscillations damp out. The geophone resonant frequency, sensitivity, and damping factor can then be determined from the damped oscillation waveform generated within the coil.

DISCUSSION

The active seismic experiment was initially turned on in the thumper mode with the central station in the high-bit-rate mode during lunar surface extravehicular activities on February 5, 1971. Vibrations from each of 13 thumper firings were received by each of the three geophones and the data were transmitted to earth. The experiment was then commanded to the standby mode, and was to remain in that mode except for 30 minutes of operation each week in the listening mode and the high-bit-rate mode. System operation was normal during the first six weeks; however, during the seventh-week monitoring cycle (March 26, 1971), at about lunar midnight, the geophone 3 data were spiking off-scale high.

All three geophone channels were calibrated, and the geophone 3 channel went off-scale high simultaneously with the application of the calibration pulse (fig. 3). The channel stayed off-scale high for the remainder of the listening period. During the 1-second period when the calibration pulse was present, the geophone 3 data showed four negative-going pulses from off-scale high. Pulse widths were shorter than corresponding oscillations on geophones 1 and 2, and decreased in width from the first to the fourth pulse. The characteristics of these pulses indicate that the geophone 3 channel was operating at a higher gain than geophones 1 and 2 during the calibration period, and that its output was biased off-scale high.

A failure in the geophone, preamplifier, or filter could produce a bias offset; however, the compressor input coupling capacitor would block the bias offset and the output signal would not remain off-scale high. Had the input capacitor shorted, the output would be shifted, but not off-scale-high. The fault, therefore, must have been within the logarithmic compressor circuit (fig. 2).
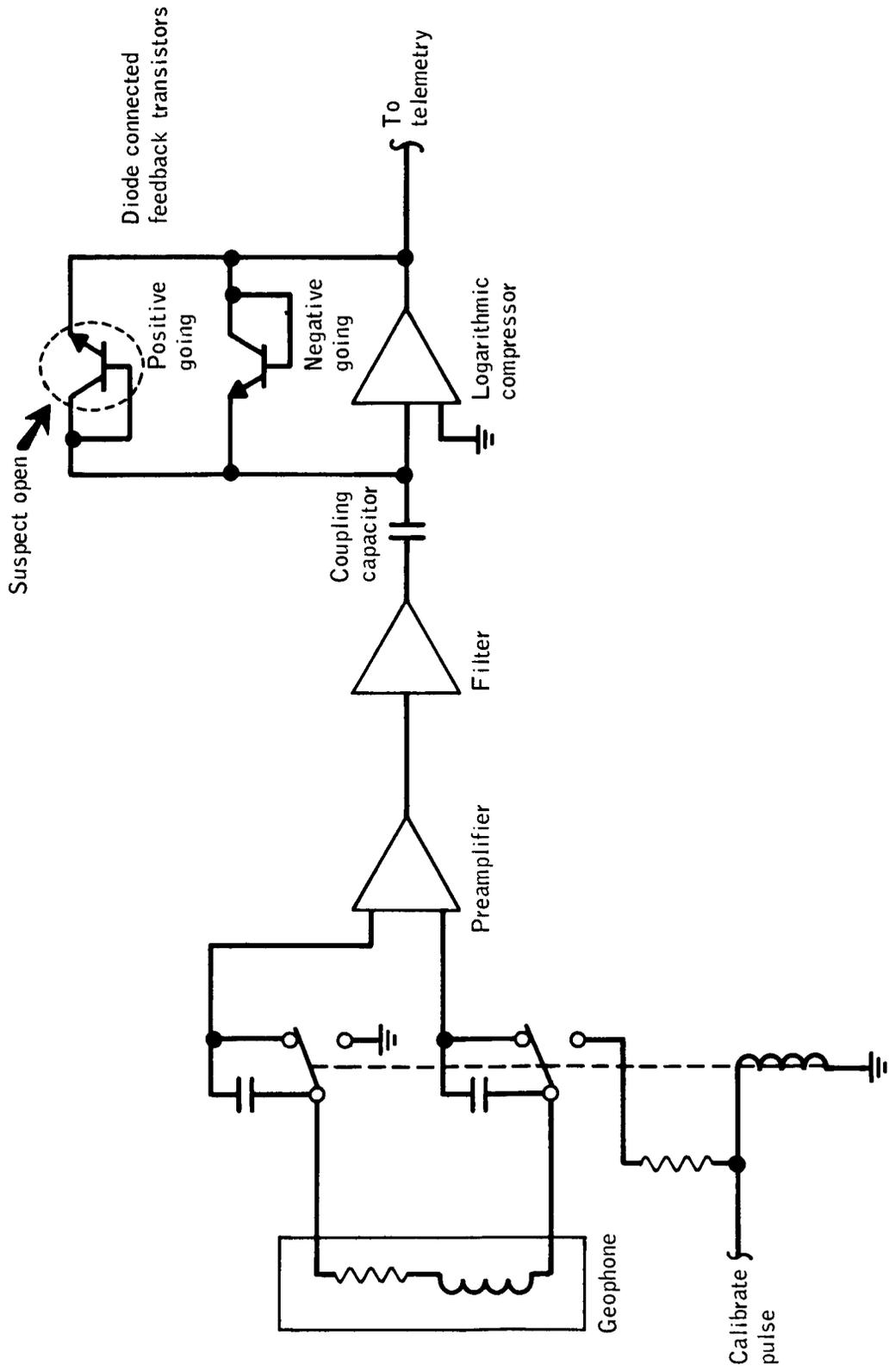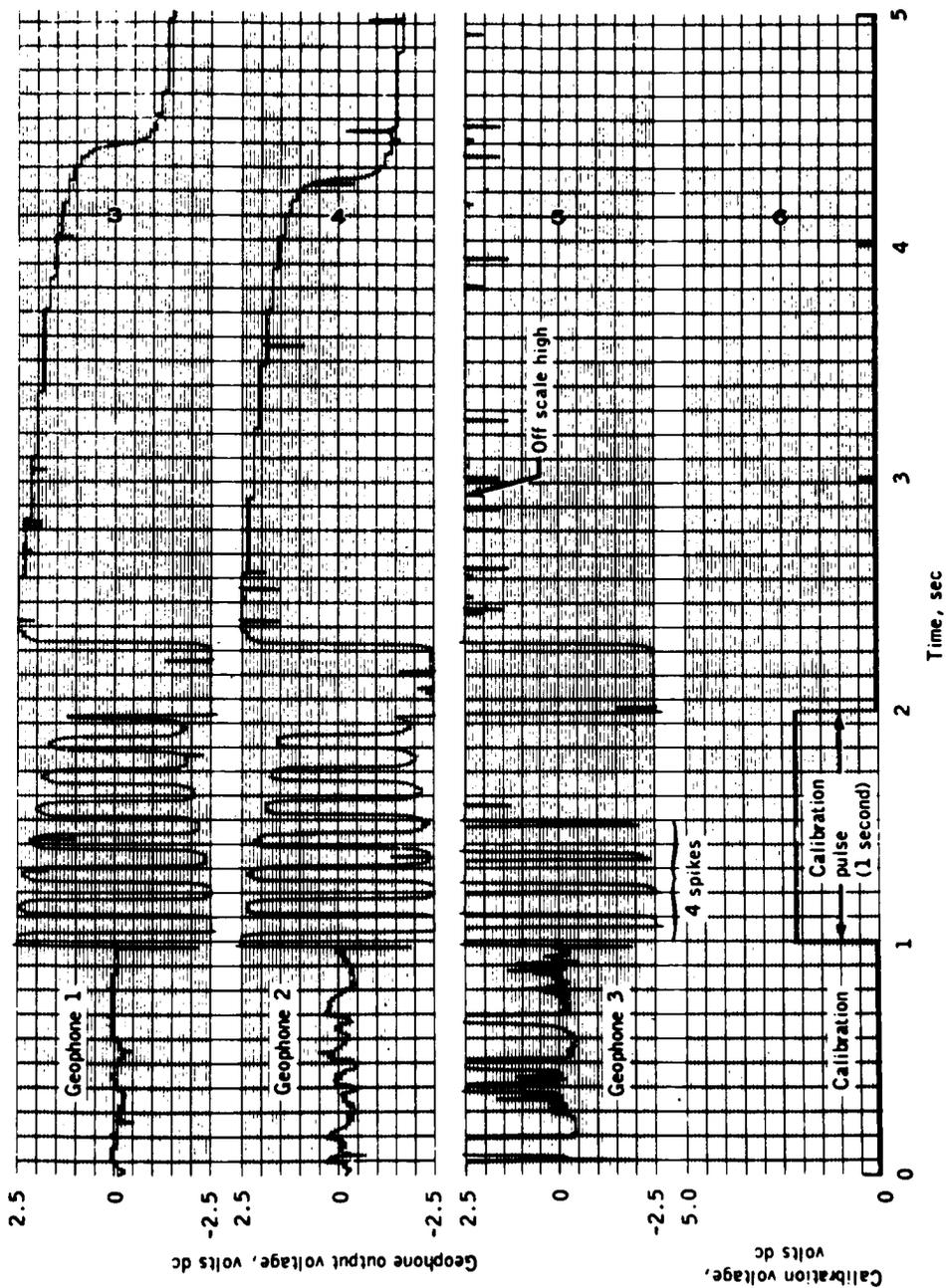
Figure 2.- Geophone and signal conditioner.

Figure 3.- Geophone calibration data on March 26, 1971.

The failure was duplicated by opening the positive-going diode-wired transistor. This saturated the amplifier input transistor, and drove the output off-scale high. When signals large enough to drive the input stage out of saturation were present, the output responded and the amplifier gain was not compressed until the output voltage was driven to zero. The part of the signal which went below zero voltage was then compressed by the negative-going feedback diode and the narrow pulses shown in figure 3 were produced.

The transistor emitter and base are connected from pin to chip by small aluminum wires (fig. 4.). A break in one of these wires, or a partial or complete bond failure between the wire and the chip would cause the open circuit. The elements could also make contact again to produce the intermittent condition when mechanically shocked by nearby relay actuation.

No failures of this type occurred during the development and test program. To determine if a generic defect existed, a group of ten transistors from the same lot were examined internally and subjected to thermal shock and bond pull tests as well as electrical tests. The transistors were tested within the manufacturer's specification limits and also beyond specification limits and were found to be satisfactory.

With a significant event, such as firing the mortar, the negative side of geophone 3 is capable of distinguishing the arrival of the event signal. Calculations of new circuit constants for an open in the positive-going transistor make the channel usable for interpretation of discernable negative data.

The experiment was flown on Apollo 16 without any changes to the active seismic detection system, and has performed without a recurrence of the Apollo 14 problem.

CONCLUSIONS

An intermittent failure (open) most likely occurred in the positive-going diode-wired transistor in the logarithmic compressor for geophone 3, resulting in the intermittent loss of data from the geophone.

CORRECTIVE ACTION

No corrective action was taken since the history of the transistor indicated that a generic problem did not exist.
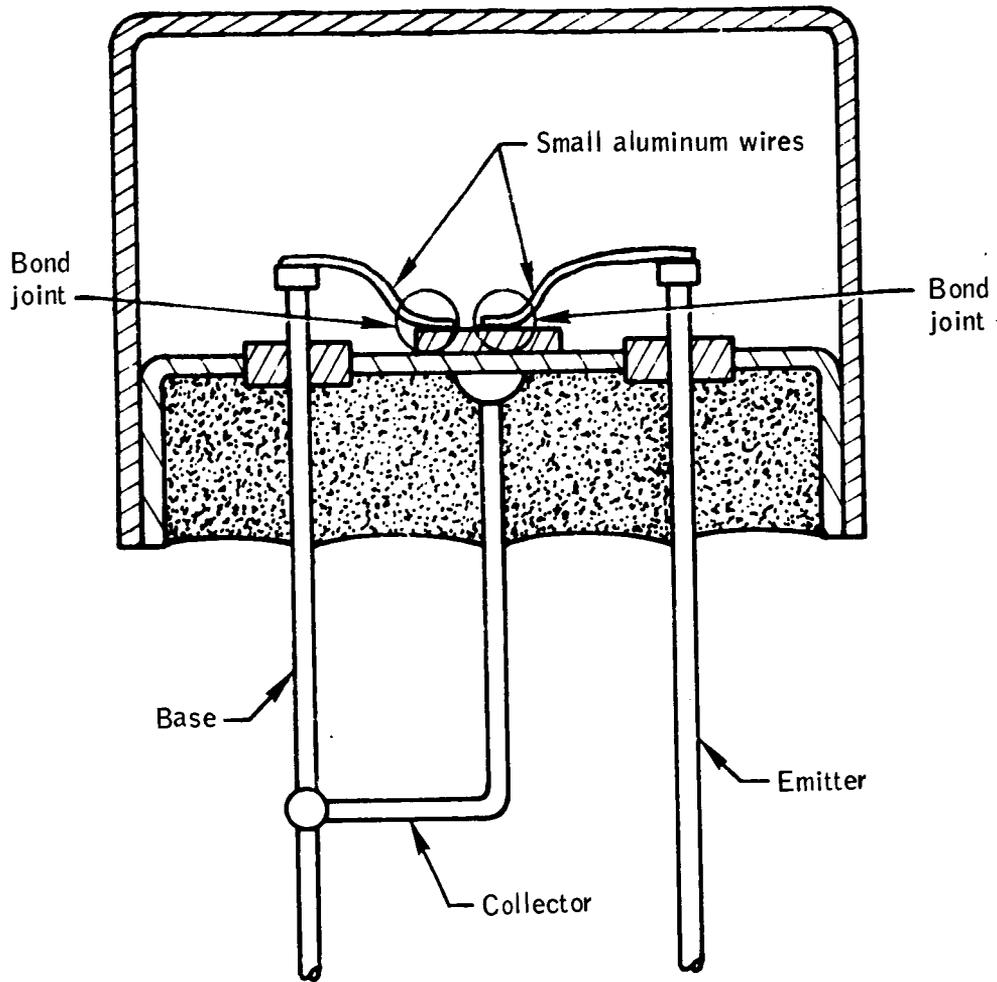
Figure 4.- Diode-wired 2N2484-2B transistor.

APOLLO 7 FAILURE OF LOWER EQUIPMENT BAY FLOODLIGHTS

The loss of the primary floodlights in the Apollo 7 command module lower equipment bay was an example of crew observation of an off-nominal condition as well as of a preflight procedure problem reflecting a lack of understanding of the life-limiting details of some components. The flight hardware was mounted in the returned command module and thus was available for examination and testing. The procedures employed in determining the cause and the necessary corrective action are apparent in the reports that follow. Extracts from Problem and Discrepancy List reports are not included because at the time of the Apollo 7 mission, this part of the reporting system had not yet been formalized and did not extend past the time of the mission report.

EXTRACT

Apollo 7 Mission Report
December, 1968

11.21 FAILED FLOODLIGHTS

Sometime during the mission, both of the primary lamps failed in the lower equipment bay floodlights. Postflight investigations revealed that the lamp filaments (cathodes) had completely vaporized, which caused a diode to short in each lamp driver.

A new lamp has a start-up voltage of about 500 volts. As the lamp ages, the cathode deteriorates, thus increasing the start-up voltage, which can go as high as 1800 volts. The diode is rated at 700 volts; therefore, it would burn out. The rate of cathode deterioration is dependent on the operating voltage. Maximum deterioration rate occurs when the dimming rheostat is halfway between the full-dim and full-bright positions.

Tests are in progress to establish lamp life at the critical operating voltage. Normally, these lamps should operate 2000 hours.

Procedural changes are being made to use only the secondary lamp on full bright during ground tests, and consideration is being given to installing flight lamps just prior to the countdown demonstration test. No hardware changes are planned. This anomaly is still open.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APOLLO 7
ANOMALY REPORT NO. 3

FAILURE OF LOWER EQUIPMENT BAY FLOODLIGHTS

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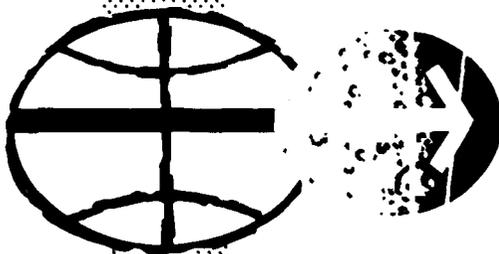
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
FEBRUARY 1969

APOLLO 7

ANOMALY REPORT NO. 3

FAILURE OF LOWER EQUIPMENT BAY FLOODLIGHTS

PREPARED BY

Mission Evaluation Team

APPROVED BY

George M. Low

George M. Low
Manager, Apollo Spacecraft Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

February 1969

FAILURE OF LOWER EQUIPMENT BAY FLOODLIGHTS

STATEMENT

Both of the primary lamps in the lower equipment bay floodlights failed during the mission.

DISCUSSION

Two floodlights, mounted on the X-X foot struts, provide illumination of the work areas and panels in the lower equipment bay. Each floodlight fixture consists of a primary and secondary fluorescent lamp and a lamp driver circuit (fig. 1).

The primary lamps in both fixtures failed during the mission. Postflight investigations revealed that the filament (cathode) in each lamp had vaporized, shorting a diode in the associated lamp driver circuit. A new lamp has a starting voltage of about 500 volts, but as the lamp is used, the cathode is expended. As the lamp approaches its life limit of 2000 hours, the starting voltage increases and may reach values as high as 1800 volts; therefore, the diode in the lamp driver circuit, rated at 700 volts, could short.

The rate of cathode expenditure is related to the operating voltage, with the expenditure rate being maximum when the dimming rheostat is about halfway between the dim and full-bright position. The floodlights on the Apollo 7 spacecraft had a minimum of 400 hours of use prior to launch, and the operating intensity was not determined. The Apollo 8 spacecraft had approximately 100 hours of use prior to launch, and no failures were experienced during that mission.

Tests were performed with a new lamp operated at a critical voltage level for maximum cathode expenditure. Although the cathode heaters failed after 80 hours, the lamp could be turned off, restarted, and dimmed until the test was terminated after 648 hours.

CONCLUSION

The primary lamps probably failed because of excessive operation time in the dimmed position prior to flight.
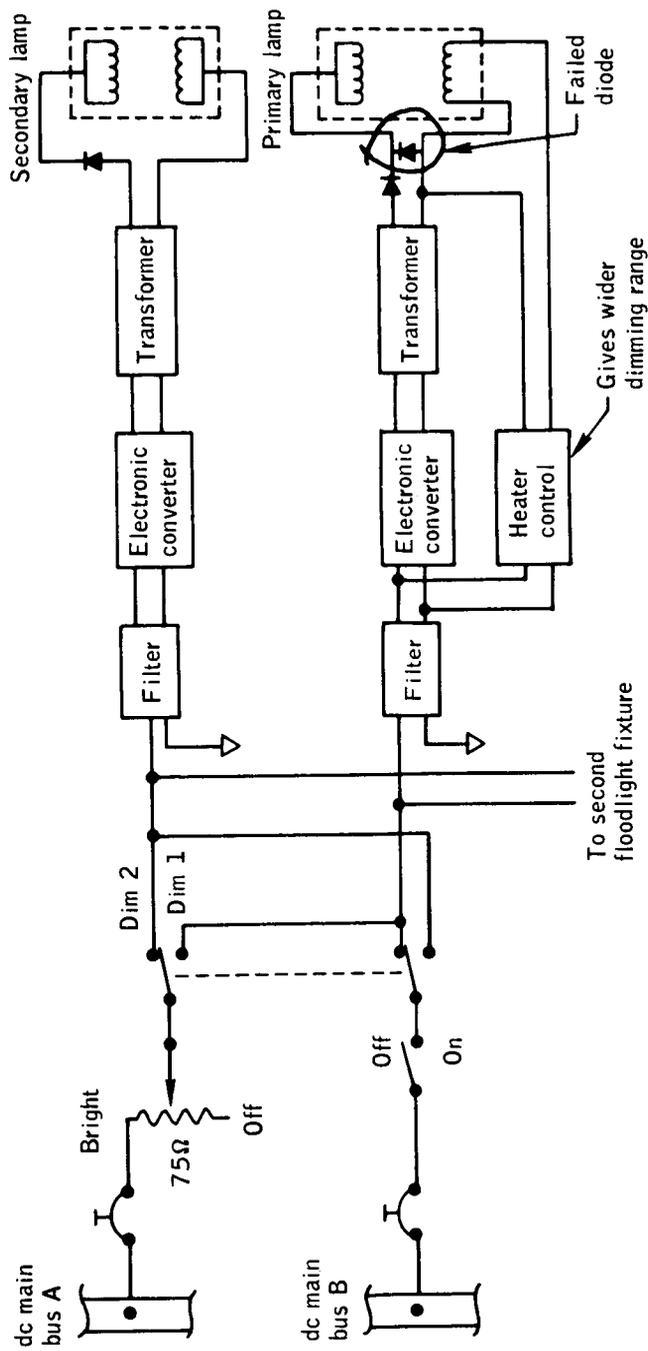
Figure 1.- Floodlight circuit.

45

APOLLO 10 AND 11 FUEL CELL CONDENSER EXIT-TEMPERATURE OSCILLATIONS

Fuel cell condenser exit-temperature oscillations had been observed on several missions. When they recurred during the Apollo 10 mission, the need for an in-depth investigation to better understand the mechanism and the significance of the oscillations was apparent. In this example, the flight hardware could not be returned for examination because it was mounted in the service module. The service module separates from the command module at the time of entry and is not recoverable.

The anomaly resolution analysis procedures and the results are presented in the report that follows. Extracts from Problem and Discrepancy Lists and mission reports are not included because the anomaly resolution applies to several missions and because the investigation was subsequent to individual mission-oriented activities.

MSC-02426

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APOLLO 10 AND 11

ANOMALY REPORT NO. 1

FUEL CELL CONDENSER EXIT TEMPERATURE OSCILLATIONS

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

APRIL 1970

MSC-02426
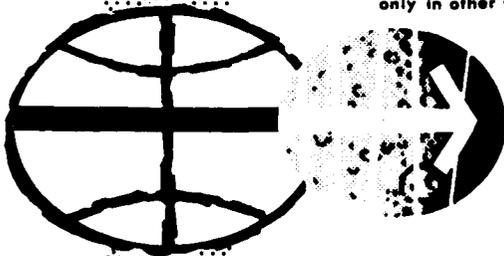
APOLLO 10 and 11

ANOMALY REPORT NO. 1

FUEL CELL CONDENSER EXIT TEMPERATURE OSCILLATIONS

PREPARED BY

Mission Evaluation Team

APPROVED BY
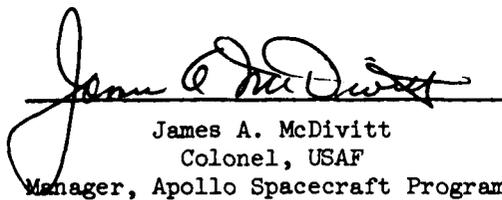
James A. McDivitt
Colonel, USAF
Manager, Apollo Spacecraft Program

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
April 1970

FUEL CELL CONDENSER EXIT TEMPERATURE OSCILLATIONS

STATEMENT OF ANOMALY

During the Apollo 10 flight, the condenser exit temperature for fuel cell 2 experienced limit-cycle oscillations of from 15° to 20° F full amplitude while in lunar orbit. Review of the flight data revealed the presence of a periodic disturbance throughout the flight, and analysis showed this disturbance was the trigger for the oscillations. The disturbance was typified by a rapid 1.5° to 2° F drop in condenser exit temperature with a slow recovery to the initial value and occurred every 3 to 8 minutes (fig. 1). The Anomaly Summary Section of the Apollo 10 Mission Report (MSC-00126) describes the disturbances and oscillations in detail.

Fuel cell 2 condenser exit temperature was also periodically disturbed during the entire Apollo 11 flight (fig. 2) but did not experience the oscillations observed in Apollo 10. A further review of available data shows the presence of a similar disturbance on either fuel cell 2 or 3 (one affected fuel cell per flight) during Apollo 7, 8, and 9. As a result, an in-depth investigation was conducted to identify the cause of the disturbance and its significance in terms of future inflight fuel cell performance. Three essentially independent investigations of these disturbances were performed by North American Rockwell, Pratt and Whitney, and the NASA Manned Spacecraft Center. The findings of these investigators were discussed in detail in meetings at the Manned Spacecraft Center on September 11 and 12, 1969, and the combined results of these analyses, are presented herein.

DISCUSSION

An intensive analysis of the available data, particularly from Apollo 10 and 11, resulted in the following observations as to the disturbance and its cause.

a. Apollo 11 data indicate the secondary bypass valve (fig. 3) did not move as a result of the periodic disturbance; this observation is based on the slow recovery time (on the order of 4 minutes) for condenser exit temperature following each disturbance. If the valve had moved, full recovery should have taken place in a matter of seconds. The Block II retrofit secondary coolant bypass valve (Block I valve poppet) may have contributed to this behavior; however, the valve characteristics do not support this conclusion, since the response times of the two valves (Block II and Block II retrofit) are virtually the same for a condenser exit temperature disturbance of the type experienced in flight.

b. Apollo 10 data indicate the secondary coolant bypass valve did respond to the disturbance, based on the rapid condenser exit temperature recovery rate after each disturbance, the slight condenser exit temperature overshoot observed on most of the Apollo 10 disturbances and the fact that oscillations were observed.

c. Apollo 7, 8, and 9 data indicate the presence of a disturbance throughout each flight with period and amplitude similar to the disturbance observed on Apollo 10 and 11.

d. Apollo 11 data indicate the condenser exit temperature disturbance characteristic was either altered or its presence was questionable during and immediately after major burns of significant duration, indicating a sensitivity to longitudinal acceleration.

e. The condenser exit temperature disturbance has only been observed under zero-g flight conditions.

f. Fuel cell performance was not affected by the condenser exit temperature disturbance nor, in the case of Apollo 10, by the resultant oscillatory behavior.

g. Only one fuel cell, either in position 2 or 3, has experienced the disturbance on each flight.

h. Apollo 10 and 11 data show a definite relationship between the frequency of the disturbance and the electrical load on the affected fuel cell (fig. 4).

Each of the following items was investigated prior to a detailed analysis of the possible causes of the disturbance and each produced negative findings.

a. Variations or similarities of secondary loop (water/glycol) plumbing for all affected fuel cells, including line routings, loop volume, and component calibrations

b. Variations or similarities of all component and powerplant acceptance and checkout test results of affected fuel cells, including line routings, loop volume, and component calibrations

c. Variations or similarities of the physical properties (surface tension and viscosity) of Type II water/glycol solutions from different lots

d. Variations or similarities of fuel cell and spacecraft interface hardware configuration regarding affected fuel cells.

Subsequent to Apollo 11, all possible causes of the disturbance were listed to serve as a basis of investigation for the three analytical teams The disturbance characteristics were also listed, and each possible cause was examined for conformance with these characteristics. Table I summarizes the possible causes and characteristics. A discussion of each of these possible causes is presented in the following paragraphs.

Possible Causes Eliminated

The following possible causes of the temperature oscillations were determined to be invalid.

Slug of cold water/glycol from the radiator.- A slug of cold water/glycol from the radiator with a radiator outlet temperature drop rate greater than 50° F/minute could cause the condenser exit temperature disturbance. As the slug entered the condenser, a drop in the condenser exit temperature on the order of 2° F would result. However, there is no reason to expect a slug of cold water/glycol to occur periodically in the radiator and exhibit a period which varies with load as observed on Apollo 10, nor would this cold slug explain the slow condenser exit temperature recovery observed on Apollo 11. Since no indication of such a radiator response was observed on any of the affected fuel cell coolant loops, this possible cause was eliminated.

Blockage of secondary regenerator cold side (hot side of secondary coolant bypass valve).- Blockage of the cold side of the secondary regenerator, as might result from bubble or sludge entrapment, could produce the disturbance in the condenser exit temperature. Such blockage would result in an incorrect hot/cold mixture ratio at the secondary bypass valve, with the colder fluid from the radiator reaching the condenser and causing a loss of coolant regeneration capability. This type of blockage is unlikely, since, to exhibit the proper rate of decrease in the condenser exit temperature, it must occur suddenly with flow blockage greater than 90 percent. In addition, the passages would have to be opened slowly to exhibit the recovery characteristic noted after the Apollo 11 disturbance. Bubble entrapment would be expected to build up slowly and exhibit a rapid recovery as the bubble passed through the regenerator. The periodic variation could possibly result from the sludge or bubble circulating around the loop. Only a minor change in the disturbance period would be expected with changing load (full regenerator versus full bypass flow), on the order of 1 minute difference between the two flow modes. The period variation with load observed on Apollo 10 was approximately 4 to 8 minutes and cannot be explained by regenerator cold side blockage.

Sticking secondary coolant bypass valve.- A secondary bypass valve which was restricted in movement could possibly cause a condenser exit temperature disturbance, since an incorrect mixture ratio could cause a cold slug of water/glycol to reach the condenser. There is, however, no apparent reason for the regularity unless sludge is circulating in the loop. A sticking valve would also require a corresponding change in electrical load or radiator outlet temperature in order for the bypass valve to be incorrectly positioned near the zero regeneration point. This possible cause requires that the valve be incorrectly positioned and restricted in travel at the time of each disturbance. Since there is no reason for the valve to ever reach the necessary position under the observed operating conditions, this possible cause was rejected.

Temporary blockage of coolant (water/glycol) side of condenser.- Temporary condenser blockage (20 to 25 percent) on the coolant side, as with a bubble or sludge entrapment, could produce the disturbance. Again, the periodicity of the occurrence could be explained by the bubble or sludge circulating through the loop, if the apparent load dependency as noted on Apollo 10 and 11 is discounted. However, the condenser exit temperature should increase slightly as the effective condensing area is reduced and then drop as the core becomes unblocked when the contaminant moves through. An increase in condenser exit temperature prior to the disturbance has not been consistently observed, with only a few such instances on Apollo 10 which are considered to be within the noise level of the data. Additionally, test and performance experience has shown the secondary bypass valve to be sooner affected by contamination than other coolant loop components.

Hydrogen pump shutdown and restart.- Intermittent stop-start operation of the hydrogen pump can exhibit the proper temperature disturbance characteristic. Testing has demonstrated extremely rapid drops in condenser exit temperature for both pump shutdown and startup. However, the regularity of the observed disturbance is inconsistent with a randomly intermittent hydrogen pump which most probably would fail completely early in the flight. Also, there is no reason why the pump would operate in this mode in zero-g operation only.

Coolant flow variations.- A slow decrease in coolant flow followed by an abrupt increase, such as might result from filter plugging and unplugging, could produce the characteristic disturbance. Periodicity might be explained by contaminant circulation. A coolant flow increase of 20 to 30 pounds per hour would cause a 2° to 3° F condenser exit temperature change. However, this change would be observable in radiator delta temperature (inlet/outlet), a condition which was not observed. Variations of the period with load are also not explained for this possible cause.

Water discharge blockage.- Loss of water discharge capability, as could be caused by high water back pressure or an intermittently sticking discharge valve, was considered as a possible cause of the disturbance. This cause, however, would not be expected to demonstrate the observed disturbance characteristics. The primary regenerator hot-side temperature and condenser inlet temperature would be reduced as the water flashed to steam in the regenerator. More significantly, rapid temperature changes in the hydrogen loop would be damped before the effects could be observed in condenser exit temperature changes, largely because of the overwhelming thermal capacitance of the primary coolant fluid system. A high water back pressure would be manifested in all three fuel cells because of the common water discharge manifolding. Additionally, a "pH Hi" indication would be expected, as was observed during a thermal vacuum test when the water discharge line froze and blocked. No "pH Hi" indications were observed during any flight when the condenser exit temperature disturbance was present.

Erratic primary bypass valve.- Erratic control by the primary bypass valve could affect condenser exit temperature, since a sudden opening would tend to increase condenser exit temperature and a sudden closure would lower the exit temperature. However, recent tests have shown that hydrogen loop temperature perturbations in the vicinity of the cell stack are well damped prior to reaching the condenser. Also, an erratic primary valve would not be expected to produce a periodic disturbance, nor is there any reason why such behavior would not also be observed during ground operation.

Restricted secondary coolant bypass valve flow.- Temporary blockage or restriction of flow through the secondary bypass valve followed by sudden release could produce the observed disturbance characteristic. Such blockage could be caused by circulating contamination, probably in a gelatinous form. Experience has shown that contamination in the coolant loop is more likely to collect in the vicinity of this valve (as during Apollo 7 and 9) than anywhere else in the loop. In theory, this mass of contamination would periodically accumulate in the vicinity of the valve, generally in the bypass flow passage of the valve and, when released, would cause a sharp decrease in condenser exit temperature because of the suddenly increased bypass fluid flow.

This phenomenon is considered to be a rather remote possibility for two reasons: (a) if the bypass flow were slowly being restricted, as it would probably be for contamination in the loop, an increase in condenser exit temperature above the normal operating value should be observed, but this was not the case unless it is assumed that the low condenser exit temperature (at the lower end of the disturbance) was the steady operating value corresponding to the valve position, and (b) the relationship of the disturbance period to load cannot be explained. Also,

the similarity of the disturbance among the five affected fuel cells tends to negate the contamination theory, since circulating contamination would not be expected to produce nearly identical results on each affected powerplant. On Apollo 7 and 9, slow condenser exit temperature excursions to abnormal values (not periodic disturbances) were attributed to restricted secondary coolant bypass valve travel resulting from loop contamination. However, none of the fuel cells with restricted bypass valves displayed any evidence of a periodically disturbed condenser exit temperature. Additionally, the Block II retrofit valve on Apollo 11 was known to be less sensitive to contamination than the standard Block II valves but was affected in the same manner as the Block II valves; this fact implies that some phenomenon other than contamination is the cause of the disturbance.

Most Probable Cause

One possible cause remained that could not be eliminated from the list; that is, condenser water retention and periodic release (a water slug from the condenser). The water slug meets more of the criteria that describe the condenser exit temperature disturbance than does any other possible cause.

Condenser water retention on the hydrogen side.- Blockage of the condenser core on the hydrogen side could produce the proper disturbance characteristics. Condensed water would have to collect and be contained either in or near the condenser exit by surface tension forces. This water would then be released periodically in fairly large quantities as the accumulated water became sufficient to overcome retaining forces. If the water were retained at the core, the temperatures would essentially equal the water/glycol inlet temperature. The subcooled water reaching the temperature probe would cause the temperature drop indicated in the data, and, if the water were retained on this probe because of surface tension until gradually blown off or evaporated, the slow recovery characteristic observed in flight could be explained. Since the condenser exit temperature sensor is downstream of the bypass valve Vernatherm sensor, the released slug of water might also impinge on the valve sensor and, if large enough and cold enough, would cause valve motion. Periodic recurrence would result from the accumulation of water in the condenser as a result of surface tension until some critical level was reached and the water was again released. Dependence of the disturbance period on electrical loads would result from water production increasing with increasing load. The rate of change of water condensation is known to bear a near-instantaneous response relationship with step load changes.

Examination of sequence photography of the hydrogen exit plenum, with the condenser operating in a horizontal position during ground tests, has

shown that surface tension plays a large part in removal of water condensate, even in one-g operation, and that the water does not leave the condenser core in a uniform fashion. Normal one-g condenser operation is in a vertical position relative to the launch pad. In these films, relatively large quantities of water were retained in some of the hydrogen passages and on the coolant passage walls at the end of the condenser core by surface tension and frequently joined together before being released as large globules into the exit plenum (fig. 5). A definite variation was observable in wetting characteristics across the end of the condenser. These results, along with the fact that a slug of water out the condenser can produce all of the characteristics of the disturbance in zero g, make this possible cause the most likely candidate of those considered.

The question of why the disturbance has not been present on every fuel cell if a water slug is the cause remains to be answered. Analyses indicate that variations in condenser passageways (hydrogen side), surface wetting properties, and/or hydrogen loop flow rates between individual powerplants allow this phenomenon to take place only on those particular powerplants where combinations of these variables are exactly right. In fact, figure 4 illustrates a difference in characteristics between two affected powerplants. From the visual data available in the condenser test films, it is reasonable to assume that water does not depart the condenser in uniformly sized droplets on any powerplant but rather, in zero g, comes off the condenser in globules of varying sizes at intervals which depend on such factors as surface tension (wettability), loop flow rate, condenser passage area (cross-section), braze uniformity, etc. If it is further assumed that a critical combination of these conditions is required to produce a water slug of a magnitude sufficient to manifest an observable condenser exit temperature disturbance, then it is likely that only a certain number of fuel cells will exhibit the disturbance. Of the 15 Block II fuel cells flown to date, five have displayed the characteristics. If a water slug is the cause of the disturbance, there is no reason to expect a change in the ratio of affected fuel cells, since no process changes were made.

The appendix to this document presents the results of an analysis of the probable condensed water behavior and its effect on condenser exit temperature.

CONCLUSIONS

From all indications, the Apollo 11 fuel cell 2 secondary bypass valve (a Block II retrofit) did not move as a result of the periodic condenser exit temperature disturbance.

If the cause of the disturbance is a water slug from the condenser, the incidence rate of the condenser exit temperature disturbance should not change significantly.

Neither the temperature disturbance nor the temperature oscillations have shown any degradation in fuel cell performance. No hardware changes will be made; however, procedures have been developed to effectively damp these oscillations, should they occur.

TABLE I.- POSSIBLE CAUSES AND CHARACTERISTICS OF DISTURBANCE

Characteristics of disturbance

1. Periodic

2. Occurred only under zero-g conditions altered or eliminated by major propulsive maneuvers

3. Condenser exit temperature typically dropped $1.5°$ to $3.0°$ F in 2 to 10 seconds

4. Period of disturbance related to fuel cell load

5. Rapid condenser exit temperature recovery for Block II bypass valve (<20 seconds)

6 Slow condenser exit temperature recovery for Block II retrofit by-pass valve (~4 minutes)

Possible causes

1. Cold water/glycol slug from radiator

2. Secondary regenerator cold side blockage

3. Secondary coolant bypass valve motion restriction (sticking)

4. Condenser coolant blockage

5. Intermittent hydrogen pump operation

6. Intermittent coolant pump operation

7. Water discharge blockage

8. Erratic primary bypass valve

9. Slugging of condenser water

10. Restricted secondary coolant bypass valve flow
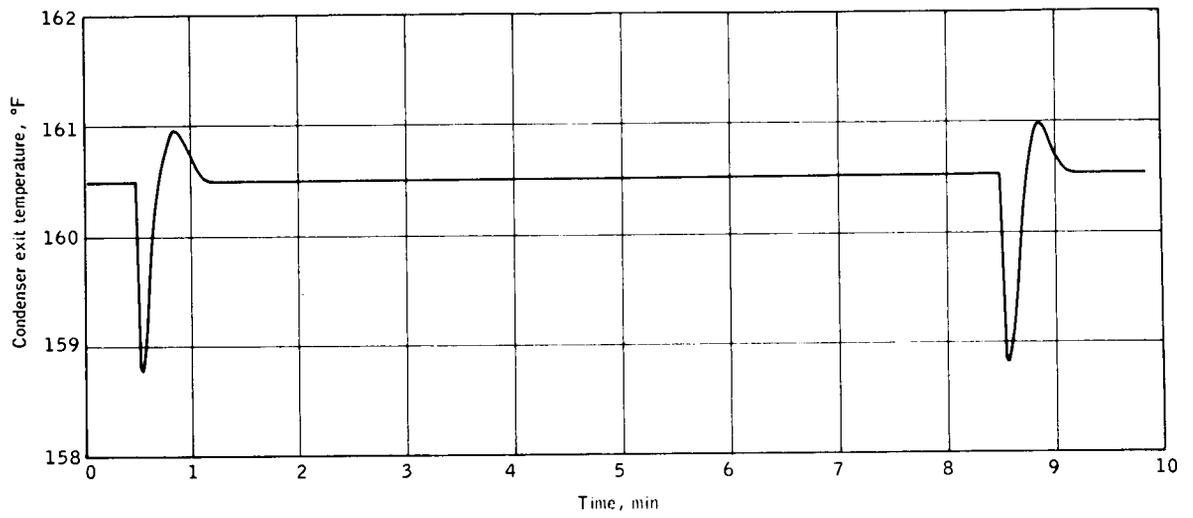
Figure 1.- Apollo 10 condenser exit temperature disturbance.
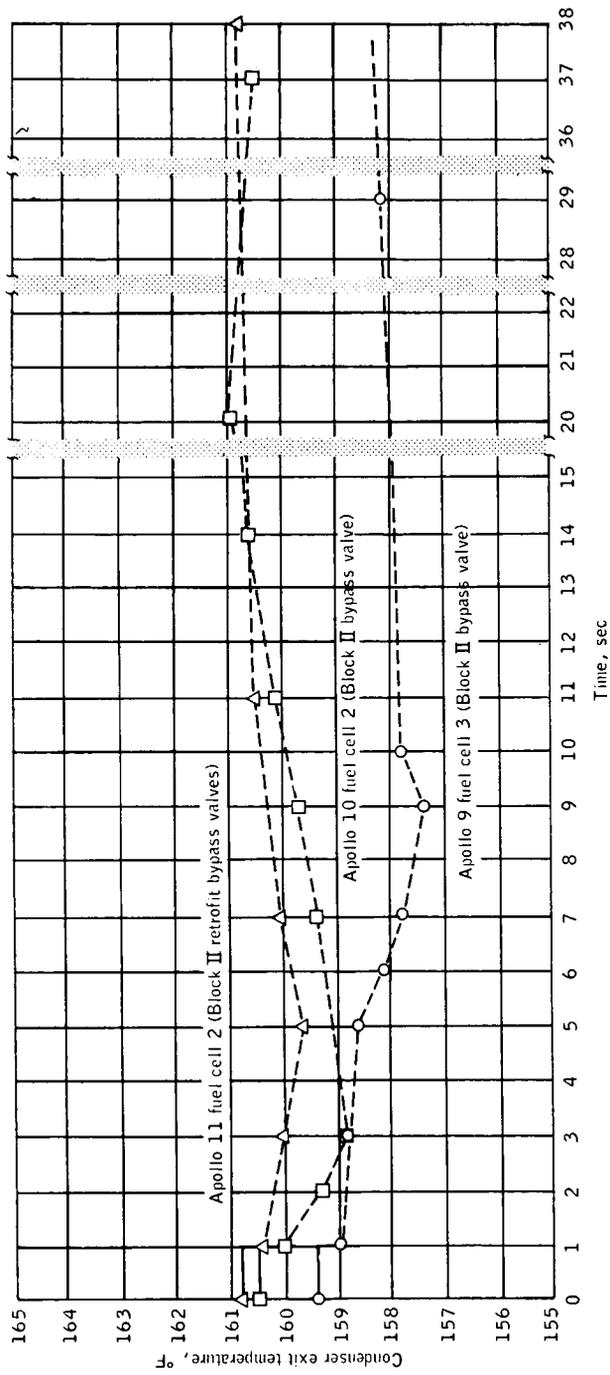
Figure 2.- Typical condenser exit temperature disturbance.
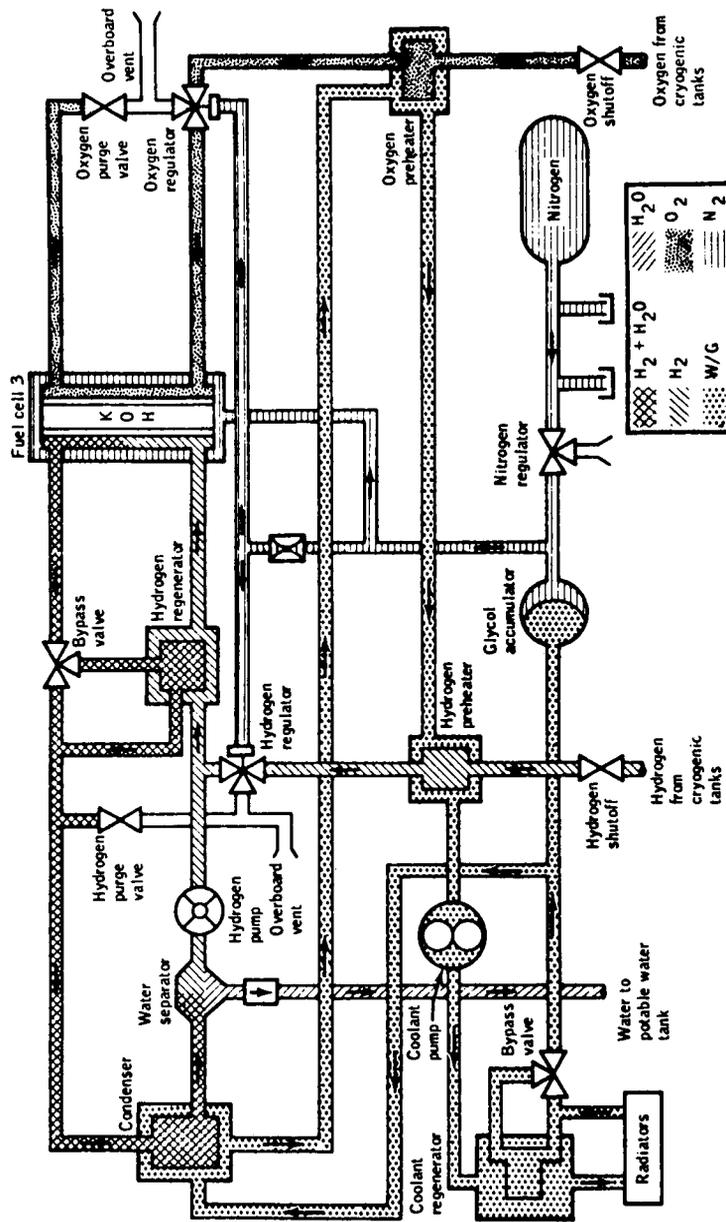
Figure 3.— Fuel cell schematic.
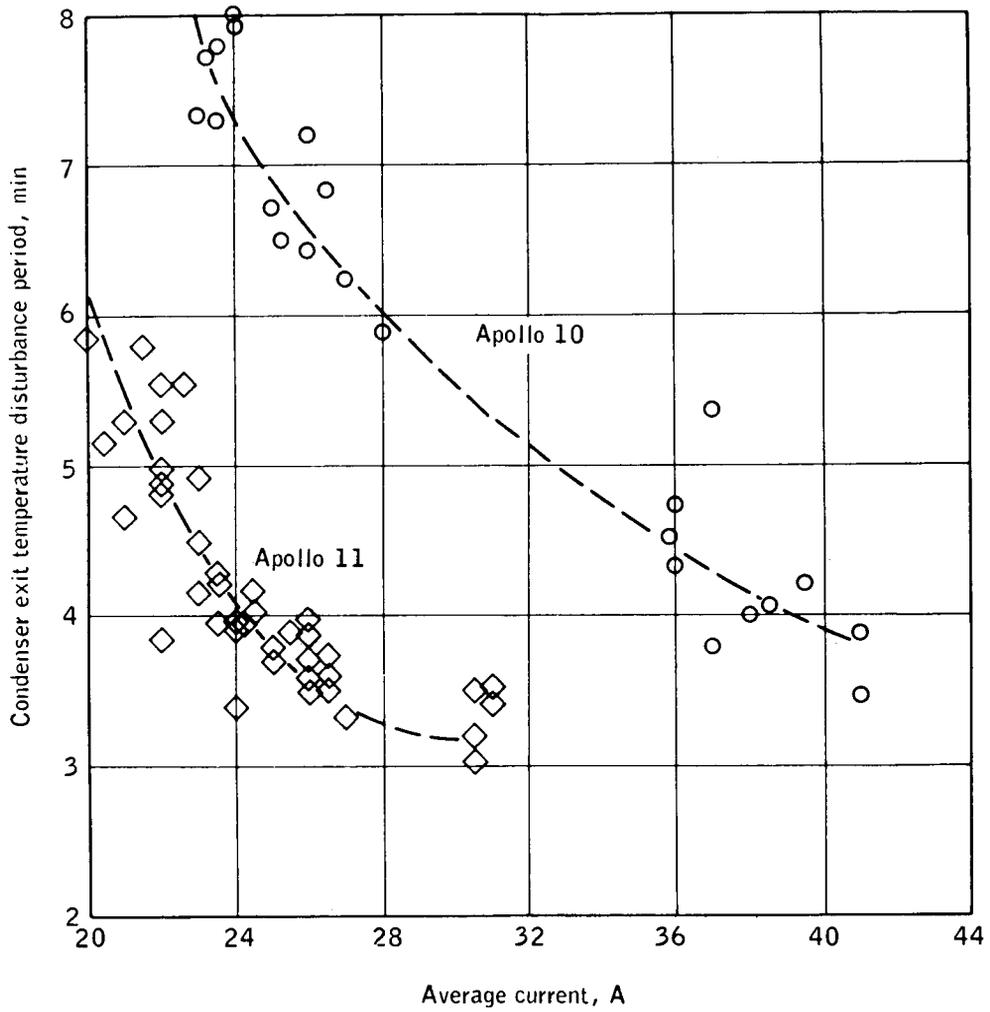
Figure 4.- Load-period relationship.
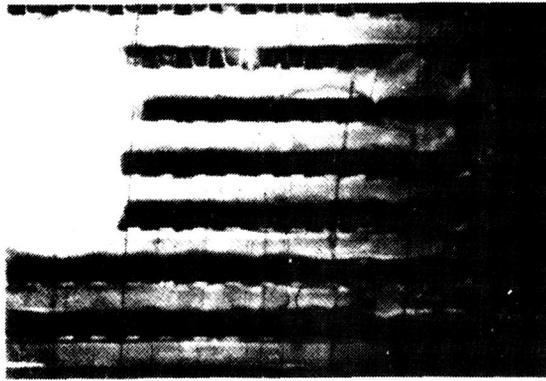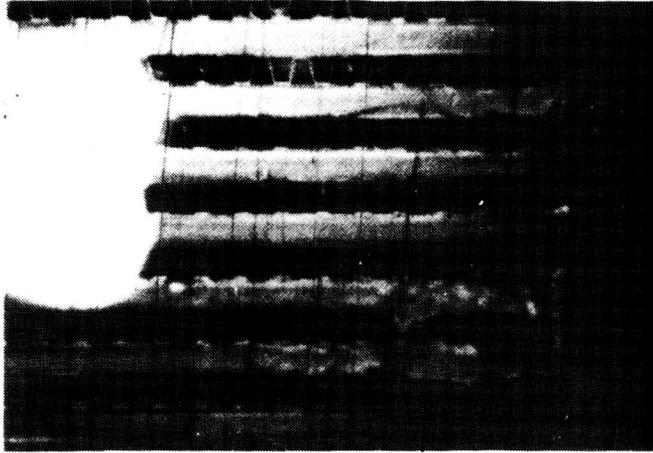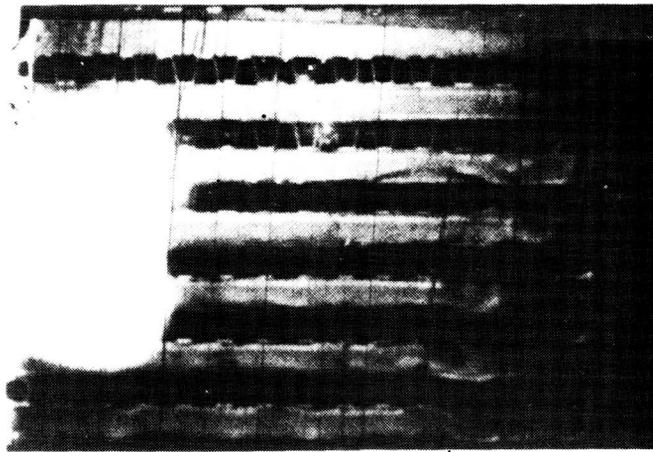
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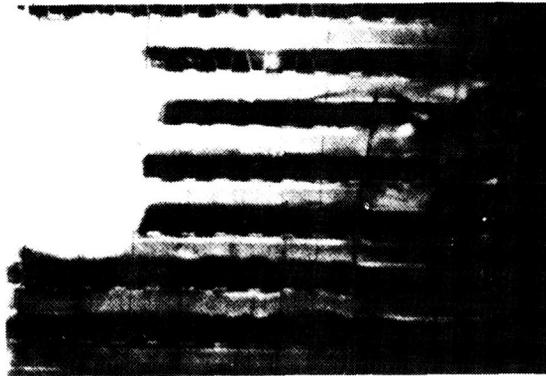
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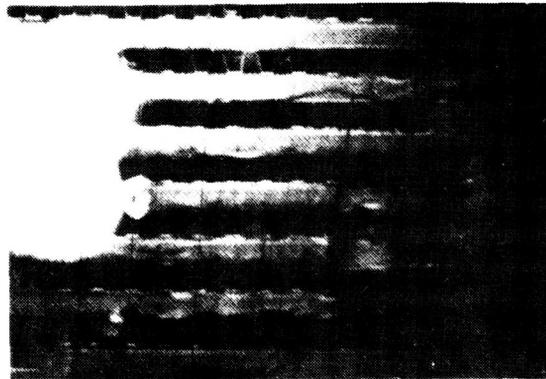
(c)

Figure 5.- Sequence photographs of hydrogen
exit plenum.

(d)

(e)

Figure 5.- Concluded.

APPENDIX

Water Condensate Behavior Analysis

Several theories have been investigated to explain the abnormal
variation of primary side condenser exit temperature. The most promis-
ing of these is a water buildup at the condenser with resultant slug
flow of subcooled condensate downstream to the temperature sensor and
the Vernatherm sensing element of the secondary bypass valve.

By calculating an effective radius of the core passages in the
condenser and assuming perfect wetting, a balance of surface tension
and pressure forces shows that a pressure differential of approximately
0.02 psi (1.96 cm H_2O) is required to clear one condenser core passage
after it has been filled with water. A test performed to measure the
gas pressures needed to blow the water out showed the average required
pressure differential to be 1.65 cm H_2O. This test was repeated on
45 tubes, and the extremes ranged from 1.55 to 1.75 cm H_2O. The fric-
tional pressure drop, on the other hand, was calculated for normal con-
ditions (clean passage) to be approximately 0.002 psi, or an order of
magnitude less than the pressure drop required to overcome capillary
forces. This would lead to the hypothesis that the small trapezoidal
passages within the condenser core fill up randomly (due to the random
nature of condensation sites) until sufficient pressure head is built
up to overcome the capillary forces, at which time the slug is blown
free. Sequence photography proves that this does indeed occur.

A cross-section of condenser core geometry is shown in figure A-1.
The coolant and condensate sections alternate, leaving a solid end-strip
of metal between each condensate layer. In a one-g test, sequence photog-
raphy shows that as the condensate accumulates at the tube ends, some
tubes become totally filled with water. When enough tubes become filled,
dynamic pressure forces push the expanding water globules out of the
condenser and into the exit plenum area. Even after the surface tension
forces within the tube are overcome, the additional capillary action of
the end strips tends to accumulate condensate on these strips. This ac-
cumulated condensate could not run off easily in the one-g test, due to
the barrier created by brazing the end plates to the core. Hence, even
in one g, all end strips can become completely covered with water during
normal operation with the condenser in a horizontal position. In zero g,
this effect would be even more pronounced, allowing much thicker layers
of water to be built up on the end of the condenser. The thickness of
these layers would build up until the combination of random pressure
fluctuations in the gas stream and viscous shear stresses at the water-
gas interface become sufficient to force globules of condensate from the
condenser. A test showed that very large globules can accumulate, even

in a one-g environment. An attempt was made to calculate the size of these globules and to correlate their transport frequency with fuel cell load. This attempt was futile because the pressure fluctuations are completely random, and the variations in core geometry due to brazing and fin shape distortion are impossible to calculate.

Large condensate globules leaving the condenser collect on the solid end strips at the glycol inlet to the condenser and could be subcooled as much as 20° F below the normal 160° F saturation temperature if allowed to remain long enough. In zero g, when a subcooled globule leaves the condenser, most of it will be clinging to the walls of the transfer tube (upper view of fig. A-2), since it will tend to collect in the exit manifold as shown in the lower view. It will then proceed downstream until it comes to the enlarged area for the Vernatherm, or valve sensing element (fig. A-3). If the condensate layer is sufficiently thick, contact will be made between the Vernatherm fins and the condensate, and the wetting properties of the fin-tube geometry will cause the condensate to cover, or attempt to cover, the entire exposed surface area of the Vernatherm element. If, on the other hand, the condensate layer is not sufficiently thick to cause adhesion to the Vernatherm element, it will be forced downstream by the viscous shearing stresses at the liquid-gas interface until it reaches the temperature sensor. Average clearance between the end of the temperature sensor probe and the tube wall is 0.19 (±0.02) inch. This clearance can vary considerably, however, with positioning of the probe angle at assembly. Vernatherm element-to-wall clearance is typically 0.1 inch. As at the Vernatherm, if the condensate layer is sufficiently thin, it will not touch the sensor. If, however, the layer exceeds a certain critical thickness, the capillary action of the condensate on the sensor will cause the water to almost immediately engulf the sensor probe (fig. A-3, lower view), which is very much smaller than the Vernatherm element. It should be emphasized that each fuel cell will have a different critical thickness between the tip of the sensor and the tube wall, depending on the tolerances at the mounting assembly of the sensor.

The following is a proposed mechanism to explain the anomalous condenser exit temperature behavior. In zero g, for a fuel cell with a very small critical thickness at the temperature-sensing element, subcooled condensate buildup occurs until a globule of water moves downstream of the condenser. Assume that the thickness of the condensate layer is not sufficient to cause adhesion at the Vernatherm element, due to the enlarged flow area for the Vernatherm, but is thick enough to engulf the temperature sensor. For the extreme case of 20° F subcooled condensate, the sensor temperature will immediately begin dropping at the rate of about 5° F/sec, which is greater than the rate seen in flight. Depending on the size of the liquid globule, the temperature will drop until the dynamic pressure forces of the gas stream blow it off the sensor, or until the heat transfer between the gas stream and the water-coated sensor allows the sensor probe to begin its recovery. After the condensate

is blown off, the temperature recovery is much slower than the drop, due to the much smaller heat transfer coefficient between the gas and the sensor. The detected variation in condenser exit temperature will be similar to that shown in figure A-4 (upper view). The temperature drop and subsequent recovery is on the order of seconds; whereas the time between disturbances varies inversely with the current and is on the order of several minutes.

For this case the temperature sensor will produce telemetry data showing temperature variations, but in reality the valve poppet position, and hence the bypass ratio, never changes.

In the case of a service propulsion firing, a momentary gravity field is created in a direction coincident with the downward flow of condensate through the condenser. This, in effect, cleans the tube walls by flushing the condenser entirely of condensate. The resulting very large subcooled condensate globule affects not only the temperature sensor but also the Vernatherm element and causes the valve to react accordingly. The resulting variation in condenser exit temperature is shown in figure A-4 (lower view).
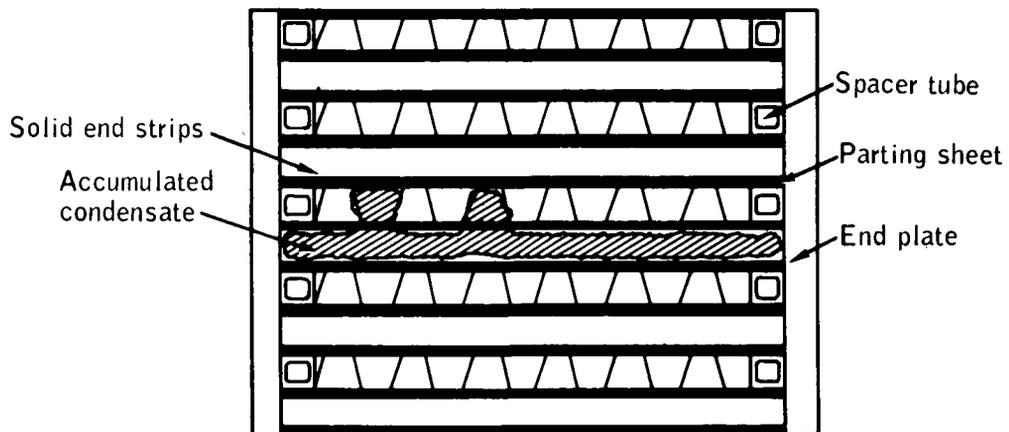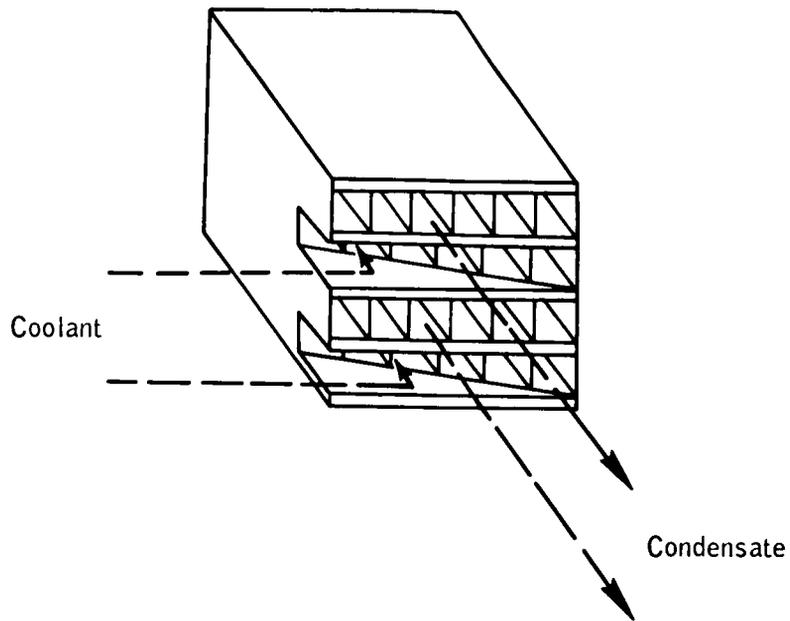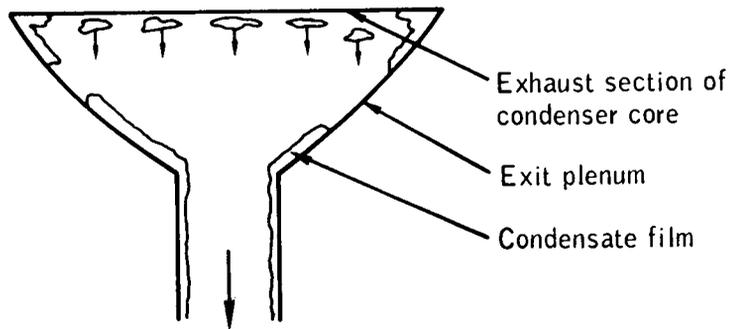
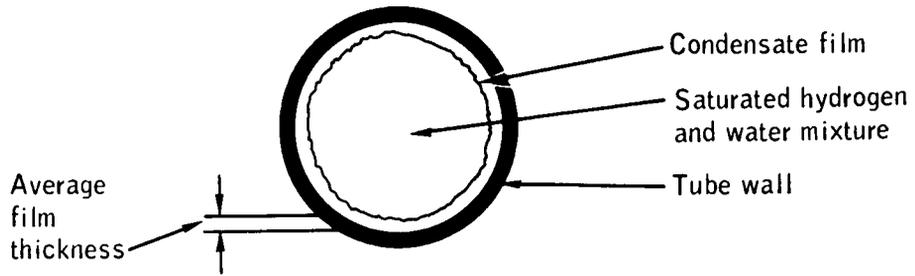Figure A-1.- Condenser core geometry.

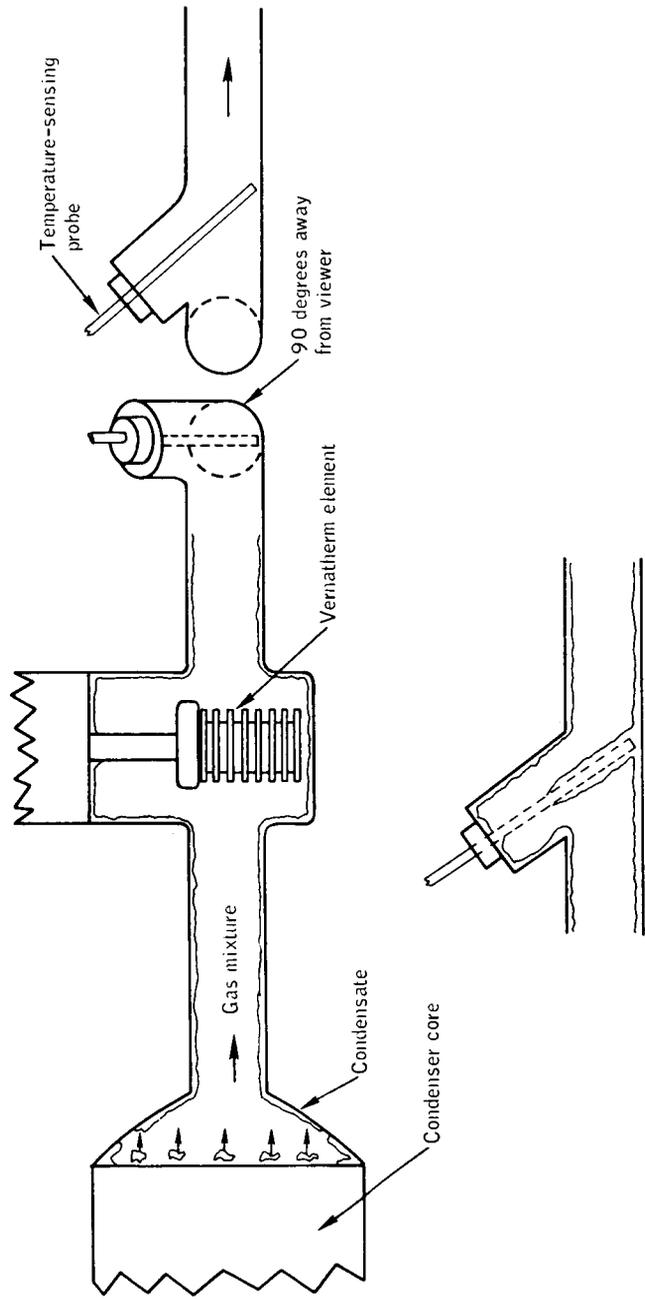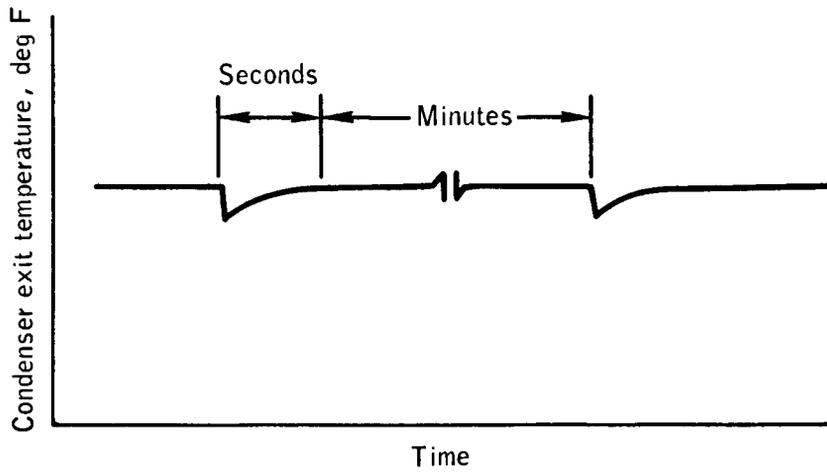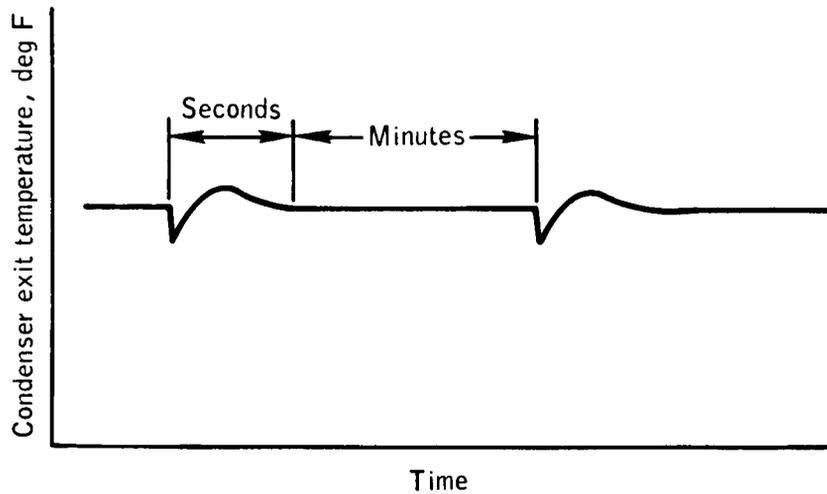Figure A-2.- Primary side condenser exit geometry.

Figure A-3.— Flow-stream geometry downstream of condenser.

(a) Disturbance of the first type.

(b) Disturbance of the second type.

Figure A-4.- Variations in condenser exit temperature resulting from condensate slug flow.