APOLLO 13 MISSION REVIEW

HEARING

BEFORE THE

COMMITTEE ON
AERONAUTICAL AND SPACE SCIENCES
UNITED STATES SENATE

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APOLLO 13 MISSION REVIEW

TUESDAY, JUNE 30, 1970

United States Senate,
Committee on Aeronautical
and Space Sciences,
Washington, D.C.

The committee met, pursuant to call, at 10:05 a.m., in room 235, Old Senate Office Building, Senator Clinton P. Anderson (chairman) presiding.

Present: Senators Anderson, Stennis, Holland, Curtis, Goldwater, and Smith of Illinois.

Also present: James J. Gehrig, staff director; Everard H. Smith, Jr., Dr. Glen P. Wilson, Craig Voorhees, and William Parker, professional staff members; Sam Bouchard, assistant chief clerk; Donald H. Brennan, research assistant, and Mary Rita Robbins, clerical assistant.

Opening Statement by the Chairman

The Chairman. The hearing will come to order.

Today the committee will continue its review of the Apollo 13 mission initiated on April 24, 1970, and will hear testimony on the findings of the Apollo 13 Review Board and the status of the Apollo program.

Dr. Thomas O. Paine, Administrator of NASA, accompanied by NASA manned space flight officials, Dr. Dale D. Myers, Associate Administrator for Manned Space Flight, and Dr. Rocco Petrone, Apollo Program Director, will testify on NASA actions to be taken with respect to the findings and recommendations of the Apollo 13 Review Board, on NASA plans for modifying the Apollo hardware and on plans for resumption of the Apollo flight program.

Mr. Edgar M. Cortright, Director of NASA's Langley Research Center, who is Chairman of the Apollo 13 Review Board, will present a brief summary highlighting the Review Board activities and provide any additional information that may have developed from tests in process when the Board report was released.

Also accompanying Dr. Paine today is Dr. Charles D. Harrington, Chairman of the NASA Aerospace Safety Advisory Panel. Dr. Paine will submit for the record a copy of a letter he received from Chairman Harrington giving the Panel's comment on the procedures and findings of the Apollo 13 Review Board. Dr. Harrington will not present a statement but is present to respond to questions committee members may have regarding the Panel's oversight of the activity of the Review Board.

If there is no objection, I will have chapter 5 of the report of the Apollo 13 Review Board placed at an appropriate point in the record.

This chapter contains the findings, determinations, and recommendations of the Board resulting from several weeks of intensive investigation into the cause of the failure which necessitated aborting the Apollo 13 mission.

The CHAIRMAN. Senator Smith is not here at the moment. Go ahead, Dr. Paine.

(Chapter 5 referred to above is as follows:)

CHAPTER 5—FINDINGS, DETERMINATIONS, AND RECOMMENDATIONS

PART 1. INTRODUCTION

The following findings, determinations, and recommendations are the product of about 7 weeks of concentrated review of the Apollo 13 accident by the Apollo 13 Review Board. They are based on that review, on the accident investigation by the Manned Spacecraft Center (MSC) and its contractors, and on an extensive series of special tests and analyses performed by or for the Board and its Panels.

Sufficient work has been done to identify and understand the nature of the malfunction and the direction which the corrective actions must take. All indications are that an electrically initiated fire in oxygen tank no. 2 in the service module (SM) was the cause of the accident. Accordingly, the Board has concentrated on this tank; on its design, manufacture, test, handling, checkout, use, failure mode, and eventual effects on the rest of the spacecraft. The accident is generally understood, and the most probable cause has been identified. However, at the time of this report, some details of the accident are not completely clear.

Further tests and analyses, which will be carried out under the overall direction of MSC, will continue to generate new information relative to this accident. It is possible that this evidence may lead to conclusions differing in detail from those which can be drawn now. However, it is most unlikely that fundamentally different results will be obtained.

Recommendations are provided as to the general direction which the corrective actions should take. Significant modifications should be made to the SM oxygen storage tanks and related equipments. The modified hardware should go through a rigorous requalification test program. This is the responsibility of the Apollo organization in the months ahead.

In reaching its findings, determinations, and recommendations, it was necessary for the Board to review critically the equipment and the organizational elements responsible for it. It was found that the accident was not the result of a chance malfunction in a statistical sense, but rather resulted from an unusual combination of mistakes, coupled with a somewhat deficient and unforgiving design. In brief, this is what happened:

(*a*) After assembly and acceptance testing, the oxygen tank No. 2 which flew on Apollo 13 was shipped from Beech Aircraft Corporation to North American Rockwell (NR) in apparently satisfactory condition.

(*b*) It is now known, however, that the tank contained two protective thermostatic switches on the heater assembly, which were inadequate and would subsequently fail during ground test operations at Kennedy Space Center (KSC).

(*c*) In addition, it is probable that the tank contained a loosely fitting fill tube assembly. This assembly was probably displaced during subsequent handling, which included an incident at the prime contractor's plant in which the tank was jarred.

(*d*) In itself, the displaced fill tube assembly was not particularly serious, but it led to the use of improvised detanking procedures at KSC which almost certainly set the stage for the accident.

(*e*) Although Beech did not encounter any problem in detanking during acceptance tests, it was not possible to detank oxygen tank No. 2 using normal procedures at KSC. Tests and analyses indicate that this was due to gas leakage through the displaced fill tube assembly.

(*f*) The special detanking procedures at KSC subjected to the tank to an extended period of heater operation and pressure cycling. These procedures had not been used before, and the tank had not been qualified by test for the conditions experienced. However, the procedures did not violate the specifications which governed the operation of the heaters at KSC.

(*g*) In reviewing these procedures before the flight, officials of NASA, NR, and Beech did not recognize the possibility of damage due to overheating. Many of these officials were not aware of the extended heater operation. In any event, adequate thermostatic switches might have been expected to protect the tank.

(*h*) A number of factors contributed to the presence of inadequate thermostatic switches in the heater assembly. The original 1962 specifications from NR to Beech Aircraft Corporation for the tank and heater assembly specified the use of 28 V dc power, which is used in the spacecraft. In 1965, NR issued a revised specification which stated that the heaters should use a 65 V dc power supply for tank pressurization; this was the power supply used at KSC to reduce pressurization time. Beech ordered switches for the Block II tanks but did not change the switch specifications to be compatible with 65 V dc.

(*i*) The thermostatic switch discrepancy was not detected by NASA, NR, or Beech in their review of documentation, nor did tests identify the incompatibility of the switches with the ground support equipment (GSE) at KSC, since neither qualification nor acceptance testing required switch cycling under load as should have been done. It was a serious oversight in which all parties shared.

(*j*) The thermostatic switches could accommodate the 65 V dc during tank pressurization because they normally remained cool and closed. However, they could not open without damage with 65 V dc power applied. They were never required to do so until the special detanking. During this procedure, as the switches started to open when they reached their upper temperature limit, they were welded permanently closed by the resulting arc and were rendered inoperative as protective thermostats.

(*k*) Failure of the thermostatic switches to open could have been detected at KSC if switch operation had been checked by observing heater current readings on the oxygen tank heater control panel. Although it was not recognized at that time, the tank temperature readings indicated that the heaters had reached their temperature limit and switch opening should have been expected.

(*l*) As shown by subsequent tests, failure of the thermostatic switches probably permitted the temperature of the heater tube assembly to reach about 1000° F in spots during the continuous 8-hour period of heater operation. Such heating has been shown by tests to severely damage the Teflon insulation on the fan motor wires in the vicinity of the heater assembly. From that time on, including pad occupancy, the oxygen tank no. 2 was in a hazardous condition when filled with oxygen and electrically powered.

(*m*) It was not until nearly 56 hours into the mission, however, that the fan motor wiring, possibly moved by the fan stirring, short circuited and ignited its insulation by means of an electric arc. The resulting combustion in the oxygen tank probably overheated and failed the wiring conduit where it enters the tank, and possibly a portion of the tank itself.

(*n*) The rapid expulsion of high-pressure oxygen which followed, possibly augmented by combustion of insulation in the space surrounding the tank, blew off the outer panel to bay 4 of the SM, caused a leak in the high-pressure system of oxygen tank no. 1, damaged the high-gain antenna, caused other miscellaneous damage, and aborted the mission.

The accident is judged to have been nearly catastrophic. Only outstanding performance on the part of the crew, Mission Control, and other members of the team which supported the operations successfully returned the crew to Earth.

In investigating the accident to Apollo 13, the Board has also attempted to identify those additional technical and mangement lessons which can be applied to help assure the success of future space flight missions; several recommendations of this nature are included.

The Board recognizes that the contents of its report are largely of a critical nature. The report highlights in detail faults or deficiencies in equipment and procedures that the Board has identified. This is the nature of a review board report.

It is important, however, to view the criticisms in this report in a broader context. The Apollo spacecraft system is not without shortcomings, but it is the only system of its type ever built and successfully demonstrated. It has flown to the Moon five times and landed twice. The tank which failed, the design of which is criticized in this report, is one of a series which had thousands of hours of successful operation in space prior to Apollo 13.

While the team of designers, engineers, and technicians that build and operate the Apollo spacecraft also has shortcomings, the accomplishments speak for themselves. By hardheaded self-criticism and continued dedication, this team can maintain this nation's preeminence in space.

PART 2. ASSESSMENT OF ACCIDENT

FAILURE OF OXYGEN TANK NO. 2

1. Findings

(*a*) The Apollo 13 mission was aborted as the direct result of the rapid loss of oxygen from oxygen tank no. 2 in the SM, followed by a gradual loss of oxygen from tank no. 1, and a resulting loss of power from the oxygen-fed fuel cells.

(*b*) There is no evidence of any forces external to oxygen tank no. 2 during the flight which might have caused its failure.

(*c*) Oxygen tank no. 2 contained materials, including Teflon and aluminum, which if ignited will burn in supercritical oxygen.

(*d*) Oxygen tank no. 2 contained potential ignition sources: electrical wiring, unsealed electric motors, and rotating aluminum fans.

(*e*) During the special detanking of oxygen tank no. 2 following the countdown demonstration test (CDDT) at KSC, the thermostatic switches on the heaters were required to open while powered by 65 V dc in order to protect the heaters from overheating. The switches were only rated at 30 V dc and have been shown to weld closed at the higher voltage.

(*f*) Data indicate that in flight the tank heaters located in oxygen tanks no. 1 and no. 2 operated normally prior to the accident, and they were not on at the time of the accident.

(*g*) The electrical circuit for the quantity probe would generate only about 7 millijoules in the event of a short circuit and the temperature sensor wires less than 3 millijoules per second.

(*h*) Telemetry data immediately prior to the accident indicate electrical disturbances of a character which would be caused by short circuits accompanied by electrical arcs in the fan motor or its leads in oxygen tank no. 2.

(*i*) The pressure and temperature within oxygen tank no. 2 rose abnormally during the 1½ minutes immediately prior to the accident.

Determinations

(1) The cause of the failure of oxygen tank no. 2 was combustion within the tank.

(2) Analysis showed that the electrical energy flowing into the tank could not account for the observed increases in pressure and temperature.

(3) The heater, temperature sensor, and quantity probe did not initiate the accident sequence.

(4) The cause of the combustion was most probably the ignition of Teflon wire insulation on the fan motor wires, caused by electric arcs in this wiring.

(5) The protective thermostatic switches on the heaters in oxygen tank no. 2 failed closed during the initial portion of the first special detanking operation. This subjected the wiring in the vicinity of the heaters to very high temperatures which have been subsequently shown to severely degrade Teflon insulation.

(6) The telemetered data indicated electrical arcs of sufficient energy to ignite the Teflon insulation, as verified by subsequent tests. These tests also verified that the 1-ampere fuses on the fan motors would pass sufficient energy to ignite the insulation by the mechanism of an electric arc.

(7) The combustion of Teflon wire insulation alone could release sufficient heat to account for the observed increases in tank pressure and local temperature, and could locally overheat and fail the tank or its associated tubing. The possibility of such failure at the top of the tank was demonstrated by subsequent tests.

(8) The rate of flame propagation along Teflon-insulated wires as measured in subsequent tests is consistent with the indicated rates of pressure rise within the tank.

SECONDARY EFFECTS OF TANK FAILURE

2. Findings

(*a*) Failure of the tank was accompanied by several events including:

A "bang" as heard by the crew.

Spacecraft motion as felt by the crew and as measured by the attitude control system and the accelerometers in the command module (CM).

Momentary loss of telemetry.

Closing of several valves by shock loading.

Loss of integrity of the oxygen tank no. 1 system.

Slight temperature increases in bay 4 and adjacent sectors of the SM.

Loss of the panel covering bay 4 of the SM, as observed and photographed by the crew.

Displacement of the fuel cells as photographed by the crew.

Damage to the high-gain antenna as photographed by the crew.

(*b*) The panel covering of bay 4 could be blown off by pressurization of the bay. About 25 psi of uniform pressure in bay 4 is required to blow off the panel.

(*c*) The various bays and sectors of the SM are interconnected with open passages so that all would be pressurized if any one were supplied with a pressurant at a relatively slow rate.

(*d*) The CM attachments would be failed by an average pressure of about 10 psi on the CM heat shield and this would separate the CM from the SM.

Determinations

(1) Failure of the oxygen tank no. 2 caused a rapid local pressurization of bay 4 of the SM by the high-pressure oxygen that escaped from the tank. This pressure pulse may have blown off the panel covering bay 4. This possibility was substantiated by a series of special tests.

(2) The pressure pulse from a tank failure might have been augmented by combustion of Mylar or Kapton insulation or both when subjected to a stream of oxygen and hot particles emerging from the top of the tank, as demonstrated in subsequent tests.

(3) Combustion or vaporization of the Mylar or Kapton might account for the discoloration of the SM engine nozzle as observed and photographed by the crew.

(4) Photographs of the SM by the crew did not establish the condition of the oxygen tank no. 2.

(5) The high-gain antenna damage probably resulted from striking by the panel, or a portion thereof, as it left the SM.

(6) The loss of pressure on oxygen tank no. 1 and the subsequent loss of power resulted from the tank no. 2 failure.

(7) Telemetry, although good, is insufficient to pin down the exact nature, sequence, and location of each event of the accident in detail.

(8) The telemetry data, crew testimony, photographs, and special tests and analyses already completed are sufficient to understand the problem and to proceed with corrective actions.

OXYGEN TANK NO. 2 DESIGN

3. *Findings*

(*a*) The cryogenic oxygen storage tanks contained a combination of oxidizer, combustible material, and potential ignition sources.

(*b*) Supercritical oxygen was used to minimize the weight, volume, and fluid-handling problems of the oxygen supply system.

(*c*) The heaters, fans, and tank instrumentation are used in the measurement and management of the oxygen supply.

Determinations

(1) The storage of supercritical oxygen was appropriate for the Apollo system.

(2) Heaters are required to maintain tank pressure as the oxygen supply is used.

(3) Fans were used to prevent excessive pressure drops due to stratification, to mix the oxygen to improve accuracy of quantity measurements, and to insure adequate heater input at low densities and high oxygen utilization rates. The need for oxygen stirring on future flights requires further investigation.

(4) The amount of material in the tank which could be ignited and burned in the given environment could have been reduced significantly.

(5) The potential ignition sources constituted an undue hazard when considered in the light of the particular tank design with its assembly difficulties.

(6) NASA, the prime contractor, and the supplier of the tank were not fully aware of the extent of this hazard.

(7) Examination of the high-pressure oxygen system in the service module following the Apollo 204 fire, which directed attention to the danger of fire in a pure oxygen environment, failed to recognize the deficiencies of the tank.

PREFLIGHT DAMAGE TO TANK WIRING

4. Findings

(*a*) The oxygen tank no. 2 heater assembly contained two thermostatic switches designed to protect the heaters from overheating.

(*b*) The thermostatic switches were designed to open and interrupt the heater current at 80° ± 10° F.

(*c*) The heaters are operated on 28 V dc in flight and at NR.

(*d*) The heaters are operated on 65 V ac at Beech Aircraft Corporation and 65 V dc at the Kennedy Space Center. These higher voltages are used to accelerate tank pressurization.

(*e*) The thermostatic switches were rated at 7 amps at 30 V dc. While they would carry this current at 65 V dc in a closed position, they would fail if they started to open to interrupt this load.

(*f*) Neither qualification nor acceptance testing of the heater assemblies or the tanks required thermostatic switch opening to be checked at 65 V dc. The only test of switch opening was a continuity check at Beech in which the switch was cycled open and closed in an oven.

(*g*) The thermostatic switches had never operated in flight because this would only happen if the oxygen supply in a tank were depleted to nearly zero.

(*h*) The thermostatic switches had never operated on the ground under load because the heaters had only been used with a relatively full tank which kept the switches cool and closed.

(*i*) During the CDDT, the oxygen tank no. 2 would not detank in a normal manner. On March 27 and 28, a special detanking procedure was followed which subjected the heater to about 8 hours of continuous operation until the tanks were nearly depleted of oxygen.

(*j*) A second special detanking of shorter duration followed on March 30, 1970.

(*k*) The oxygen tanks had not been qualification tested for the conditions encountered in this procedure. However, specified allowable heater voltages and currents were not exceeded.

(*l*) The recorded internal tank temperature went off-scale high early in the special detanking. The thermostatic switches would normally open at this point but the electrical records show no thermostatic switch operation. These indications were not detected at the time,

(*m*) The oxygen tank heater controls at KSC contained ammeters which would have indicated thermostatic switch operation.

Determinations

(1) During the special detanking of March 27 and 28 at KSC, when the heaters in oxygen tank No. 2 were left on for an extended period, the thermostatic switches started to open while powered by 65 V dc and were probably welded shut.

(2) Failure of the thermostatic switches to open could have been detected at KSC if switch operation had been checked by observing heater current readings on the oxygen tank heater control panel. Although it was not recognized at the time, the tank temperature readings indicated that the heaters had reached their temperature limit and switch opening should have been expected.

(3) The fact that the switches were not rated to open at 65 V dc was not detected by NASA, NR, or Beech in their reviews of documentation or in qualification and acceptance testing.

(4) The failed switches resulted in severe overheating. Subsequent tests showed that heater assembly temperatures could have reached about 1000° F.

(5) The high temperatures severely damaged the Teflon insulation on the wiring in the vicinity of the heater assembly and set the stage for subsequent short circuiting. As shown in subsequent tests, this damage could range from cracking to total oxidation and disappearance of the insulation.

(6) During and following the special detanking, the oxygen tank no. 2 was in a hazardous condition whenever it contained oxygen and was electrically energized.

PART 3. SUPPORTING CONSIDERATIONS

DESIGN, MANUFACTURING, AND TEST

5. Finding

The pressure vessel of the supercritical oxygen tank is constructed of Inconel 718, and is moderately stressed at normal operating pressure.

Determination

From a structural viewpoint, the supercritical oxygen pressure vessel is quite adequately designed, employing a tough material well chosen for this application. The stress analysis and the results of the qualification burst test program confirm the ability of the tank to exhibit adequate performance in its intended application.

6. *Findings*

(*a*) The oxygen tank design includes two unsealed electric fan motors immersed in supercritical oxygen.

(*b*) Fan motors of this design have a test history of failure during acceptance test which includes phase-to-phase and phase-to-ground faults.

(*c*) The fan motor stator windings are constructed with Teflon-coated, ceramic-insulated, number 36 AWG wire. Full phase-to-phase and phase-to-ground insulation is not used in the motor design.

(*d*) The motor case is largely aluminum.

Determinations

(1) The stator winding insulation is brittle and easily fractured during manufacture of the stator coils.

(2) The use of these motors in supercritical oxygen was a questionable practice.

7. *Findings*

(*a*) The cryogenic oxygen storage tanks contained materials that could be ignited and which will burn under the conditions prevailing within the tank, including Teflon, aluminum, solder, and Drilube 822.

(*b*) The tank contained electrical wiring exposed to the supercritical oxygen. The wiring was insulated with Teflon.

(*c*) Some wiring was in close proximity to heater elements and to the rotating fan.

(*d*) The design was such that the assembly of the equipment was essentially "blind" and not amenable to inspection after completion.

(*e*) Teflon insulation of the electrical wiring inside the cryogenic oxygen storage tanks of the SM was exposed to relatively sharp metal edges of tank inner parts during manufacturing assembly operations.

(*f*) Portions of this wiring remained unsupported in the tank on completion of assembly.

Determinations

(1) The tank contained a hazardous combination of materials and potential ignition sources.

(2) Scraping of the electrical wiring insulation against metal inner parts of the tank constituted a substantial cumulative hazard during assembly, handling, test, checkout, and operational use.

(3) "Cold flow" of the Teflon insulation, when pressed against metal corners within the tank for an extended period of time, could result in an eventual degradation of insulation protection.

(4) The externally applied electrical tests (500-volt Hi-pot) could not reveal the extent of such possible insulation damage but could only indicate that the relative positions of the wires at the time of the tests were such that the separation or insulation would withstand the 500-volt potential without electrical breakdown.

(5) The design was such that it was difficult to insure against these hazards.

(6) There is no evidence that the wiring was damaged during manufacturing.

9. *Findings*

(*a*) Dimensioning of the short Teflon and Inconel tube segments of the cryogenic oxygen storage tank fill line was such that looseness to the point of incomplete connection was possible in the event of worst-case tolerance buildup.

(*b*) The insertion of these segments into the top of the tank quantity probe assembly at the point of its final closure and welding was difficult to achieve.

(*c*) Probing with a hand tool was used in manufacturing to compensate for limited visibility of the tube segment positions.

Determination

It was possible for a tank to have been assembled with a set of relatively loose fill tube parts that could go undetected in final inspection and be subsequently displaced.

10. Findings

(*a*) The Apollo spacecraft system contains numerous pressure vessels, many of which carry oxidants, plus related valves and other plumbing.

(*b*) Investigation of potential hazards associated with these other systems was not complete at the time of the report, but is being pursued by the Manned Spacecraft Center.

(*c*) One piece of equipment, the fuel cell oxygen supply valve module, has been identified as containing a similar combination of high-pressure oxygen, Teflon, and electrical wiring as in the oxygen tank no. 2. The wiring is unfused and is routed through a 10-amp circuit breaker.

Determination

The fuel cell oxygen supply valve module has been identified as potentially hazardous.

11. Findings

(*a*) In the normal sequence of cryogenic oxygen storage tank integration and checkout, each tank undergoes shipping, assembly into an oxygen shelf for a service module, factory transportation to facilitate shelf assembly test, and then integration of shelf assembly to the SM.

(*b*) The SM undergoes factory transportation, air shipment to KSC, and subsequent ground transportation and handling.

Determination

There were environments during the normal sequence of operations subsequent to the final acceptance tests at Beech that could cause a loose-fitting set of fill tube parts to become displaced.

12. Findings

(*a*) At North American Rockwell, Downey, California, in the attempt to remove the oxygen shelf assembly from SM 106, a bolt restraining the inner edge of the shelf was not removed.

(*b*) Attempts to lift the shelf with the bolt in place broke the lifting fixture, thereby jarring the oxygen tanks and valves.

(*c*) The oxygen shelf assembly incorporating S/N XTA0008 in the tank no. 2 position, which had been shaken during removal from SM 106, was installed in SM 109 one month later.

(*d*) An analysis, shelf inspection, and a partial retest emphasizing electrical continuity of internal wiring were accomplished before reinstallation.

Determinations

(1) Displacement of fill tube parts could have occurred, during the "shelf drop" incident at the prime contractor's plant, without detection.

(2) Other damage to the tank may have occurred from the jolt, but special tests and analyses indicate that this is unlikely.

(3) The "shelf drop" incident was not brought to the attention of project officials during subsequent detanking difficulties at KSC.

13. Finding

Detanking, expulsion of liquid oxygen out the fill line of the oxygen tank by warm gas pressure applied through the vent line, was a regular activity at Beech Aircraft, Boulder, Colorado, in emptying a portion of the oxygen used in end-item acceptance tests.

Determination

The latter stages of the detanking operation on oxygen tank no. 2 conducted at Beech on February 3, 1967, were similar to the standard procedure followed at KSC during the CDDT.

14. Findings

(*a*) The attempt to detank the cryogenic oxygen tanks at KSC after the CDDT by the standard procedures on March 23, 1970, was unsuccessful with regard to tank no. 2.

(*b*) A special detanking procedure was used to empty oxygen tank no. 2 after CDDT. This procedure involved continuous protracted heating with repeated cycles of pressurization to about 300 psi with warm gas followed by venting.

(*c*) It was employed both after CDDT and after a special test to verify that the tank could be filled.

(*d*) There is no indication from the heater voltage recording that the thermostatic switches functioned and cycled the heaters off and on during these special detanking procedures.

(*e*) At the completion of detanking following CDDT, the switches are only checked to see that they remain closed at −75° F as the tank is warmed up. They are not checked to verify that they will open at +80° F.

(*f*) Tests subsequent to the flight showed that the current associated with the KSC 65 V dc ground powering of the heaters would cause the thermostatic switch contacts to weld closed if they attempted to interrupt this current.

(*g*) A second test showed that without functioning thermostatic switches, temperatures in the 800° to 1000° F range would exist at locations on the heater tube assembly that were in close proximity with the motor wires. These temperatures are high enough to damage Teflon and melt solder.

Determinations

(1) Oxygen tank no. 2 (XTA 0008) did not detank after CDDT in a manner comparable to its performance the last time it had contained liquid oxygen, i.e., in acceptance test at Beech.

(2) Such evidence indicates that the tank had undergone some change of internal configuration during the intervening events of the previous 3 years.

(3) The tank conditions during the special detanking procedures were outside all prior testing of Apollo CSM cryogenic oxygen storage tanks. Heater assembly temperatures measured in subsequent tests exceeded 1000° F.

(4) Severe damage to the insulation of electrical wiring internal to the tank, as determined from subsequent tests, resulted from the special procedure.

(5) Damage to the insulation, particularly on the long unsupported lengths of wiring, may also have occurred due to boiling associated with this procedure.

(6) MSC, KSC, and NR personnel did not know that the thermostatic switches were not rated to open with 65 V dc GSE power applied.

15. Findings

(*a*) The change in detanking procedures on the cryogenic oxygen tank was made in accordance with the existing change control system during final launch preparations for Apollo 13.

(*b*) Launch operations personnel who made the change did not have a detailed understanding of the tank internal components, or the tank history. They made appropriate contacts before making the change.

(*c*) Communications, primarily by telephone, among MSC, KSC, NR, and Beech personnel during final launch preparations regarding the cryogenic oxygen system included incomplete and inaccurate information.

(*d*) The MSC Test Specification Criteria Document (TSCD) which was used by KSC in preparing detailed tank test procedures states the tank allowable heater voltage and current as 65 to 85 V dc and 9 to 17 amperes with no restrictions on time.

Determinations

(1) NR and MSC personnel who prepared the TSCD did not know that the tank heater themostatic switches would not protect the tank.

(2) Launch operations personnel assumed the tank was protected from overheating by the switches.

(3) Launch operations personnel at KSC stayed within the specified tank heater voltage and current limits during the detanking at KSC.

16. Findings

(*a*) After receipt of the Block II oxygen tank specifications from NR, which required the tank heater assembly to operate with 65 V dc GSE power only during tank pressurization, Beech Aircraft did not require their Block I thermostatic switch supplier to make a change in the switch to operate at the higher voltage.

(*b*) NR did not review the tank or heater to assure compatibility between the switch and the GSE.

(*c*) MSC did not review the tank or heater to assure compatibility between the switch and the GSE.

(*d*) No tests were specified by MSC, NR, or Beech to check this switch under load.

Determinations

(1) NR and Beech specifications governing the powering and the thermostatic switch protection of the heater assemblies were inadequate.

(2) The specifications governing the testing of the heater assemblies were inadequate.

17. Finding

The hazard associated with the long heater cycle during detanking was not given consideration in the decision to fly oxygen tank no. 2.

Determinations

(1) MSC, KSC, and NR personnel did not know that the tank heater thermostatic switches did not protect the tank from overheating.

(2) If the long period of continuous heater operation with failed thermostatic switches had been known, the tank would have been replaced.

18. Findings

(*a*) Management controls requiring detailed reviews and approvals of design, manufacturing processes, assembly procedures, test procedures, hardware acceptance, safety, reliability, and flight readiness are in effect for all Apollo hardware and operations.

(*b*) When the Apollo 13 cryogenic oxygen system was originally designed, the management controls were not defined in as great detail as they are now.

Determination

From review of documents and interviews, it appears that the management controls existing at that time were adhered to in the case of the cryogenic oxygen system incorporated in Apollo 13.

19. Finding

The only oxygen tank no. 2 anomaly during the final countdown was a small leak through the vent quick disconnect, which was corrected.

Determination

No indications of a potential inflight malfunction of the oxygen tank no. 2 were present during the launch countdown.

MISSION EVENTS THROUGH ACCIDENT

20. Findings

(*a*) The center engine of the S–II stage of the Saturn V launch vehicle prematurely shut down at 132 seconds due to large 16 hertz oscillations in thrust chamber pressure.

(*b*) Data indicated less than 0.1g vibration in the CM.

Determinations

(1) Investigation of this S–II anomaly was not within the purview of the Board except insofar as it relates to the Apollo 13 accident.

(2) The resulting oscillations or vibration of the space vehicle probably did not affect the oxygen tank.

21. Findings

(*a*) Fuel cell current increased between 46:40:05 and 46:40:08 indicating that the oxygen tank no. 1 and tank no. 2 fans were turned on during this interval.

(*b*) The oxygen tank no. 2 quantity indicated off-scale high at 46:40:08.

Determinations

(1) The oxygen tank no. 2 quantity probe short circuited at 46:40:08.

(2) The short circuit could have been caused by either a completely loose fill tube part or a solder splash being carried by the moving fluid into contact with both elements of the probe capacitor.

22. Findings

(*a*) The crew acknowledged Mission Control's request to turn on the tank fans at 55:53:06.

(*b*) Spacecraft current increased by 1 ampere at 55:53:19.

(*c*) The oxygen tank no. 1 pressure decreased 8 psi at 55:53:19 due to normal destratification.

Determination

The fans in oxygen tank no. 1 were turned on and began rotating at 55:53:19.

23. Findings

(*a*) Spacecraft current increased by 1½ amperes and ac bus 2 voltage decreased 0.6 volt at 55 :53 :20.

(*b*) Stabilization and Control System (SCS) gimbal command telemetry channels, which are sensitive indicators of electrical transients associated with switching on or off of certain spacecraft electrical loads, showed a negative initial transient during oxygen tank no. 2 fan turnon cycles and a positive initial transient during oxygen tank no. 2 fan turnoff cycles during the Apollo 13 mission. A negative initial transient was measured in the SCS at 55 :53 :20.

(*c*) The oxygen tank no. 2 pressure decreased about 4 psi when the fans were turned on at 55 :53 :21.

Determinations

(1) The fans in oxygen tank no. 2 were turned on at 55 :53 :20.

(2) It cannot be determined whether or not they were rotating because the pressure decrease was too small to conclusively show destratification. It is likely that they were.

24. Finding

An 11.1-amp spike in fuel cell 3 current and a momentary 1.2-volt decrease were measured in ac bus 2 at 55 :53 :23.

Determinations

(1) A short circuit occurred in the circuits of the fans in oxygen tank no. 2 which resulted in either blown fuses or opened wiring, and one fan ceased to function.

(2) The short circuit probably dissipated an energy in excess of 10 joules which, as shown in subsequent tests, is more than sufficient to ignite Teflon wire insulation by means of an electric arc.

25. Findings

(*a*) A momentary 11-volt decrease in ac bus 2 voltage was measured at 55 :53 :38.

(*b*) A 22.9-amp spike in fuel cell 3 current was measured at 55 :53 :41.

(*c*) After the electrical transients, CM current and ac bus 2 voltage returned to the values indicated prior to the turnon of the fans in oxygen tank no. 2.

Determination

Two short circuits occurred in the oxygen tank no. 2 fan circuits between 55 :53 :38 and 55 :53 :41 which resulted in either blown fuses or opened wiring, and the second fan ceased to function.

26. Finding

Oxygen tank no. 2 telemetry showed a pressure rise from 887 to 954 psia between 55 :53 :36 and 55 :54 :00. It then remained nearly constant for about 15 seconds and then rose again from 954 to 1008 psia, beginning at 55 :54 :15 and ending at 55 :54 :45.

Determinations

(1) An abnormal pressure rise occurred in oxygen tank no. 2.

(2) Since no other known energy source in the tank could produce this pressure buildup, it is concluded to have resulted from combustion initiated by the first short circuit which started a wire insulation fire in the tank.

27. Findings

(*a*) The pressure relief valve was designed to be fully open at about 1000 psi.

(*b*) Oxygen tank no. 2 telemetry showed a pressure drop from 1008 psia at 55 : 54 : 45 to 996 psia at 55 : 54 : 53, at which time telemetry data were lost.

Determination

This drop resulted from the normal operation of the pressure relief valve as verified in subsequent tests.

28. Findings

(*a*) At 55 : 54 : 29, when the pressure in oxygen tank no. 2 exceeded the master caution and warning trip level of 975 psia, the CM master alarm was inhibited by the fact that a warning of low hydrogen pressure was already in effect, and neither the crew nor Mission Control was alerted to the pressure rise.

(*b*) The master caution and warning system logic for the cryogenic system is such that an out-of-tolerance condition of one measurement which triggers a master alarm prevents another master alarm from being generated when any other parameter in the same system becomes out-of-tolerance.

(*c*) The low-pressure trip level of the master caution and warning system for the cryogenic storage system is only 1 psi below the specified lower limit of the pressure switch which controls the tank heaters. A small imbalance in hydrogen tank pressures or a shift in transducer or switch calibration can cause the master caution and warning to be triggered preceding each heater cycle. This occurred several times on Apollo 13.

(d) A limit sense light indicating abnormal oxygen tank no. 2 pressure should have come on in Mission Control about 30 seconds before oxygen tank no. 2 failed. There is no way to ascertain that the light did, in fact, come on. If it did come on, Mission Control did not observe it.

Determinations

(1) If the pressure switch setting and master caution and warning trip levels were separated by a greater pressure differential, there would be less likelihood of unnecessary master alarms.

(2) With the present master caution and warning system, a spacecraft problem can go unnoticed because of the presence of a previous out-of-tolerance condition in the same subsystem.

(3) Although a master alarm at 55 : 54 : 29 or observance of a limit sense light in Mission Control could have alerted the crew or Mission Control in sufficient time to detect the pressure rise in oxygen tank no. 2, no action could have been taken at that time to prevent the tank failure. However, the information could have been helpful to Mission Control and the crew in diagnosis of spacecraft malfunctions.

(4) The limit sense system in Mission Control can be modified to constitute a more positive backup warning system.

29. Finding

Oxygen tank no. 2 telemetry showed a temperature rise of 38° F beginning at 55 : 54 : 31 sensed by a single sensor which measured local temperature. This sensor indicated off-scale low at 55 : 54 : 53.

Determinations

(1) An abnormal and sudden temperature rise occurred in oxygen tank no. 2 at approximately 55 : 54 : 31.

(2) The temperature was a local value which rose when combustion had progressed to the vicinity of the sensor.

(3) The temperature sensor failed at 55 : 54 : 53.

30. Finding

Oxygen tank no. 2 telemetry indicated the following changes: (1) quantity decreased from off-scale high to off-scale low in 2 seconds at 55 : 54 : 30, (2) quantity increased to 75.3 percent at 55 : 54 : 32, and (3) quantity was off-scale high at 55 : 54 : 51 and later became erratic.

Determinations

(1) Oxygen tank no. 2 quantity data between 55 : 54 : 32 and 55 : 54 : 50 may represent valid measurements.

(2) Immediately preceding and following this time period, the indications were caused by electrical faults.

31. Findings

(*a*) At about 55 : 54 : 53, or about half a second before telemetry loss, the body-mounted linear accelerometers in the command module, which are sampled at 100 times per second, began indicating spacecraft motions. These disturbances were erratic, but reached peak values of 1.17g, 0.65g, and 0.65g in the X, Y, and Z directions, respectively, about 13 milliseconds before data loss.

(*b*) The body-mounted roll, pitch, and yaw rate gyros showed low-level activity for ¼ second beginning at 55 : 54 : 53.220.

(*c*) The integrating accelerometers indicated that a velocity increment of approximately 0.5 fps was imparted to the spacecraft between 55 : 54 : 53 and 55 : 54 : 55.

(*d*) Doppler tracking data measured an incremental velocity component of 0.26 fps along a line from the Earth to the spacecraft at approximately 55 : 54 : 55.

(*e*) The crew heard a loud "bang" at about this time.

(*f*) Telemetry data were lost between approximately 55 : 54 : 53 and 55 : 54 : 55 and the spacecraft switched from the narrow-beam antenna to the wide-beam antenna.

(*g*) Crew observations and photographs showed the bay 4 panel to be missing and the high-gain antenna to be damaged.

Determinations

(1) The spacecraft was subjected to abnormal forces at approximately 55 : 54 : 53. These disturbances were reactions resulting from failure and venting of the oxygen tank no. 2 system and subsequent separation and ejection of the bay 4 panel.

(2) The high-gain antenna was damaged either by the panel or a section thereof from bay 4 at the time of panel separation.

32. Finding

Temperature sensors in bay 3, bay 4, and the central column of the SM indicated abnormal increases following reacquisition of data at 55 : 54 : 55.

Determination

Heating took place in the SM at approximately the time of panel separation.

33. Findings

(*a*) The telemetered nitrogen pressure in fuel cell 1 was off-scale low at reacquisition of data at 55 : 54 : 55.

(*b*) Fuel cell 1 continued to operate for about 3 minutes past this time.

(*c*) The wiring to the nitrogen sensor passes along the top of the shelf which supports the fuel cells immediately above the oxygen tanks.

Determinations

(1) The nitrogen pressure sensor in fuel cell 1 or its wiring failed at the time of the accident.

(2) The failure was probably caused by physical damage to the sensor wiring or shock.

(3) This is the only known instrumentation failure outside the oxygen system at that time.

34. Finding

Oxygen tank no. 1 pressure decreased rapidly from 879 psia to 782 psia at approximately 55 : 54 : 54 and then began to decrease more slowly at 55 : 54 : 56.

Determination

A leak caused loss of oxygen from tank no. 1 beginning at approximately 55 : 54 : 54.

35. Findings

(*a*) Oxygen flow rates to fuel cells 1 and 3 decreased in a 5-second period beginning at 55 : 54 : 55, but sufficient volume existed in lines feeding the fuel cells to allow them to operate about 3 minutes after the oxygen valves were cut off.

(*b*) The crew reported at 55 : 57 : 44 that five valves in the reaction control system (RCS) were closed. The shock required to close the oxygen supply valves is of the same order of magnitude as the shock required to close the RCS valves.

(*c*) Fuel cells 1 and 3 failed at about 55 : 58.

Determination

The oxygen supply valves to fuel cells 1 and 3, and the five RCS valves, were probably closed by the shock of tank failure or panel ejection or both.

MISSION EVENTS AFTER ACCIDENT

36. Findings

(*a*) Since data presented to flight controllers in Mission Control are updated only once per second, the 1.8-second loss of data which occurred in Mission Control was not directly noticed. However, the Guidance Officer did note and report a "hardware restart" of the spacecraft computer. This was quickly followed by the crew's report of a problem.

(*b*) Immediately after the crew's report of a "bang" and a main bus B undervolt, all fuel cell output currents and all bus voltages were normal, and the cryogenic oxygen tank indications were as follows:

Oxygen tank no. 1: Pressure: Several hundred psi below normal. Quantity: Normal. Temperature: Normal.

Oxygen tank no. 2: Pressure: Off-scale low. Quantity: Off-scale high. Temperature: Off-scale high.

(*c*) The nitrogen pressure in fuel cell 1 indicated zero, which was incompatible with the hydrogen and oxygen pressures in this fuel cell, which were normal. The nitrogen pressure is used to regulate the oxygen and hydrogen pressure, and hydrogen and oxygen pressures in the fuel cell would follow the nitrogen pressure.

(*d*) Neither the crew nor Mission Control was aware at the time that oxygen tank no. 2 pressure had risen abnormally just before the data loss.

(*e*) The flight controllers believed that a probable cause of these indications could have been a cryogenic storage system instrumentation failure, and began pursuing this line of investigation.

Determination

Under these conditions it was reasonable to suspect a cryogenic storage system instrumentation problem, and to attempt to verify the readings before taking any action. The fact that the oxygen tank no. 2 quantity measurement was known to have failed several hours earlier also contributed to the doubt about the creditability of the telemetered data.

37. Findings

(*a*) During the 3 minutes following data loss, neither the flight controllers nor the crew noticed the oxygen flows to fuel cells 1 and 3 were less than 0.1 lb/hr. These were unusually low readings for the current being drawn.

(*b*) Fuel cells 1 and 3 failed at about 3 minutes after the data loss.

(*c*) After the fuel cell failures, which resulted in dc main bus B failure and the undervoltage condition on dc main bus A, Mission Control diverted its prime concern from what was initially believed to be a cryogenic system instrumentation problem to the electrical power system.

(*d*) Near-zero oxygen flow to fuel cells 1 and 3 was noted after the main bus B failure, but this was consistent with no power output from the fuel cells.

(*e*) The flight controllers believed that the fuel cells could have been disconnected from the busses and directed the crew to connect fuel cell 1 to dc main bus A and fuel cell 3 to dc main bus B.

(*f*) The crew reported the fuel cells were configured as directed and that the talkback indicators confirmed this.

Determinations

(1) Under these conditions it was logical for the flight controllers to attempt to regain power to the busses since the fuel cells might have been disconnected as a result of a short circuit in the electrical system. Telemetry does not indicate whether or not fuel cells are connected to busses, and the available data would not distinguish between a disconnected fuel cell and a failed one.

(2) If the crew had been aware of the reactant valve closure, they could have opened them before the fuel cells were starved of oxygen. This would have simplified subsequent actions.

38. Finding

The fuel cell reactant valve talkback indicators in the spacecraft do not indicate closed unless both the hydrogen and oxygen valves are closed.

Determinations

(1) If these talkbacks were designed so that either a hydrogen or oxygen valve closure would indicate "barberpole," the Apollo 13 crew could possibly have acted in time to delay the failure of fuel cells 1 and 3, although they would nevertheless have failed when oxygen tank no. 1 ceased to supply oxygen.

(2) The ultimate outcome would not have been changed, but had the fuel cells not failed, Mission Control and the crew would not have had to contend with the failure of dc main bus B and ac bus 2 or attitude control problems while trying to evaluate the situation.

REACTION CONTROL SYSTEM

39. Findings

(*a*) The crew reported the talkback indicators for the helium isolation valves in the SM RCS quads B and D indicated closed shortly after the dc main bus B failure. The secondary fuel pressurization valves for quads A and C also were reported closed.

(*b*) The SM RCS quad D propellant tank pressures decreased until shortly after the crew was requested to confirm that the helium isolation valves were opened by the crew.

(*c*) During the 1½-hour period following the accident, Mission Control noted that SM RCS quad C propellant was not being used, although numerous firing signals were being sent to it.

(*d*) Both the valve solenoids and the onboard indications of valve position of the propellant isolation valves for quad C are powered by dc main bus B.

(*e*) During the 1½-hour period immediately following the accident, Mission Control advised the crew which SM RCS thrusters to power and which ones to unpower.

Determinations

(1) The following valves were closed by shock at the time of the accident:
Helium isolation valves in quads B and D
Secondary fuel pressurization valves in quads A and C

(2) The propellant isolation valves in quad C probably were closed by the same shock.

(3) Mission Control correctly determined the status of the RCS system and properly advised the crew on how to regain automatic attitude control.

MANAGEMENT OF ELECTRICAL SYSTEM

40. Findings

(*a*) After fuel cell 1 failed, the total dc main bus A load was placed on fuel cell 2 and the voltage dropped to approximately 25 volts, causing a caution and warning indication and a master alarm.

(*b*) After determining the fuel cell 2 could not supply enough power to dc main bus A to maintain adequate voltage, the crew connected entry battery A to this bus as an emergency measure to increase the bus voltage to its normal operating value.

(*c*) Mission Control directed the crew to reduce the electrical load on dc main bus A by following the emergency powerdown checklist contained in the onboard Flight Data File.

(*d*) When the power requirements were sufficiently reduced so that the one remaining fuel cell would maintain adequate bus voltage, Mission Control directed the crew to take the entry battery off line.

(*e*) Mission Control then directed the crew to charge this battery in order to get as much energy back into it as possible, before the inevitable loss of the one functioning fuel cell.

Determinations

(1) Emergency use of the entry battery helped prevent potential loss of dc main bus A, which could have led to loss of communications between spacecraft and ground and other vital CM functions.

(2) Available emergency powerdown lists facilitated rapid reduction of loads on the fuel cell and batteries.

ATTEMPTS TO RESTORE OXYGEN PRESSURE

41. Findings

(*a*) After determining that the CM problems were not due to instrumentation malfunctions, and after temporarily securing a stable electrical system configuration, Mission Control sought to improve oxygen pressure by energizing the fan and heater circuits in both oxygen tanks.

(*b*) When these procedures failed to arrest the oxygen loss, Mission Control directed the crew to shut down fuel cells 1 and 3 by closing the hydrogen and oxygen flow valves.

Determinations

(1) Under more normal conditions oxygen pressure might have been increased by turning on heaters and fans in the oxygen tanks; no other known actions had such a possibility.

(2) There was a possibility that oxygen was leaking downstream of the valves; had this been true, closing of the valves might have preserved the remaining oxygen in oxygen tank no. 1.

LUNAR MODULE ACTIVATION

42. Findings

(*a*) With imminent loss of oxygen from oxygen tanks no. 1 and no. 2, and failing electrical power in the CM, it was necessary to use the lunar module (LM) as a "lifeboat" for the return to Earth.

(*b*) Mission Control and the crew delayed LM activation until about 15 minutes before the SM oxygen supply was depleted.

(*c*) There were three different LM activation checklists contained in the Flight Data File for normal and contingency situations; however, none of these was appropriate for the existing situation. It was necessary to activate the LM as rapidly as possible to conserve LM consumables and CM reentry batteries to the maximum extent possible.

(*d*) Mission Control modified the normal LM activation checklist and referred the crew to specific pages and instructions. This bypassed unecessary steps and reduced the activation time to less than an hour.

(*e*) The LM inertial platform was aligned during an onboard checklist procedure which manually transferred the CM alignment to the LM.

Determinations

(1) Initiation of LM activation was not undertaken sooner because the crew was properly more concerned with attempts to conserve remaining SM oxygen.

(2) Mission Control was able to make workable on-the-spot modifications to the checklists which sufficiently shortened the time normally required for powering up the LM.

43. Findings

(*a*) During the LM powerup and the CSM powerdown, there was a brief time interval during which Mission Control gave the crew directions which resulted in neither module having an active attitude control system.

(*b*) This caused some concern in Mission Control because of the possibility of the spacecraft drifting into inertial platform gimbal lock condition.

(*c*) The Command Module Pilot (CMP) stated that he was not concerned because he could have quickly reestablished direct manual attitude control if it became necessary.

Determination

This situation was not hazardous to the crew because had gimbal lock actually occurred, sufficient time was available to reestablish an attitude reference.

44. Findings

(*a*) LM flight controllers were on duty in Mission Control at the time of the accident in support of the scheduled crew entry into the LM.

(*b*) If the accident had occurred at some other time during the translunar coast phase, LM system specialists would not have been on duty, and it would have taken at least 30 minutes to get a fully manned team in Mission Control.

Determination

Although LM flight controllers were not required until more than an hour after the accident, it was beneficial for them to be present as the problem developed.

LM CONSUMABLES MANAGEMENT

45. Findings

(*a*) The LM was designed to support two men on a 2-day expedition to the lunar surface. Mission Control made major revisions in the use rate of water, oxygen, and electrical power to sustain three men for the 4-day return trip to the Earth.

(*b*) An emergency powerdown checklist was available in the Flight Data File on board the LM. Minor revisions were made to the list to reduce electrical energy requirements to about 20 percent of normal operational values with a corresponding reduction in usage of coolant loop water.

(*c*) Mission Control determined that this maximum powerdown could be delayed until after 80 hours ground elapsed time, allowing the LM primary guidance and navigation system to be kept powered up for the second abort maneuver.

(*d*) Mission Control developed contingency plans for further reduction of LM power for use in case an LM battery problem developed. Procedures for use of CM water in the LM also were developed for use if needed.

(*e*) Toward the end of the mission, sufficient consumable margins existed to allow usage rates to be increased above earlier planned levels. This was done.

(*f*) When the LM was jettisoned at 141 : 30 the approximate remaining margins were:

Electrical power, 4½ hours.
Water, 5½ hours.
Oxygen, 124 hours.

Determinations

(1) Earlier contingency plans and available checklists were adequate to extend life support capability of the LM well beyond its normal intended capability.

(2) Mission Control maintained the flexibility of being able to further increase the LM consumables margins.

MODIFICATION OF LM CARBON DIOXIDE REMOVAL SYSTEM

46 Findings

(*a*) The lithium hydroxide (LiOH) cartridges, which remove water and carbon dioxide from the LM cabin atmosphere, would have become ineffective due to saturation at about 100 hours.

(*b*) Mission rules set maximum allowable carbon dioxide partial pressure at 7.5mm Hg. LiOH cartridges are normally changed before cabin atmosphere carbon dioxide partial pressure reaches this value.

(*c*) Manned Spacecraft Center engineers devised and checked out a procedure for using the CM LiOH cannisters to achieve carbon dioxide removal. Instructions were given on how to build a modified cartridge container using materials in the spacecraft.

(*d*) The crew made the modification at 93 hours, and carbon dioxide partial pressure in the LM dropped rapidly from 7.5mm Hg to 0.1mm Hg.

(*e*) Mission Control gave the crew further instructions for attaching additional cartridges in series with the first modification. After this addition, the carbon dioxide partial pressure remained below 2mm Hg for the remainder of the Earth-return trip.

Determination

The Manned Spacecraft Center succeeded in improvising and checking out a modification to the filter system which maintained carbon dioxide concentration well within safe tolerances.

LM ANOMALY

47. Findings

(*a*) During the time interval between 97 :13 :53 and 97 :13 :55, LM descent battery current measurements on telemetry showed a rapid increase from values of no more than 3 amperes per battery to values in excess of 30 amperes per battery. The exact value in one battery cannot be determined because the measurement for battery 2 was off-scale high at 60 amperes.

(*b*) At about that time the Lunar Module Pilot (LMP) heard a "thump" from the vicinity of the LM descent stage.

(*c*) When the LMP looked out the LM right-hand window, he observed a venting of small particles from the general area where the LM descent batteries 1 and 2 are located. This venting continued for a few minutes.

(*d*) Prior to 97 :13 the battery load-sharing among the four batteries had been equal, but immediately after the battery currents returned to nominal, batteries 1 and 2 supplied 9 of the 11 amperes total. By 97 :23 the load-sharing had returned to equal.

(*e*) There was no electrical interface between the LM and the CSM at this time.

(*f*) An MSC investigation of the anomaly is in progress.

Determination

(1) An anomalous incident occurred in the LM electrical system at about 97:13:53 which appeared to be a short circuit.
(2) The thump and the venting were related to this anomaly.
(3) The apparent short circuit cleared itself.
(4) This anomaly was not directly related to the CSM or to the accident.
(5) This anomaly represents a potentially serious electrical problem.

CM BATTERY RECHARGING

48. Findings

(a) About one half of the electrical capacity of reentry battery A (20 of 40 amp-hours) was used during emergency conditions following the accident. A small part of the capacity of the reentry batter B was used in checking out dc main bus B at 95 hours. The reduced charge remaining in the batteries limited the amount of time the CM could operate after separation from the LM.

(b) Extrapolation of LM electrical power use rates indicated a capacity in excess of that required for LM operation for the remainder of the flight.

(c) Mission Control worked out a procedure for using LM battery power to recharge CM batteries A and B. This procedure used the electrical umbilical between the LM and the CM which normally carried electrical energy from the CM to the LM. The procedure was nonstandard and was not included in checklists.

(d) The procedure was initiated at 112 hours and CM batteries A and B were fully recharged by 128 hours.

Determination

Although there is always some risk involved in using new, untested procedures, analysis in advance of use indicated no hazards were involved. The procedure worked very well to provide an extra margin of safety for the reentry operation.

TRAJECTORY CHANGES FOR SAFE RETURN TO EARTH

49. Findings

(*a*) After the accident, it became apparent that the lunar landing could not be accomplished and that the spacecraft trajectory must be altered for a return to Earth.

(*b*) At the time of the accident, the spacecraft trajectory was one which would have returned it to the vicinity of the Earth, but it would have been left in orbit about the Earth rather than reentering for a safe splashdown.

(*c*) To return the spacecraft to Earth, the following midcourse corrections were made:

A 38-fps correction at 61:30, using the LM descent propulsion system (DPS), required to return the spacecraft to the Earth.

An 81-fps burn at 79:28, after swinging past the Moon, using the DPS engine, to shift the landing point from the Indian Ocean to the Pacific and to shorten the return trip by 9 hours.

A 7.8-fps burn at 105:18 using the DPS engine to lower Earth perigee from 87 miles to 21 miles.

A 3.2-fps correction at 137:40 using LM RCS thrusters, to assure that the CM would reenter the Earth's atmosphere at the center of its corridor.

(*d*) All course corrections were executed with expected accuracy and the CM reentered the Earth's atmosphere at 142:40 to return the crew safely at 142:54, near the prime recovery ship.

(*e*) Without the CM guidance and navigation system, the crew could not navigate or compute return-to-Earth maneuver target parameters.

Determinations

(1) This series of course corrections was logical and had the best chance of success because, as compared to other options, it avoided use of the damaged SM; it put the spacecraft on a trajectory, within a few hours after the accident, which had the best chance for a safe return to Earth; it placed splashdown where the best recovery forces were located; it shortened the flight time to increase safety margins in the use of electrical power and water; it conserved fuel for other course corrections which might have become necessary; and it kept open an option to further reduce the flight time.

(2) Mission Control trajectory planning and maneuver targeting were essential for the safe return of the crew.

ENTRY PROCEDURES AND CHECKLISTS

50. Findings

(*a*) Preparation for reentry required nonstandard procedures because of the lack of SM oxygen and electrical power supplies.

(*b*) The SM RCS engines normally provide separation between the SM and the CM by continuing to fire after separation.

(*c*) Apollo 13 SM RRCS engines could not continue to fire after separation because of the earlier failure of the fuel cells.

(*d*) The CM guidance and navigation system was powered down due to the accident. The LM guidance and navigation system had also been powered down to conserve electrical energy and water. A spacecraft inertial attitude reference had to be established prior to reentry.

(*e*) The reentry preparation time had to be extended in order to accomplish the additional steps required by the unusual situation.

(*f*) In order to conserve the CM batteries, LM jettison was delayed as long as practical. The LM batteries were used to supply part of the power necessary for CM activation.

(*g*) The procedures for accomplishing the final course correction and the reentry preparation were developed by operations support personnel under the direction of Mission Control.

(*h*) An initial set of procedures was defined within 12 hours after the accident. These were refined and modified during the following 2 days, and evaluated in simulators at MSC and KSC by members of the backup crew.

(*i*) The procedures were read to the crew about 24 hours prior to reentry, allowing the crew time to study and rehearse them.

(*j*) Trajectory evaluations of contingency conditions for LM and SM separation were conducted and documented prior to the mission by mission-planning personnel at MSC.

(*k*) Most of the steps taken were extracted from other procedures which had been developed, tested, and simulated earlier.

Determinations

(1) The procedures developed worked well and generated no new hazards beyond those unavoidably inherent in using procedures which have not been carefully developed, simulated, and practiced over a long training period.

(2) It is not practical to develop, simulate, and practice procedures for use in every possible contingency.

51. Findings

(*a*) During the reentry preparations, after SM jettison, there was a half-hour period of very poor communications with the CM due to the spacecraft being in a poor attitude with the LM present.

(*b*) This condition was not recognized by the crew or by Mission Control.

Determination

Some of the reentry preparations were unnecessarily prolonged by the poor communications, but since the reentry preparation time-line was not crowded, the delay was more of a nuisance than an additional hazard to the crew.

52. Findings

(*a*) The crew maneuvered the spacecraft to the wrong LM roll attitude in preparation for LM jettison. This attitude put the CM very close to gimbal lock which, had it occurred, would have lost the inertial attitude reference essential for an automatic guidance system control of reentry.

(*b*) If gimbal lock had occurred, a less accurate but adequate attitude reference could have been reestablished prior to reentry.

Determination

The most significant consequence of losing the attitude reference in this situation would have been the subsequent impact on the remaining reentry preparation timeline. In taking the time to reestablish this reference, less time would have been available to accomplish the rest of the necessary procedures. The occurrence of gimbal lock in itself would not have significantly increased the crew hazard.

PART 4. RECOMMENDATIONS

The cryogenic oxygen storage system in the service module should be modified to:

a. Remove from contact with the oxygen all wiring, and the unsealed motors, which can potentially short circuit and ignite adjacent materials; or otherwise insure against a catastrophic electrically induced fire in the tank.

b. Minimize the use of Teflon, aluminum, and other relatively combustible materials in the presence of the oxygen and potential ignition sources.

2. The modified cryogenic oxygen storage system should be subjected to a rigorous requalification program, including careful attention to potential operational problems.

3. The warning systems on board the Apollo spacecraft and in the Mission Control Center should be carefully reviewed and modified where appropriate, with specific attention to the following:

a. Increasing the differential between master alarm trip levels and expected normal operating ranges to avoid unnecessary alarms.

b. Changing the caution and warning system logic to prevent an out-of-limits alarm from blocking another alarm when a second quantity in the same subsystem goes out of limits.

c. Establishing a second level of limit sensing in Mission Control on critical quantities with a visual or audible alarm which cannot be easily overlooked.

d. Providing independent talkback indicators for each of the six fuel cell reactant valves plus a master alarm when any valve closes.

4. Consumables and emergency equipment in the LM and the CM should be reviewed to determine whether steps should be taken to enhance their potential for use in a "lifeboat" mode.

5. The Manned Spacecraft Center should compete the special tests and analyses now underway in order to understand more completely the details of the Apollo 13 accident. In addition, the lunar module power system anomalies should receive careful attention. Other NASA Centers should continue their support to MSC in the areas of analysis and test.

6. Whenever significant anomalies occur in critical subsystems during final preparation for launch, standard procedures should require a presentation of all prior anomalies on that particular piece of equipment, including those which have previously been corrected or explained. Furthermore, critical decisions involving the flightworthiness of subsystems should require the presence and full participation of an expert who is intimately familiar with the details of that subsystem.

7. NASA should conduct a thorough reexamination of all of its spacecraft, launch vehicle, and ground systems which contain high-density oxygen, or other strong oxidizers, to identify and evaluate potential combustion hazards in the light of information developed in this investigation.

8. NASA should conduct additional research on materials compatibility, ignition, and combustion in strong oxidizers at various g levels; and on the characteristics of supercritical fluids. Where appropriate, new NASA design standards should be developed.

9. The Manned Spacecraft Center should reassess all Apollo spacecraft subsystems, and the engineering organizations responsible for them at MSC and at its prime contractors, to insure adequate understanding and control of the engineering and manufacturing details of these subsystems at the subcontractor and vendor level. Where necessary, organizational elements should be strengthened and in-depth reviews conducted of selected subsystems with emphasis on soundness of design, quality of manufacturing, adequacy of test, and operational experience.

STATEMENTS OF DR. THOMAS O. PAINE, ADMINISTRATOR OF NASA; EDGAR M. CORTRIGHT, DIRECTOR, LANGLEY RESEARCH CENTER AND CHAIRMAN OF THE APOLLO 13 REVIEW BOARD; DR. CHARLES D. HARRINGTON, CHAIRMAN, AEROSPACE SAFETY ADVISORY PANEL; DR. DALE D. MYERS, ASSOCIATE ADMINISTRATOR FOR MANNED SPACE FLIGHT; AND DR. ROCCO A. PETRONE, APPOLLO PROGRAM DIRECTOR

Dr. Paine. I would like to ask Mr. Cortright to begin the testimony this morning, Mr. Chairman, by giving a brief summary of the report of the Apollo 13 Review Board.

(Biographical data of the witnesses appear at the end of this hearing.)

STATEMENT BY MR. CORTRIGHT

Mr. Cortright. Mr. Chairman, members of the committee, with your permission I would like to submit for the record today a statement and summarize it for the committee. The statement recounts in some detail the establishment and operation of the Apollo 13 Review Board including the extensive test program conducted for the Board.

SUMMARY OF BOARD'S REPORT

The Board's report which was submitted to the Administrator on June 15 and copies of which were submitted to this committee on the same date contains over 30 pages of findings and determinations. It is these findings and determinations which I would like to summarize for you this morning by reading from the introduction to chapter 5 of the report.

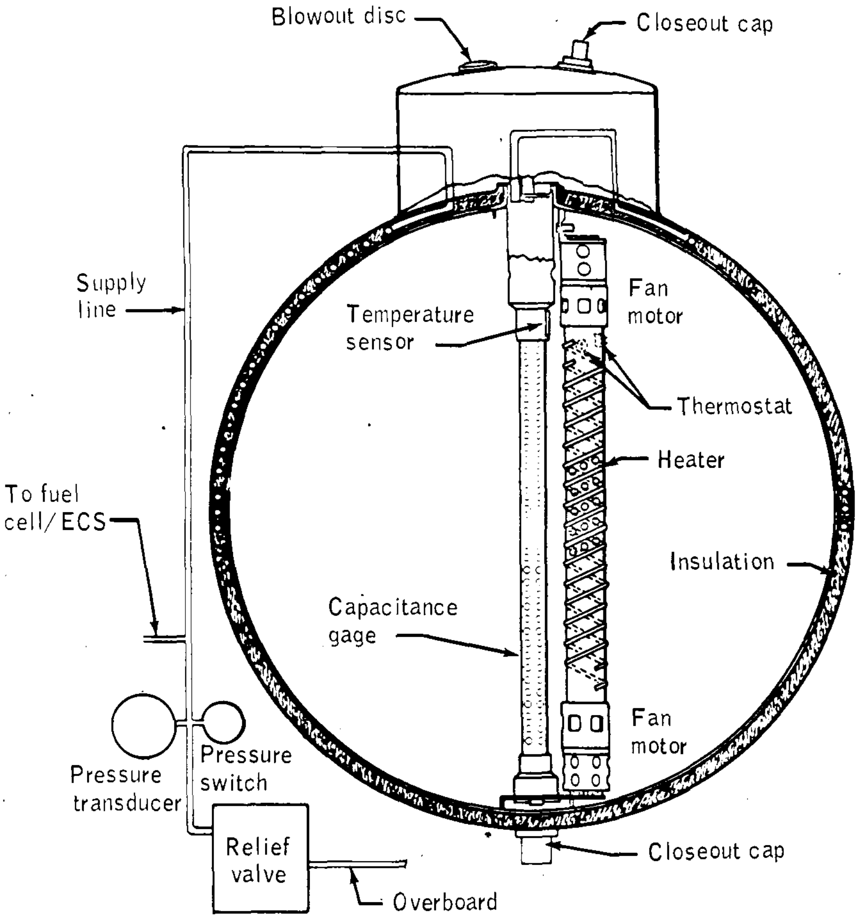


FIGURE 1. Oxygen tank No. 2 internal components.

Slide 1 (see fig. 1) shows the simplified drawing of the oxygen storage tank in which the accident occurred. I will just say a brief word about this slide to orient you to the nature of the problem that was encountered.

The tank itself was a high-pressure vessel which contains oxygen in a supercritical high density state. The tank is made of high strength Inconel. It is a doubled wall tank. The inner wall carries the pressure and the outer wall is there for insulation purposes. There is insulation between the two walls.

Now, the two major assemblies within the tank are a quantity gage which is shown on the left and a heater-fan assembly which is shown on the right. The problem as I will describe shortly, occurred primarily with the heater-fan assembly which was overheated and damaged.

I will come to the next slide in a moment.

On the table in front of me are the quantity probe itself and the heater-fan assembly which I will be happy to show you after the hearing if you care to look at it.

In addition, on my left is a cut open tank which was subjected to a fire simulating that which actually occurred during the mission, and this tank is available for your examination.

Now, in brief, this is what happened. After assembly and acceptance testing the oxygen tank No. 2 which flew on Apollo 13 was shipped from Beech Aircraft Corp. to North American Rockwell in apparently satisfactory condition. It is now known, however, that the tank contained two protective thermostatic switches on the heater assembly. These switches were inadequate and subsequently failed during ground test operation at Kennedy Space Center.

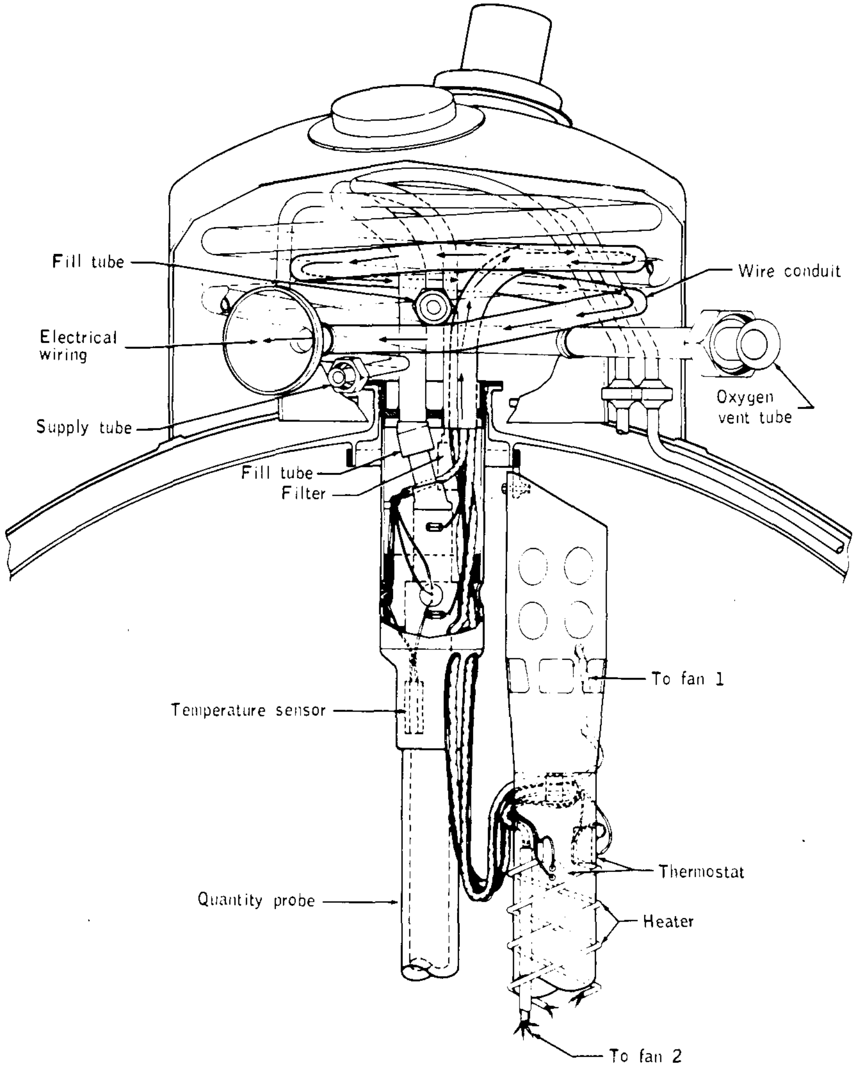


FIGURE 2. Oxygen tank wiring and lines.

Now, the second slide (see figure 2) shows this in a little more detail. As you can see at the top of the heater-fan assembly the word "thermostat" is shown with two arrows. These arrows point to the two thermostatic switches which failed. In addition, there is a fill tube assembly shown right here at the top of the quantity probe which was loose in a manner which I will describe in just a moment and this led to a special detanking procedure which failed those switches and ultimately damaged the wiring.

Now, in addition to these thermostatic switches which subsequently failed, it is probable that the tank contained a loosely fitting fill tube assembly which I just pointed out. This assembly was probably displaced during subsequent handling after shipment and this handling included an incident at the prime contractor's plant in which the tank was jarred.

In itself the displaced fill tube assembly was not particularly serious, but it led to the use of improvised detanking procedures at the Kennedy Space Center which almost certainly set the stage for the accident.

Now, although Beech did not encounter any problem in detanking during the acceptance test of this tank, it was not possible to detank the oxyen tank No. 2 using normal procedures at the Kennedy Space Center. Tests and analyses indicate that this was due to gas leakage through this displaced fill tube assembly that I mentioned.

Now, the special detanking procedures at Kennedy subjected the tank to an extended period of heater operation and pressure cycling. These procedures had not been used before and the tank had not been qualified by tests for the conditions experienced. However, the procedures did not violate the specifications which govern the operation of the heaters at the Kennedy Space Center.

In reviewing these procedures before the flight, officials of NASA, North American Rockwell, and Beech did not recognize the possibility of damage due to overheating. Many of these officials were not aware of the extended heater operation. In any event, the thermostatic switches might have been expected to protect the tank.

A number of factors contributed to the presence of inadequate thermostatic switches in the heater assembly. The original 1962 specifications from North American Rockwell to Beech Aircraft Corp. for the tank and heater assembly specified the use of 28 volt D.C. power which is used in the spacecraft. In 1965 North American Rockwell issued a revised specification which stated that the heater should use a 65 volt d.c. power supply for tank pressurization. This was the power supply used at Kennedy to reduce pressurization time. Beech ordered switches for the block 2 tanks but did not change the switch specifications to be compatible with 65 volt D.C.

The thermostatic switch discrepancy was not detected by NASA, North American Rockwell or Beech in their review of documentation, nor did tests identify the incompatibility of the switches with the ground support equipment at Kennedy, since neither qualification nor acceptance testing required switch cycling under load as should have been done. It was a serious oversight in which all parties shared.

Thermostatic switches could accommodate the 65 volt D.C. during tank pressurization, however, because they normally remain cool and closed. However, they could not open without damage with the 65 volt d.c. power supply. They were never required to do so until the special detanking.

During this procedure as the switches started to open when they reached their upper temperature—they were welded permanently closed or otherwise failed permanently closed by the resulting arc and were rendered inoperative as protective thermostats.

Now, the next slide (see fig. 3) shows a photograph of a switch

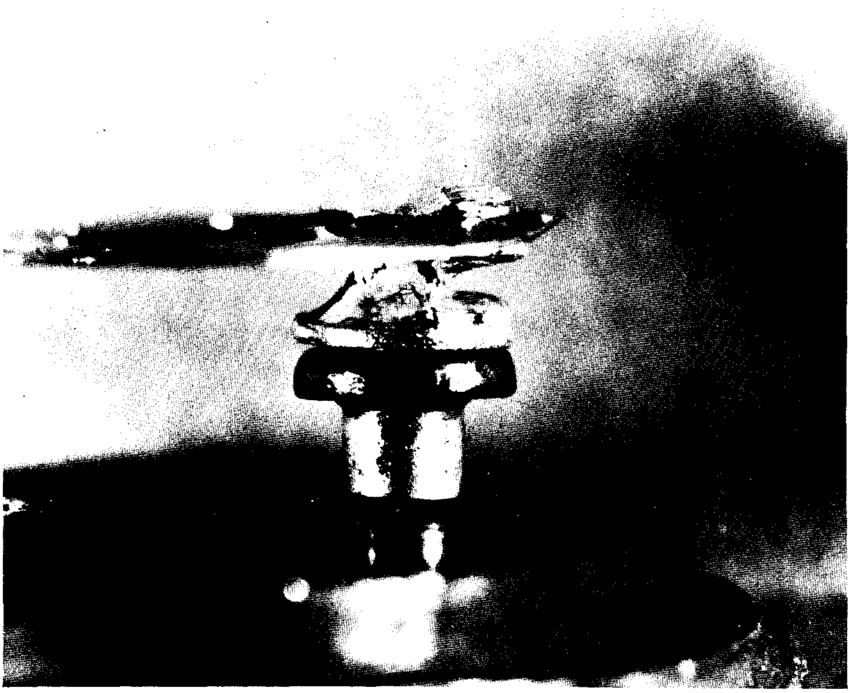


FIGURE 3

which was failed with this current during tests at the Manned Spacecraft Center. The drawing is in the report and in the statement that I submitted today—the photograph is in there.

Failure of the thermostatic switches to open could have been detected at Kennedy Space Center if switch operation had been checked by observing heater current readings on the oxygen tank heater control panel. Although it was not recognized at that time, the tank temperature readings indicated that the heaters had reached their temperature limit and switch openings should have been expected. As shown by subsequent tests, failure of the thermostatic switches probably permitted the temperature of the heater tube assembly to reach about a 1,000 degrees Fahrenheit in spots during the continuous eight-hour period of heater operation. Such heating has been shown by tests to damage severely the Teflon insulation on the fan motor wires in the vicinity of the heater assembly as shown in the next slide. This is

FIGURE 4

a picture of wiring which was taken from the heater assembly after the simulated tank operation in a nitrogen environment. Had this been in an oxygen environment other tests have shown that the insulation deterioration can be even worse. (See fig. 4.)

From that time on, including pad occupancy, the oxygen tank No. 2 was in a hazardous condition when filled with oxygen and electrically powered. It was not until nearly 56 hours into the mission, however, that the fan motor wiring, possibly moved by the fan stirring of the contents of the tank, shortcircuited and ignited this insulation by means of an electric arc. The resulting combustion in the oxygen tank probably overheated and failed the wiring conduit where it enters the tank. This is the tube up here [indicating] where it goes into the top of the tank, and possibly a portion of the tank itself, primarily the cap that goes through the tank at this point.

The rapid expulsion of high pressure oxygen which followed, possibly augmented by combustion of the insulation in the space surrounding the tank, blew off the outer panel to bay No. 4 in the service module, caused a leak in the high pressure system of oxygen tank No. 1, damaged the high gain antenna, caused other miscellaneous damage and aborted the mission.

The accident is judged to have been nearly catastrophic. Only outstanding performance on the part of the crew, mission control and other members of the team which supported the operation successfully returned the crew to earth.

Now, in investigating the accident to Apollo 13, Mr. Chairman, the Board has also attempted to identify those additional technical and management lessons which can be applied to help assure the success of future space flight missions. Several recommendations of this nature are included. In addition, I would like to say that the Board recognizes that the contents of this report are largely of a critical nature. The report highlights in detail faults or deficiencies in equipment and procedures that the Board has identified. This is the nature of a review board report.

It is important, however, in our judgment, to deal with criticisms of this report in a broader context. The Apollo spacecraft system is not without shortcomings but it is the only system of its type ever built and successfully demonstrated. It has flown to the moon five times and landed twice. The tank which failed, the design of which is criticized in this report, is one of a series which has thousands of hours of successful operation in space prior to Apollo 13.

In addition, while the team of designers, engineers and technicians who have built and operate the Apollo spacecraft also has its shortcomings, the accomplishments speak for themselves. We feel by hardheaded criticism and continued dedication this team can maintain this Nation's preeminence in space.

Thank you very much.

(Mr. Cortright's prepared statement follows:)

STATEMENT OF EDGAR M. CORTRIGHT, CHAIRMAN, APOLLO 13 REVIEW BOARD, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION BEFORE THE COMMITTEE ON AERONAUTICAL AND SPACE SCIENCES, U.S. SENATE

Mr. Chairman and Members of the Committee: I appreciate this opportunity to appear before the Committee to summarize the Report of the Apollo 13 Review Board.

As you know, I presented this Report on behalf of the Board to the Administrator and Deputy Administrator on June 15, 1970. At that time, copies of the Report were given to the Members and Staff of the Committee, and the Report was made public.

This morning I would like first to outline for the Committee how the Board was established and how it organized itself to review and report on the Apollo 13 accident. Then I will cover in some detail the findings and determinations of the Board regarding the accident, including pre-accident mission events, the events of the accident itself, and the recovery procedures which were implemented to return the crew safely to earth. I will also summarize the Board's findings and determinations regarding the management, design, manufacturing, and test procedures employed in the Apollo Program as they relate specifically to the accident.

Based on its findings and determinations, the Board made a series of detailed recommendations. These are set forth at the end of my statement.

ESTABLISHMENT AND HISTORY OF THE BOARD

The Apollo 13 Review Board was established, and I was appointed Chairman, on April 17, 1970. The charter of the Board was set forth in the memorandum which established it. Under this charter the Board was directed to:

"(a) Review the circumstances surrounding the accident to the spacecraft which occurred during the flight of Apollo 13 and the subsequent flight and ground actions taken to recover, in order to establish the probable cause or causes of the accident and assess the effectiveness of the recovery actions.

"(b) Review all factors relating to the accident and recovery actions the Board determines to be significant and relevant, including studies, findings, recommendations, and other actions that have been or may be undertaken by the program offices, field centers, and contractors involved.

"(c) Direct such further specific investigations as may be necessary.

"(d) Report as soon as possible its findings relating to the cause or causes of the accident and the effectiveness of the flight and ground recovery actions.

"(e) Develop recommendations for corrective or other actions, based upon its findings and determinations or conclusions derived therefrom.

"(f) Document its findings, determinations, and recommendations and submit a final report."

The Membership of the Board was established on April 21, 1970. The members are:

Mr. Edgar M. Cortright, Chairman (Director, Langley Research Center)
Mr. Robert F. Allnutt (Assistant to the Administrator, NASA Hqs)
Mr. Neil Armstrong (Astronaut, Manned Spacecraft Center)
Dr. John F. Clark (Director, Goddard Space Flight Center)
Brig. General Walter R. Hedrick, Jr. (Director of Space, DCS/R&D, Hqs USAF)
Mr. Vincent L. Johnson (Deputy Associate Administrator, Engineering, Office of Space Science and Applications)
Mr. Milton Klein (Manager, AEC-NASA Space Nuclear Propulsion Office)
Dr. Hans M. Mark (Director, Ames Research Center)

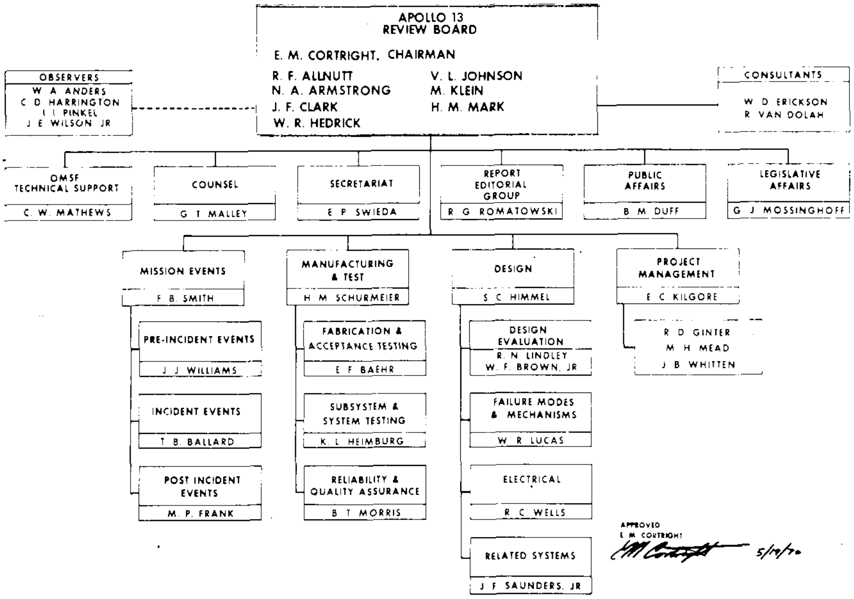
Legal Counsel to the Board is Mr. George T. Malley, Chief Counsel, Langley Research Center.

Appointed as Observers were:

Mr. William A. Anders (Executive Secretary, National Aeronautics and Space Council)
Dr. Charles D. Harrington (Chairman, NASA Aerospace Safety Advisory Panel)
Mr. I. I. Pinkel (Director, Aerospace Safety Research and Data Institute, NASA Lewis Research Center)
Mr. James E. Wilson, Jr., (Technical Consultant, House of Representatives, Committee on Science and Astronautics)

The documents establishing the Board and its membership and other relevant documents are included in Chapter 1 of the Board's Report.

The Review Board convened at the Manned Spacecraft Center (MSC), Houston, Texas, on Tuesday, April 21, 1970. Four Panels of the Board were formed, each under the overview of a member of the Board. Each of the Panels was chaired by a senior official experienced in the area of review assigned to the Panel. In addition, each Panel was manned by a number of experienced specialists to provide in-depth technical competence for the review activity. During the period of the Board's activities, the Chairmen of the four Panels were responsible for the conduct of reviews, evaluations, analyses, and other studies bearing on their Panel assignments and for preparing documented reports for the Board's consideration. Complementing the Panel efforts, each member of the Board assumed specific responsibilities related to the overall review.



On figure 5 is shown a chart depicting the organization of the Board. The four Panels—Mission Events, Manufacturing and Test, Design, and Project Management—are shown along with the subpanels and the supporting office structure. The membership and responsibilities of each Panel are set forth in the Report.

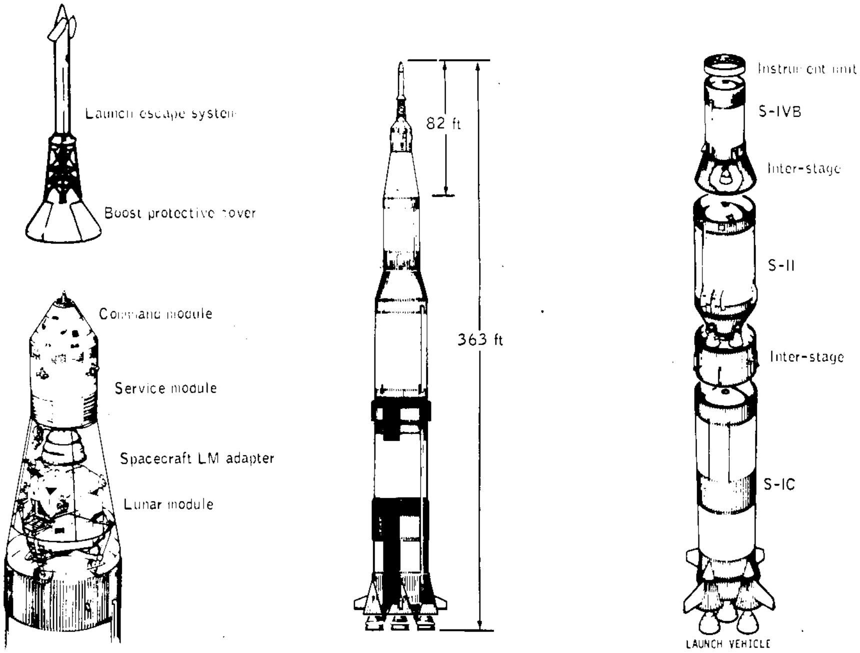
While the Board's intensive review activities were underway, the Manned Spacecraft Center Apollo 13 Investigation Team, under James A. McDivitt, Director of the MSC Apollo Spacecraft Program Office, was also conducting its own analysis of the Apollo 13 accident. Coordination between the Investigation Team work and the Apollo 13 Review Board activities was effected through the Manned Space Flight Technical Support official and by maintaining a close and continuing working relationship between the Panel Chairmen and officials of the MSC Investigation Team. In addition, Board members regularly attended daily status meetings of the Manned Spacecraft Center Investigation Team.

In general, the Board relied on Manned Spacecraft Center post-mission evaluation activities to provide the factual data base for evaluation, assessment, and analysis efforts. However, the Board, through a regular procedure, also levied specific data collection, reduction, and analysis requirements on MSC. Test support for the Board was provided by MSC, but in addition, the Board established an extensive series of special tests and analyses at other NASA Centers and at contractor facilities. Members of the Board and its Panels also visited contractor facilities to review manufacturing, assembly, and test procedures applicable to Apollo 13 mission equipment.

In this test program, which included nearly 100 separate tests, and which involved several hundred people at its peak, the elements of the inflight accident were reproduced. All indications are that electrically initiated combustion of Teflon insulation in oxygen tank No. 2 in the service module was the cause of the Apollo 13 accident. One series of tests demonstrated electrical ignition of Teflon insulation in supercritical oxygen under zero g and at one g, and provided data on ignition energies and burning rates. Other tests, culminating in a complete flight tank combustion test, demonstrated the most probable tank failure mode. Simulated tank rupture tests in a ½ scale service module verified the pressure levels necessary to eject the panel from the service module. Other special tests and analyses clarified how they might have been generated. I have with me a brief film, highlighting these tests, which I would like to show at the conclusion of my statement.

APOLLO 13 SYSTEMS

Before tracing the analyses which led to the Board's conclusions—and to place them in proper context—I would like to explain the design and functions of the oxygen tank #2 as a part of the Apollo system. Details of the entire Apollo/Saturn Space Vehicle are set forth in the Report and its Appendices.



Spacecraft

Space vehicle

Launch vehicle

FIGURE 6

Figure 6 shows the Apollo/Saturn Space Vehicle, with which you are all familiar. Figure 7 shows the service module which, as you know, is designed to provide the main spacecraft propulsion and maneuvering capability during a

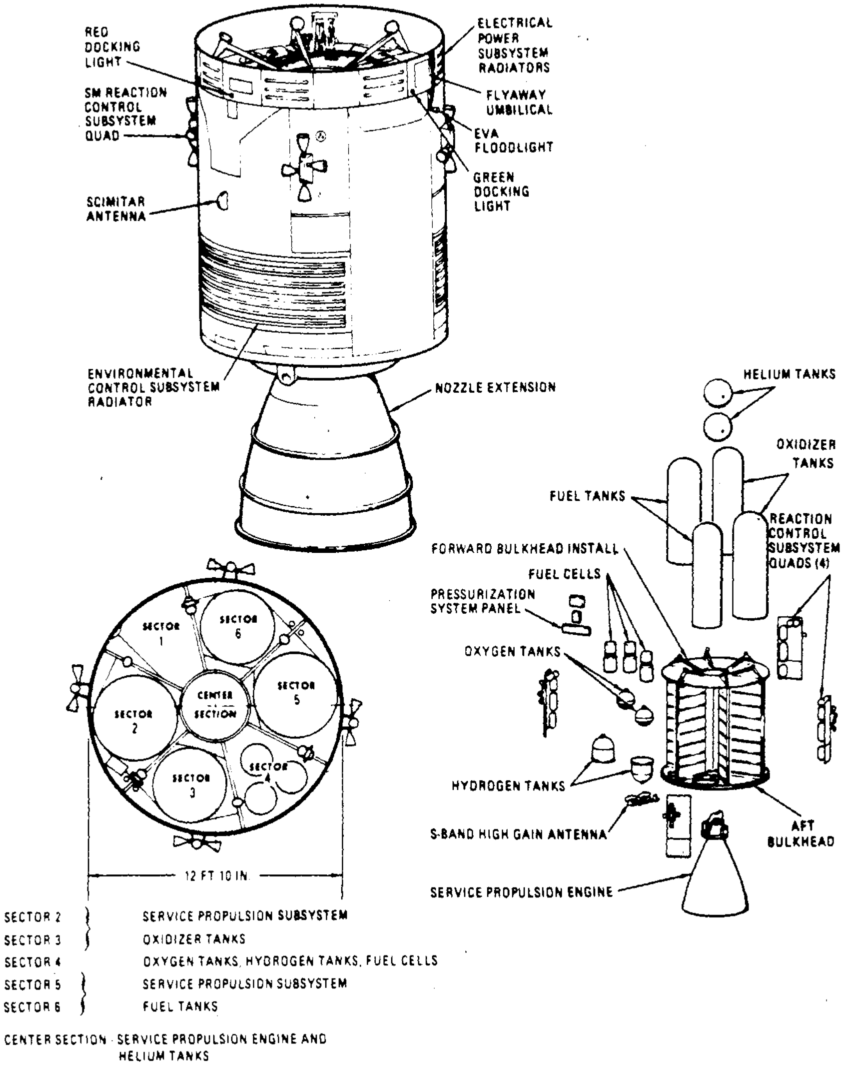


FIGURE 7

mission. It also contains most of the spacecraft consumables (oxygen, water, propellant, and hydrogen) and supplies electrical power. The service module is divided into six sectors or bays surrounding a center section. The oxygen tank, to which I referred, is located in Bay 4 (shown in more detail on figure 8), NASA-S-70-512-V

ARRANGEMENT OF FUEL CELLS AND CRYOGENIC SYSTEMS IN BAY 4

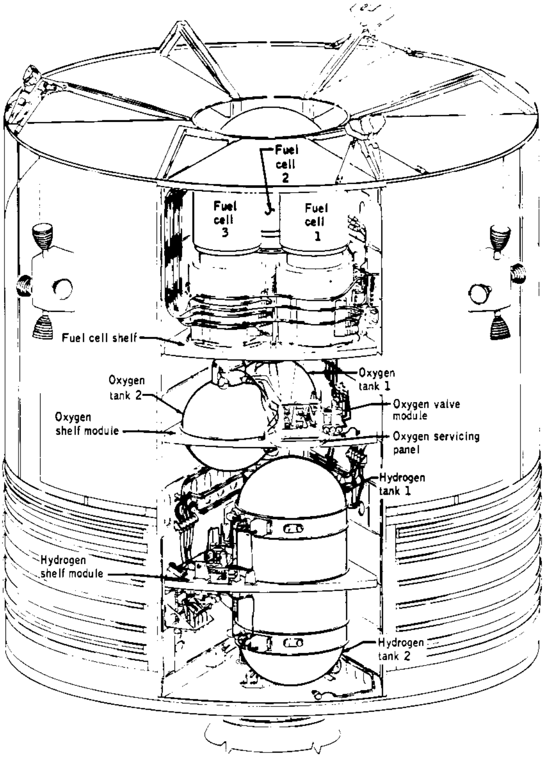


FIGURE 8

along with another oxygen tank, two hydrogen tanks, three fuel cells and interconnecting lines, and measuring and control equipment. The tanks supply oxygen to the environmental control system (ECS) for the astronauts to breathe, and oxygen and hydrogen to the fuel cells. The fuel cells generate the electrical power for the command and service modules during a mission. The next slides (figures 9, 10, and 11) are photographs of Bay 4 of the service module for Apollo 13, showing the major elements and their interconnection. Slide 7 shows the oxygen tank #2 in place.

Figure 9

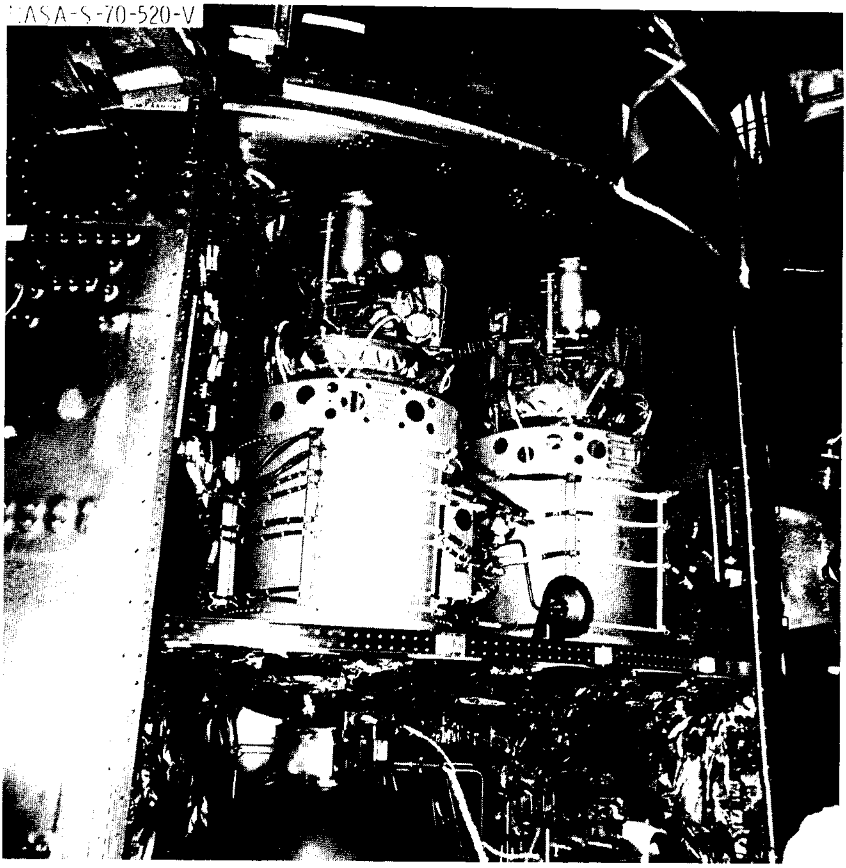


FIGURE 10

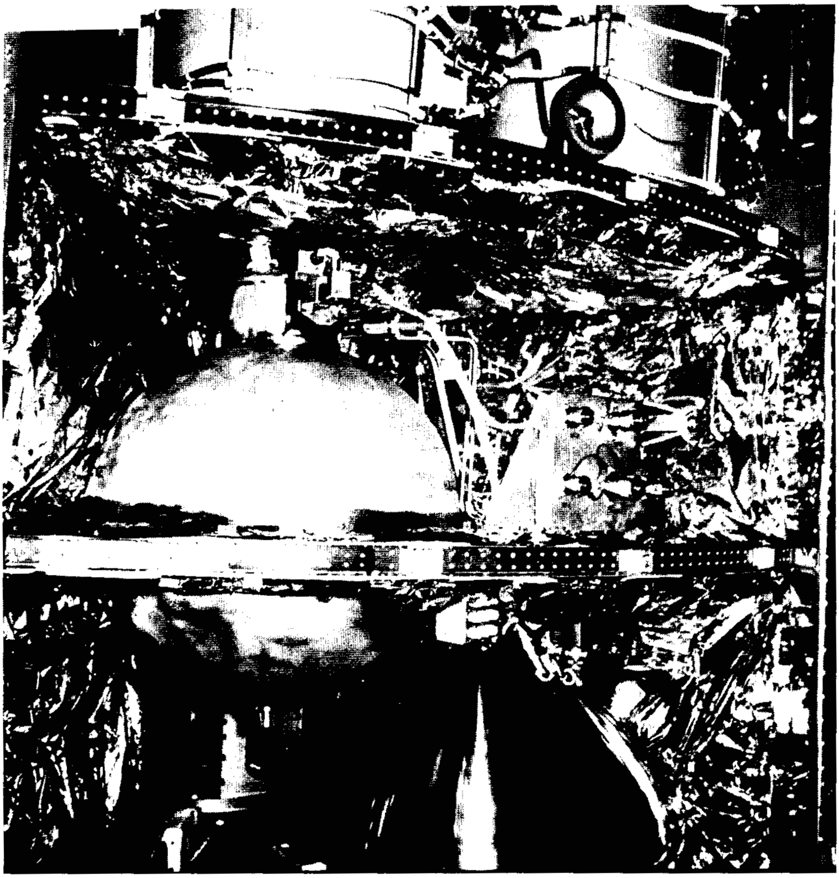


FIGURE 11

As the simplified drawing in the next slide indicates (see figure 12) each oxygen tank has an outer shell and an inner shell, arranged to provide a vacuum space to reduce heat leak, and a dome enclosing paths into the tank for transmission of fluids, and electrical power and signals. The space between the shells and the space in the dome are filled with insulating materials. Mounted in the tank are two tubular assemblies. One, called the heater tube, contains two thermostatically protected heater coils and two small fans driven by 1800 RPM motors to stir the tank contents. The other assembly, called the quantity probe, consists of a cylindrical capacitance gage used to measure electrically the quantity of fluid in the tank. The inner cylinder of this probe is connected through the top

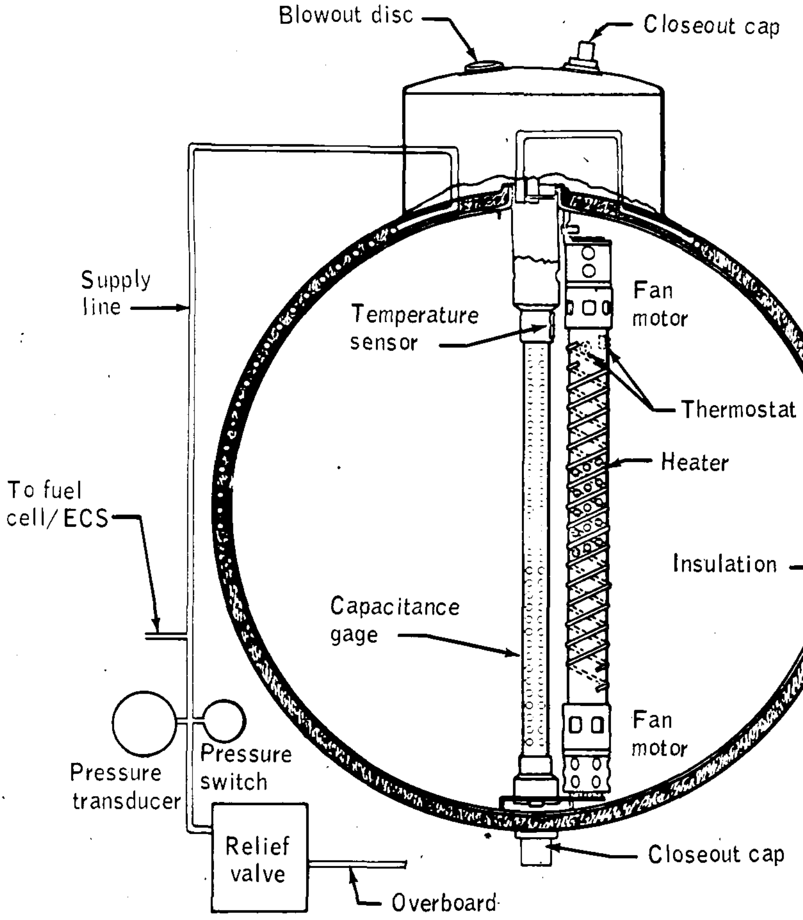


FIGURE 12

of the tank to a fill line from the exterior of the SM and serves both as a fill and drain tube and as one plate of the capacitance gage. In addition, a temperature sensor is mounted on the outside of the quantity probe near the head. Wiring for the quantity gage, the temperature sensor, the fan motors, and the heaters passes through the head of the quantity probe, through a conduit in the dome and to a connector to the appropriate external circuits in the CSM. The routing of wires and lines from the tank through the dome is shown in slide 9 (see figure 13).

The oxygen tank, as designed, contained materials, which if ignited will burn in supercritical oxygen. These include Teflon, used, for example, to insulate the wiring, and aluminum.

Pressure in the tank is measured by a pressure gage in the supply line, and a pressure switch near this gage is provided to turn on the heaters in the oxygen tank if the pressure drops below a preselected value. This periodic addition of heat to the tank maintains the pressure at a sufficient level to satisfy the demand for oxygen as tank quantity decreases during a flight mission.

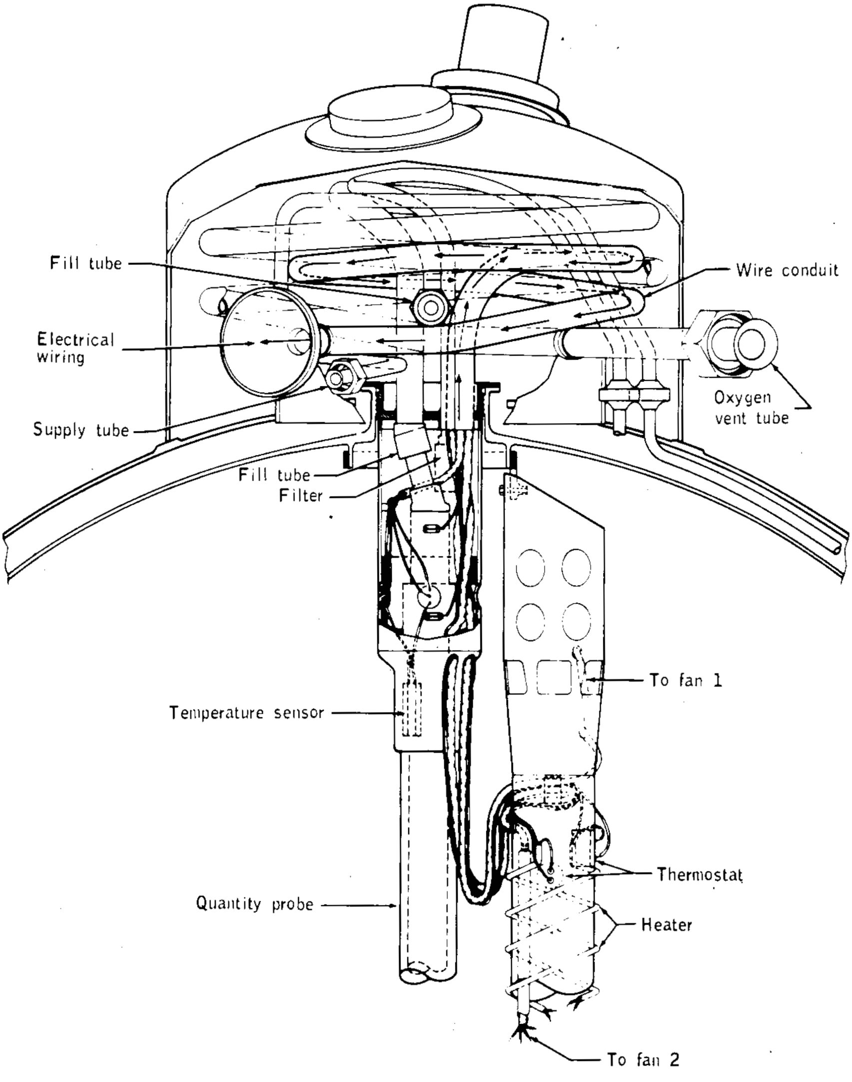


FIGURE 13

The oxygen tank is designed for a capacity of 320 pounds of supercritical oxygen at pressures ranging between 865 and 935 pounds per square inch absolute (psia). The tank is initially filled with liquid oxygen at —297°F and operates over the range from —340°F to +80°F. The term "supercritical" means that the oxygen is maintained at a temperature and pressure which assures that it is a homogenous, single-phase fluid.

The burst pressure of the oxygen tank is about 2200 psia at —150°F, over twice the normal operating pressure at that temperature. A relief valve in the supply line leading to the fuel cells and the ECS is designed to relieve pressure in the oxygen tank at a pressure of approximately 1000 psi. The oxygen tank dome is open to the vacuum between the inner and outer tank shell and contains a rupture disc designed to blow out at about 75 psi.

As shown in figure 13, each heater coil is protected with a thermostatic switch, mounted on the heater tube, which is intended to open the heater circuit when it senses a temperature of 80°F. As I will point out later in tracing the Board's conclusions as to the cause of the accident, when the heaters were powered from a 65 volt DC supply at KSC during an improvised detanking procedure, these thermostatic switches, because they were rated at only 30 V DC, could not prevent an overheating condition of the heaters and the associated wiring. Tests conducted for the Board indicate that the heater tube assembly was probably heated to a temperature of as much as 1000°F during this detanking procedure.

THE APOLLO 13 MISSION

With this general background, I will now summarize the Apollo 13 mission. This mission, as you know, was designed to perform the third manned lunar landing. The selected site was in the hilly uplands of the Fra Mauro formation. A package of five scientific experiments was planned for emplacement on the lunar surface near the lunar module landing point. Additionally the Apollo 13 landing crew was to gather the third set of selenological samples of the lunar surface for return to earth for extensive scientific analysis. Candidate future landing sites were scheduled to be photographed from lunar orbit. The crew consisted of Captain Jame A. Lovell, Commander; Fred W. Haise, Lunar Module Pilot; and John L. Swigert, Jr., Command Module Pilot, who replaced Thomas K. Mattingly, III, who had been exposed to rubella and, after tests, found not to be immune.

Launch was on time at 2:13 p.m., EST on April 11 from the KSC Launch Complex 39A. The spacecraft was inserted into a 100-nautical mile circular earth orbit. The only significant launch phase anomaly was premature shutdown of the center engine of the S–II second stage. This anomaly, although serious, was not related to the subsequent accident. It is being investigated by the Apollo organization. As a result of this shutdown, the remaining four S–II engines burned 34 seconds longer than planned and the S–IVB third stage engine burned a few seconds longer than planned. At orbital insertion, the velocity was within 1.2 feet per second of the planned velocity. Moreover, an adequate propellant margin was maintained in the S–IVB for the translunar injection burn.

After spacecraft systems checkout in earth orbit, the S–IVB restarted for the translunar injection (TLI) burn, with shutdown coming some six minutes later. After TLI, Apollo 13 was on the planned free-return trajectory with a predicted closest approach to the lunar surface of 210 nautical miles.

The command and service module (CSM) was separated from the S–IVB about three hours into the mission, and after a brief period of station-keeping, the crew maneuvered the CSM into dock with the LM vehicle in the LM adapter atop the S–IVB stage. The S–IVB stage was separated from the docked CSM and LM shortly after four hours into the mission, and placed on a trajectory to ultimately impact the moon near the site of the seismometer emplaced by the Apollo 12 crew.

At 30:40:49 g.e.t. (ground elapsed time) a midcourse correction maneuver was made using the service module propulsion system. This maneuver took Apollo 13 off a free-return trajectory and placed it on a non-free return trajectory. A similar profile had been flown on Apollo 12. The objective of leaving a free-return trajectory is to control the arrival time at the moon to insure the proper lighting conditions at the landing site. The transfer maneuver lowered the predicted closest approach to the moon, or pericynthion altitude, from 210 to 64 nautical miles.

From launch through the first 46 hours of the mission, the performance of the oxygen tank #2 was normal, so far as telemetered data and crew observations indicate. At 46:40:02, the crew turned on the fans in oxygen tank #2 as a routine operation, and the oxygen tank #2 quantity indication changed from a normal reading to an obviously incorrect reading "off scale high" of over 100 percent. Subsequent events indicate that the cause was a short circuit which was not hazardous in this case.

At 47:54:50 and at 51:07:44 the oxygen tank #2 fans were turned on again, with no apparent adverse effects. The quantity gage continued to read "off scale high."

Following a rest period, the Apollo 13 crew began preparations for activating and powering up the lunar module for checkout. At about 53 and one-half hours g.e.t. Astronauts Lovell and Haise were cleared to enter the LM to commence in-flight inspection for the LM. After this inspection period, the lunar module was powered down and preparations were underway to close the LM hatch and run through the presleep checklist when the accident in oxygen tank #2 occurred.

At about 55:53, flight controllers in the Mission Control Center at MSC requested the crew to turn on the cryogenic system fans and heaters, since a master alarm on the CM Caution and Warning System had indicated a low pressure condition in the cryogenic hydrogen tank #1. This tank had reached the low end of its normal operating pressure range several times previously during the flight. Swigert acknowledged the fan cycle request and data indicate that current was applied to the oxygen tank #2 fan motors at 55:53:20.

About 2½ minutes later, at 55:54:53.5, telemetry from the spacecraft was lost almost totally for 1.8 seconds. During the period of data loss, the Caution and Warning System alerted the crew to a low voltage condition on DC Main Bus B, one of the two main buses which supply electrical power for the command module. At about the same time, the crew heard a loud "bang" and realized that a problem existed in the spacecraft. It is now clear that oxygen tank #2 or its associated tubing lost pressure integrity because of combustion within the tank, and that the effects of oxygen escaping from the tank caused the removal of the panel covering Bay 4 and a relatively slow leak in oxygen tank #1 or its lines or valves. Photographs of the service module taken by the crew later in the mission (figure 14) show the panel missing, the fuel cells on the shelf above the oxygen shelf tilted, and the high gain antenna damaged.

The resultant loss of oxygen made the fuel cells inoperative, leaving the CM with batteries normally used only during reentry as the sole power source and with only that oxygen contained in a surge tank and repressurization packages. The lunar module, therefore, became the only source of sufficient battery power and oxygen to permit safe return of the crew to earth.

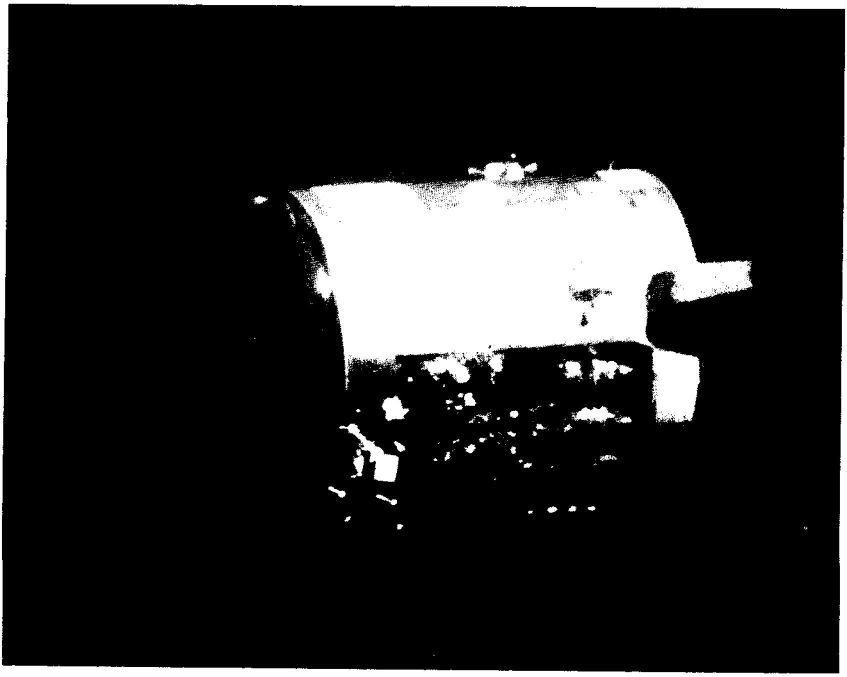


FIGURE 14

SUMMARY ANALYSIS OF THE ACCIDENT

The Board determined that combustion in oxygen tank #2 led to failure of that tank, damage to oxygen tank #1 or its lines or valves adjacent to tank #2, removal of the Bay 4 panel and, through the resultant loss of all three fuel cells, to the decision to abort the Apollo 13 mission. In the attempt to determine the cause of ignition in oxygen tank #2, the course of propagation of the combustion, the mode of tank failure, and the way in which subsequent damage occurred, the Board has carefully sifted through all available evidence and examined the results of nearly 100 special tests and analyses conducted by the Apollo organization and by or for the Board after the accident.

Although tests and analyses are continuing, sufficient information is now available to provide a clear picture of the nature of the accident and the events which led up to it. It is now apparent that the extended heater operation at KSC damaged the insulation on wiring in the tank and that this set the stage for the electrical short circuits which initiated combustion within the tank. While the exact point of initiation of combustion and the specific propagation path involved may never be known with certainty, the nature of the occurrence is sufficiently well understood to permit taking corrective steps to prevent its recurrence.

The Board has identified the most probable failure mode.

The following discussion treats the accident in its key phases: initiation, propagation and energy release, loss of oxygen tank No. 2 system integrity, and loss of oxygen tank No. 1 system integrity. Figure 15 shows the key events in the sequence.

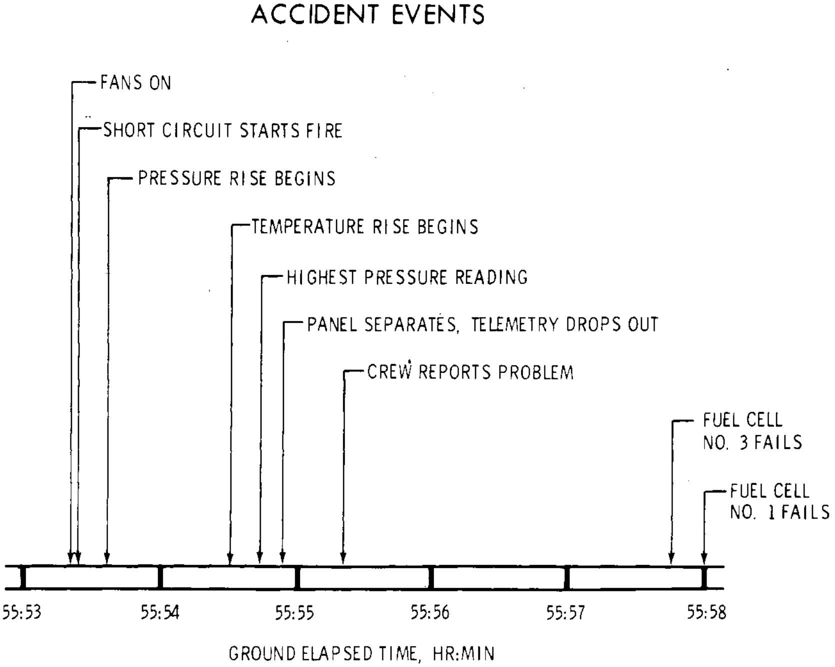


FIGURE 15

Initiation

The evidence points strongly to an electrical short circuit with arcing as the initiating event. Near the end of the 55th hour of flight, about 2.7 seconds after the fans were turned on in the SM oxygen tanks, an 11.1 ampere current spike and simultaneously a voltage drop spike were recorded in the spacecraft electrical system. Immediately thereafter current drawn from the fuel cells decreased by an amount consistent with the loss of power to one fan. No other changes in spacecraft power were being made at the time. No power was on the heaters in the tanks at the time and the quantity gage and temperature sensor are very low power devices. The next anomalous event recorded was the beginning of a pressure rise in oxygen tank No. 2, 13 seconds later. Such a time lag is possible with low level combustion at the time. These facts point to the likelihood that an electrical short circuit with arcing occurred in the fan motor or its leads to initiate the accident sequence. The energy available from the short circuit is estimated to have been at least 10 to 20 joules. Tests conducted during this investigation have shown that this energy is more than adequate to ignite Teflon wire insulation of the type contained within the tank.

This likelihood of electrical initiation is enhanced by the high probability that the electrical wires within the tank were damaged during the abnormal detanking operation at KSC prior to launch. The likelihood of damage and the possibility of electrical ignition have been verified by tests.

Propagation

While there is enough electrical power in the tank to cause ignition in the event of an arcing short circuit in defective wire, there is not sufficient electric power to account for all of the energy required to produce the observed pressure rise.

There are materials within the tank that can, if ignited in the presence of supercritical oxygen, react chemically with the oxygen in heat-producing chemical reactions. The most readily reactive is Teflon, used for electrical insulation in the tank. Also potentially reactive are aluminum and solder. Our analyses indicate that there is more than sufficient Teflon in the tank, if reacted with oxygen, to account for the pressure and temperature increases recorded. Furthermore, the pressure rise took place over a period of more than 69 seconds, a relatively long period, and one which would be more likely characteristic of Teflon combustion than metal-oxygen reactions.

Thus, the Board concluded that combustion caused the pressure and temperature increases recorded in oxygen tank #2. The pressure reading for oxygen tank #2 began to increase about 13 seconds after the first electrical spike and about 55 seconds later the temperature began to increase. The temperature sensor reads local temperature, which need not represent bulk fluid temperature. Since the rate of pressure rise in the tank indicates a relatively slow propagation of burning along the wiring, it is likely that the region immediately around the temperature sensor did not become heated until this time.

The data on the combustion of Teflon in supercritical oxygen in zero gravity, developed in special tests in support of the Board, indicate that the rate of combustion is generally consistent with these observations.

Loss of oxygen tank #2 system integrity

After the relatively slow propagation process described above took place, there was a relatively abrupt loss of oxygen tank #2 integrity. About 69 seconds after the pressure began to rise, it reached the peak recorded, 1008 psia, the pressure at which the cryogenic oxygen tank relief valve is designed to be fully open. Pressure began a decrease for 8 seconds, dropping to 996 psia before readings were lost. About 1.85 seconds after the last presumably valid reading from within the tank (a temperature reading) and .8 seconds after the last presumably valid pressure reading (which may or may not reflect the pressure within the tank itself since the pressure transducer is about 20 feet of tubing length distant), virtually all signal from the spacecraft was lost. Abnormal spacecraft accelerations were recorded approximately .42 seconds after the last pressure reading and approximately .38 seconds before the loss of signal. These facts all point to a relatively sudden loss of integrity. At about this time, several solenoid valves, including the oxygen valves feeding two of the three fuel cells, were shocked to the closed position. The "bang" reported by the crew also occurred in this time period. Telemetry signals from Apollo 13 were lost for a period of 1.8 seconds. When signal was reacquired, all instrument indicators from oxygen tank #2 were off-scale, high or low. Temperatures recorded by sensors in several different locations in the service module showed slight increases in the several seconds following reacquisition of signal.

Data are not adequate to determine precisely the way in which the oxygen tank #2 system failed. However, available information, analyses, and tests performed during this investigation indicate that the combustion within the pressure vessel ultimately led to localized heating and failure at the pressure vessel closure. It is at this point, the upper end of the quantity probe, that the ½-inch Inconel conduit is located, through which the Teflon insulated wires enter the pressure vessel. It is likely that the combustion progressed along the wire insulation and reached this location where all of the wires come together. This, possibly augmented by ignition of other Teflon parts and even metal in the upper end of the probe, led to weakening and failure of the closure or the conduit or both.

Failure at this point would release the nearly-1000 psi pressure in the tank into the tank dome, which is equipped with a rupture disc rated at 75 psi. Rupture of this disc or of the entire dome would then release oxygen, accompanied by combustion products, into Bay 4. The accelerations recorded were probably caused by this release.

Release of the oxygen then began to rapidly pressurize the oxygen shelf space of Bay 4. If the hole formed in the pressure vessel were large enough and formed rapidly enough, the escaping oxygen alone would be adequate to blow off the Bay 4 panel. However, it is also quite possible that the escape of oxygen was accompanied by combustion of Mylar and Kapton (used extensively as thermal insulation in the oxygen shelf compartment and in the tank dome) which would augment the pressure caused by the oxygen itself. The slight temperature increases recorded at various locations in the service module indicate that combustion external to the tank probably took place. The ejected Bay 4 panel then struck the high gain antenna, disrupting communications from the spacecraft for the 1.8 seconds.

Loss of oxygen tank #1 integrity

There is no clear evidence of abnormal behavior associated with oxygen tank #1 prior to loss of signal, although the one data bit (4 psi) drop in pressure in the last tank #1 pressure reading prior to loss of signal may indicate that a problem was beginning. Immediately after signal strength was regained, data show that the tank #1 system had lost its integrity. Pressure decreases were recorded over a period of approximately 130 minutes, indicating that a relatively slow leak had developed in the tank #1 system. Analysis has indicated that the leak rate is less than that which would result from a completely ruptured line, but could be consistent with a partial line rupture or a leaking check valve or relief valve.

Since there is no evidence that there were any anomalous conditions arising within oxygen tank #1, it is presumed that the loss of oxygen tank #1 integrity resulted from the oxygen tank #2 system failure. The relatively sudden, and possibly violent, event associated with the failure of the oxygen tank #2 system could have ruptured a line to oxygen tank #1, or have caused a valve to leak because of mechanical shock.

APOLLO 13 RECOVERY

Understanding the problem

In the period immediately following the Caution and Warning Alarm for Main Bus B undervoltage, and the associated "bang" reported by the crew, the cause of the difficulty and the degree of its seriousness were not apparent.

The 1.8-second loss of telemetered data was accompanied by the switching of the CSM high gain antenna mounted on the SM adjacent to Bay 4 from narrow beam width to wide beam width. The high gain antenna (HGA) does this automatically 200 milliseconds after its directional lock on the ground signal has been lost.

A confusing factor was the repeated firings of various SM attitude control thrusters during the period after data loss. In all probability, these thrusters were being fired to overcome the effects that oxygen venting and panel blow-off were having on spacecraft attitude, but it was believed for a time that perhaps the thrusters were malfunctioning.

The failure of oxygen tank #2 and consequent removal of the Bay 4 panel produced a shock which closed valves in the oxygen supply lines to fuel cells 1 and 3. These fuel cells ceased to provide power in about three minutes, when the supply of oxygen between the closed valves and the cells was depleted.

The crew was not alerted to closure of the oxygen feed valves to fuel cells 1 and 3 because the valve position indicators in the CM were arranged to give warning only if both the oxygen and hydrogen valves closed. The hydrogen valves remained open. The crew had not been alerted to the oxygen tank #2 pressure rise or to its subsequent drop because a hydrogen tank low pressure warning had blocked the cryogenic subsystem portion of the Caution and Warning System several minutes before the accident. A limit sense light presumably came on in Mission Control during the brief period of tank overpressure, but was not noticed.

When the crew heard the "bang" and got the master alarm for low DC Main Bus B voltage, Lovell was in the lower equipment bay of the command module, stowing a television camera which had just been in use. Haise was in the tunnel between the CSM and the LM, returning to the CSM. Swigert was in the left hand couch, monitoring spacecraft performance. Because of the master alarm indicating low voltage, Swigert moved across to the right hand couch where CSM voltages can be observed. He reported that voltages were "looking good" at 55:56:10. At this time, voltage on Main Bus B had returned to normal levels and fuel cells 1 and 3 did not fail for another 1½ to 2 minutes. He also reported fluctuations in the oxygen tank #2 quantity, followed by a return to the off-scale high position.

When fuel cells 1 and 3 electrical output readings went to zero, the ground controllers could not be certain that the cells had not somehow been disconnected from their respective buses and were not otherwise all right. Consequently about five minutes after the accident, controllers asked the crew to connect fuel cell 3 to DC Main Bus B in order to be sure that the configuration was known. When it was realized that fuel cells 1 and 3 were not functioning, the crew was directed to perform an emergency power-down to reduce the load on the remaining fuel cell. Observing the rapid decay in oxygen tank #1 pressure, controllers asked the crew to re-power instrumentation in oxygen tank #2. When this was done, and it was realized that oxygen tank #2 had failed, the extreme seriousness of the situation became clear.

During the succeeding period, efforts were made to save the remaining oxygen in the oxygen tank #1. Several attempts were made, but had no effect. The pressure, continued to decrease.

It was obvious by about one-and-one-half hours after the accident that the oxygen tank #1 leak could not be stopped and that it would soon become necessary to use the LM as a "lifeboat" for the remainder of the mission.

By 58:40, the LM had been activated, the inertial guidance reference transferred from the CSM guidance system to the LM guidance system, and the CSM systems were turned off.

Return to earth

The remainder of the mission was characterized by two main activities—planning and conducting the necessary propulsion maneuvers to return the spacecraft to earth, and managing the use of consumables in such a way that the LM, which is designed for a basic mission with two crewmen for a relatively short duration, could support three men and serve as the control vehicle for the time required.

One significant anomaly was noted during the remainder of the mission. At about 97 hours 14 minutes into the mission, Haise reported hearing a "thump" and observing venting from the LM. Subsequent data review shows that the LM electrical power system experienced a brief but major abnormal current flow at that time. There is no evidence that this anomaly was related to the accident. Analysis by the Apollo organization is continuing.

A number of propulsion options were developed and considered. It was necessary to return the spacecraft to a free-return trajectory and to make any required midcourse corrections. Normally, the Service Propulsion Systems (SPS) in the SM would be used for such maneuvers. However, because of the high electrical power requirements for using that engine, and in view of its uncertain condition and the uncertain nature of the structure of the SM after the accident, it was decided to use the LM descent engine if possible.

The minimum practical return time was 133 hours to the Atlantic Ocean, and the maximum was 152 hours to the Indian Ocean. Recovery forces were deployed in the Pacific. The return path selected was for splashdown in the Pacific Ocean at 142:40 g.e.t. This required a minimum of two burns of the LM descent engine. A third burn was subsequently made to correct the normal maneuver execution variations in the first two burns. One small velocity adjustment was also made with reaction control system thrusters. All burns were satisfactory. Figures 16 and 17 depict the flight plan followed from the time of the accident to splashdown.

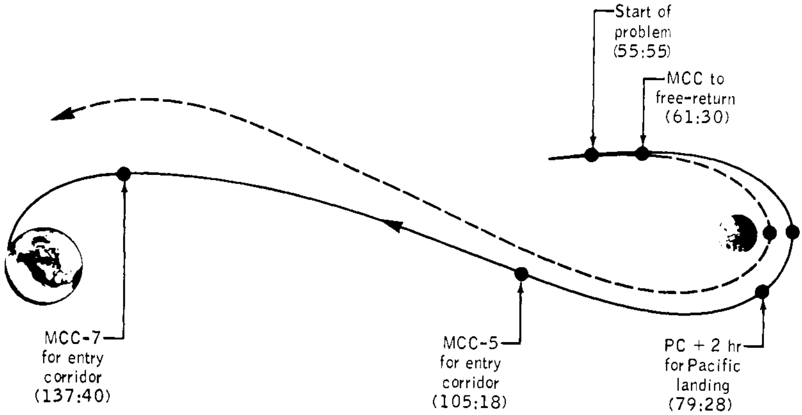


FIGURE 16

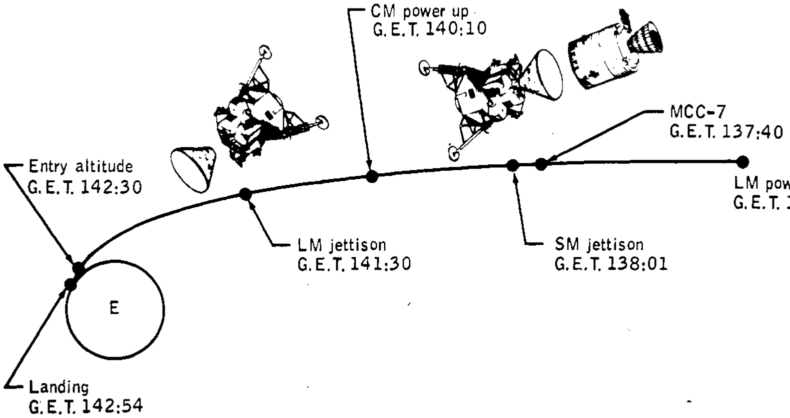


FIGURE 17

The most critical consumables were water, used to cool the CSM and LM systems during use; CSM and LM battery power, the CSM batteries being for use during reentry and the LM batteries needed for the rest of the mission; LM oxygen for breathing; and lithium hydroxide (LiOH) filter cannisters used to remove carbon dioxide from the spacecraft cabin atmosphere. These consumables, and in particular the water and LiOH cannisters, appear to be extremely marginal in quality shortly after the accident, but once the LM was powered down to conserve electric power and to generate less heat and thus use less water. the situation greatly improved. Engineers at MCS developed a method which allowed the crew to use materials onboard to fashion a device allowing the use of the CM LiOH cannisters in the LM cabin atmosphere cleaning system. At splashdown time, many hours of each consumable remained available.

With respect to the steps taken after the accident, Mission Control and the crew worked, under trying circumstances, as well as was humanly possible, which was very well indeed.

The Board's conclusion that the Apollo 13 accident resulted from an unusual combination of mistakes, coupled with a somewhat deficient and unforgiving design, is based on the Board's in-depth analysis of the oxygen tank, its design, manufacturing, test, handling, checkout, use, failure mode, and eventual effects on the rest of the spacecraft.

OXYGEN TANK #2 HISTORY

On February 26, 1966, the North American Aviation Corporation, now North American Rockwell (NR), prime contractor for the Apollo command and service modules (CSM), awarded a subcontract to the Beech Aircraft Corporation (Beech) to design, develop, fabricate, assemble, test, and deliver the Block II Apollo cryogenic gas storage subsystem. This was a follow-on to an earlier subcontract under which the somewhat different Block I subsystem was procured.

Manufacture

The manufacture of oxygen tank #2 began in 1966. In its review, the Board noted that the design inherently requires during assembly a substantial amount of wire movement inside the tank, where movement cannot be readily observed, and where possible damage to wire insulation by scraping or flexing cannot be easily detected before the tank is capped off and welded closed. It does not appear, however, that these design deficiencies played any part in the accident.

Several minor manufacturing flaws were discovered in the oxygen tank #2 in the course of testing. A porosity in a weld on the lower half of the outer shell necessitated grinding and rewelding. Rewelding was also required when it was determined that incorrect welding wire had been inadvertently used for a small weld on a vacuum pump mounted on the outside tank dome. The upper fan motor originally installed was noisy and drew excessive current. The tank was disassembled and the heater assembly fans, and heaters were replaced.

Following acceptance testing at Beech; during which the tank was filled and detanked without apparent difficulty, oxygen tank #2 was shipped to NR on May 3, 1967, for installation, which was completed on March 11, 1968, on a shelf to be installed in service module 106 for flight in the Apollo 10 mission.

From April 27 to May 29, 1968, the assembled oxygen shelf underwent standard proof pressure, leak, and functional checks. One valve on the shelf leaked and was repaired, but no anomalies were noted with regard to oxygen tank #2, and therefore no rework of oxygen tank #2 was required.

On June 4, 1968, the shelf was installed in SM 106.

Between August 3 and August 8, 1968, testing of the shelf in the SM was conducted, including operation of the heater controls and fan motors. No anomalies were noted.

Due to electromagnetic interference problems with the vacuum pumps on cryogenic tank domes in earlier Apollo spacecraft, a modification was introduced and a decision was made to replace the complete oxygen shelf in SM 106. An oxygen shelf was approved modifications was prepared for installation in SM 106. On October 21, 1968, the oxygen shelf was removed from SM 106 for the required modification and installation in a later spacecraft.

During the initial attempt to remove the shelf, one shelf bolt was mistakenly left in place; and as a consequence, after the shelf was raised about two inches, the lifting support broke, allowing the shelf to drop back into place. At the time, it was believed that the oxygen shelf had simply dropped back into place, and an analysis was performed to calculate the forces resulting from a drop of two inches. It now seems likely that the shelf was first accelerated upward and then dropped.

The remaining bolt was then removed, the incident recorded, and the oxygen shelf was removed without further difficulty. Following removal, the oxygen shelf was retested to check shelf integrity, including proof pressure tests, leak tests, and fan and heater operation. Visual inspection revealed no problem. These tests would have disclosed external leakage or serious internal malfunctions of most types, but would not disclose fill line leakage within oxygen tank #2. Further calculations and tests conducted during this investigation have indicated that the forces experienced by the shelf were probably close to those originally calculated, assuming a 2-inch drop only. The probability of tank damage from this incident, therefore, is now considered to be rather low, although it is possible that a loosely fitting fill tube assembly could have been displaced by the event.

The shelf passed these tests and was installed in SM 109, the Apollo 13 service module, on November 22, 1968. The shelf tests accomplished earlier in SM 106 were repeated in SM 109 in late December and early January, with no significant problems, and SM 109 was shipped to KSC in June of 1969 for further testing, assembly on the launch vehicle, and launch.

Testing at KSC

At the Kennedy Space Center the CM and the SM were mated, checked, assembled on the Saturn V launch vehicle, and the total vehicle was moved to the launch pad.

The Countdown Demonstration Test (CDDT) began on March 16, 1970. Up to this point, nothing unusual about oxygen tank #2 had been noted during the extensive testing at KSC. Cryogenic oxygen loading and tank pressurization to 33 psi was completed without abnormalities. At the time during CDDT when the oxygen tanks are normally vented down to about 50 percent of capacity, oxygen tank #1 behaved normally, but oxygen tank #2 only went down to 92 percent of its capacity. The normal procedure during CDDT to reduce the quantity in the tank is to apply gaseous oxygen at 80 psi through the vent line and to open the fill line. When this procedure failed, it was decided to proceed with the CDDT until completion and then look at the oxygen detanking problem in detail.

On Friday, March 27, 1970, detanking operations were resumed, after discussions of the problem had been held with KSC, MSC, NR, and Beech personnel participating, either personally or by telephone. As a first step, oxygen tank #2, which had self-pressurized to 178 psi and was about 83 percent full, was vented through its fill line. The quantity decreased to 65 percent. Further discussions between KSC, MSC, NR, and Beech personnel considered that the problem might be due to a leak in the path between the fill line and the quantity probe due to loose fit in the sleeves and tube. Such a leak would allow the gaseous oxygen being supplied to the vent line to leak directly to the fill line without forcing any significant amount of LOX out of the tank. At this point, a Discrepancy Report against the spacecraft system was written.

A "normal" detanking procedure was then conducted on both oxygen tanks, pressurizing through the vent line and opening the fill lines. Tank #1 emptied in a few minutes; tank #2 did not. Additional attempts were made with higher pressures without effect, and a decision was made to try to "boil off" the remaining oxygen in tank #2 by use of the tank heaters. The heaters were energized with the 65 volt DC GSE power supply and, about 1½ hours later, the fans were turned on to add more heat and mixing. After 6 hours of heater operation, the quantity had only decreased to 35 percent, and it was decided to attempt a pressure cycling technique. With the heaters and fans still energized, the tank was pressurized to about 300 psi, held for a few minutes, and then vented through the fill line. The first cycle produced a 7 percent quantity decrease, and the process was continued, with the tank emptied after five pressure/vent cycles. The fans and heaters were turned off after 8 hours of heater operation.

Suspecting the loosely fitting fill line connection to the quantity probe inner cylinder, KSC personnel consulted with cognizant personnel at MSC and at NR. It was decided that if the tank could be filled, the leak in the fill line would not be a problem in flight, since it was felt that even a loose tube resulting in an electrical short between the capacitance plates of the quantity gage would result in an energy level too low to cause any other damage. Replacement of the oxygen shelf in the CM would have been difficult and would have taken at least 45 hours. In addition, shelf replacement would have had the potential of damaging or degrading other elements of the service module in the course of replacement activity. Therefore, the decision was made to test the ability to fill oxygen tank #2 on March 30, 1970, 12 days prior to the scheduled Saturday, April 11, launch, so as to be in a position to decide on shelf replacement well before the launch date.

Flow tests were first made with gaseous oxygen on oxygen tank #2 and on oxygen tank #1 for comparison. No problems were encountered, and the flow rates in the two tanks were similar. In addition, Beech was asked to test the electrical energy level reached in the event of a short circuit between plates of the quantity probe capacitance gage. This test showed that very low energy levels would result. Then, oxygen tanks #1 and #2 were filled with LOX to about 20 percent of capacity on March 30 with no difficulty. Tank #1 emptied in the normal manner, but emptying oxygen tank #2 again required pressure cycling with the heaters turned on.

As the launch date approached, the oxygen tank #2 detanking problem was considered by the Apollo organization. At this point, the "shelf drop" incident on October 21, 1968, at NR was not considered and it was felt that the apparently normal detanking which had occurred in 1967 at Beech was not pertinent because it was believed that a different procedure was used by Beech. In fact, however, the last portion of the procedure was quite similar, although at a slightly lower pressure.

Throughout these considerations, which involved technical and management personnel of KSC, MSC, NR, Beech, and NASA Headquarters, emphasis was directed toward the possibility and consequence of a loose fill tube; very little attention was paid to the extended heater and fan operation, except to note that they operated during and after the detanking sequences.

Many of the principals in the discussion were not aware of the extended heater operations. Those that did know the details of the procedure did not consider the possibility of damage due to excessive heat within the tank, and therefore did not advise management officials of any possible consequences of the unusually long heater operations.

As I noted earlier, each heater is protected with a thermostatic switch, mounted on the heater tube, which is intended to open the heater circuit when it senses a temperature of about 80°F. In tests conducted since the accident, however, it was found that the switches failed to open when the heaters were powered from a 65 volt DC supply similar to the power used at KSC during the detanking sequence. Subsequent investigations have shown that the thermostatic switches used, while rated as satisfactory for the 28 volt DC spacecraft power supply, could not open properly at 65 volts DC with 6–7 amps of current. A review of the voltage recordings made during the detanking at KSC indicates that, in fact, the switches did not open when the temperature of the switches rose past 80° F. Figure 18 shows a thermostatic switch welded closed after application of 1½ amperes of 65 volts DC. Further tests have shown that the temperatures on the heater tube subsequent to the switch failures may have reached as much as 1000°F during the detanking. This temperature can cause serious damage to adjacent Teflon insulation, and such damage almost certainly occurred. Figures 19 and 20 show the condition of wires, such as those used in the fan motor circuit, after they have been subjected to temperatures of about 1000°F.

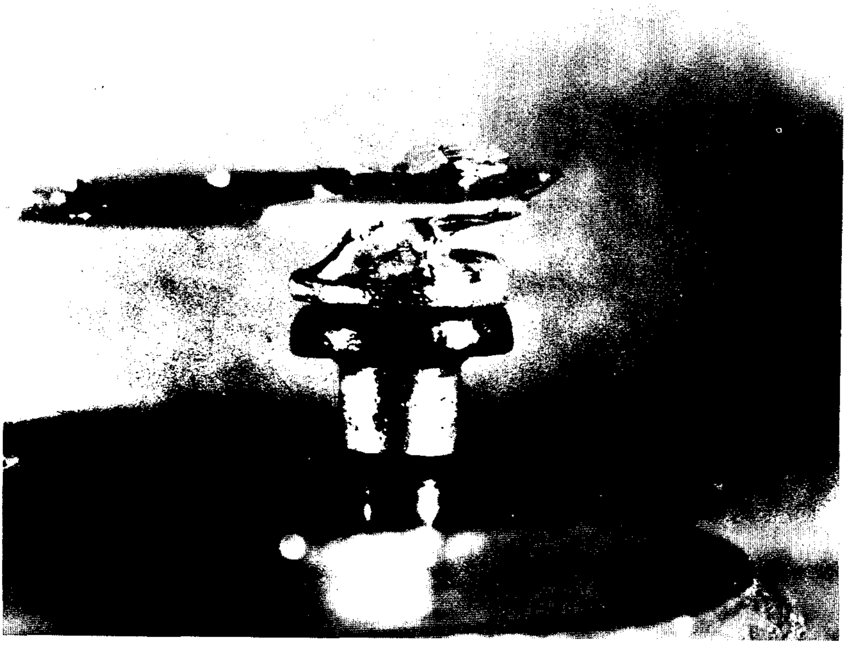


FIGURE 18

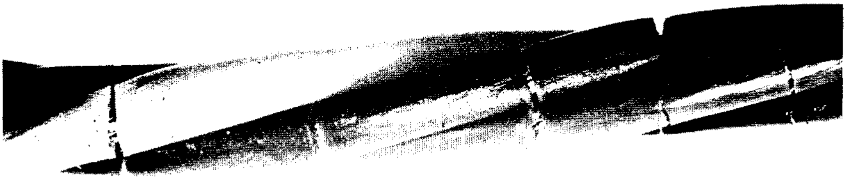


Figure 19

Figure 20

None of the above, however, was known at the time and, after extensive consideration was given to the possibilities of damage from a loose fill tube, it was decided to leave the oxygen shelf and oxygen tank #2 in the SM and to proceed with preparations for the launch of Apollo 13. In fact, following the special detanking, the oxygen tank #2 was in a hazardous condition whenever it contained oxygen and was electrically energized. This condition caused the Apollo 13 accident, which was nearly catastrophic. Only the outstanding performance on the part of the crew, Mission Control, and other members of the team which supported the operations, successfully returned the crew to earth.

In investigating the Apollo 13 accident, the Board attempted to identify those additional technical and management lessons which can be applied to help assure the success of future spaceflight missions. Several recommendations of this nature are included.

RECOMMENDATIONS

Before reading the Board's recommendations, I would like to point out that each Member of the Board concurs in each finding, determination, and recommendation.

The Board's recommendations are as follows:

1. The cryogenic oxygen storage system in the service module should be modified to:
   - a. Remove from contact with the oxygen all wiring, and the unsealed motors, which can potentially short circuit and ignite adjacent materials; or otherwise insure against a catastrophic electrically induced fire in the tank.
   - b. Minimize the use of Teflon, aluminum, and other relatively combustible materials in the presence of the oxygen and potential ignition sources.
2. The modified cryogenic oxygen storage system should be subjected to a rigorous requalification program, including careful attention to potential operational problems.
3. The warning systems onboard the Apollo spacecraft and in the Mission Control Center should be carefully reviewed and modified where appropriate, with specific attention to the following:
   - a. Increasing the differential between master alarm trip levels and expected normal operating ranges to avoid unnecessary alarms.
   - b. Changing the caution and warning system logic to prevent an out-of-limits alarm from blocking another alarm when a second quantity in the same subsystem goes out of limits.
   - c. Establishing a second level of limit sensing in Mission Control on critical quantities with a visual or audible alarm which cannot be easily overlooked.
   - d. Providing independent talkback indicators for each of the six fuel cell reactant valves plus a master alarm when any valve closes.
4. Consumables and emergency equipment in the LM and the CM should be reviewed to determine whether steps should be taken to enhance their potential for use in a "lifeboat" mode.
5. The Manned Spacecraft Center should complete the special tests and analyses now underway in order to understand more completely the details of the Apollo 13 accident. In addition, the lunar module power system anomalies should receive careful attention. Other NASA Centers should continue their support to MSC in the areas of analysis and test.
6. Whenever significant anomalies occur in critical subsystems during final preparation for launch, standard procedures should require a presentation of all prior anomalies on that particular piece of equipment, including those which have previously been corrected or explained. Furthermore, critical decisions involving the flightworthiness of subsystems should require the presence and full participation of an expert who is intimately familiar with the details of that subsystem.
7. NASA should conduct a thorough reexamination of all of its spacecraft, launch vehicle, and ground systems which contain high-density oxygen, or other strong oxidizers, to identify and evaluate potential combustion hazards in the light of information developed in this investigation.
8. NASA should conduct additional research on materials compatibility, ignition, and combustion in strong oxidizers at various g levels; and on the characteristics of supercritical fluids. Where appropriate, new NASA design standards should be developed.

9. The Manned Spacecraft Center should reassess all Apollo spacecraft subsystems, and the engineering organizations responsible for them at MSC and at its prime contractors, to insure adequate understanding and control of the engineering and manufacturing details of these subsystems at the subcontractor and vendor level. Where necessary, organizational elements should be strengthened and in-depth reviews conducted on selected subsystems with emphasis on soundness of design, quality of manufacturing, adequacy of test, and operational experience.

CONCLUSION

In concluding, I would stress two points.

The first is that in this statement I have attempted to summarize the Board's Report. This Report and its appendices are the result of more than seven weeks of intensive work by the Board, its Panels, and staff, supported by the NASA and contractor organizations. In the interest of time, I have not included many supporting findings and determinations which are set forth in the Report.

The second point I wish to make is this:

The Apollo 13 accident, which aborted man's third mission to explore the surface of the moon, is a harsh reminder of the immense difficulty of this undertaking.

The total Apollo system of ground complexes, launch vehicle, and spacecraft constitutes the most ambitious and demanding engineering development ever undertaken by man. For these missions to succeed, both men and equipment must perform to near perfection. That this system has already resulted in two successful lunar surface explorations is a tribute to those men and women who conceived, designed, built, and flew it.

Perfection is not only difficult to achieve, but difficult to maintain. The imperfection in Apollo 13 constituted a near disaster, averted only by outstanding performance on the part of the crew and the ground control team which supported them.

The Board feels that the Apollo 13 accident holds important lessons which, when applied to future missions, will contribute to the safety and effectiveness of manned space flight.

Mr. Chairman, this concludes my prepared statement.

STATEMENT BY DR. PAINE

The CHAIRMAN. Dr. Paine, go ahead.

Dr. PAINE. Mr. Chairman, members of the committee, in our appearance before the committee on April 24, 1970, Apollo Program Director Dr. Rocco Petrone, Flight Director Glynn Lunney, and astronauts Jim Lovell and Jack Swigert reported to you our understanding as of that time of the events leading to the accident and the subsequent operations which brought the astronauts safely back to earth. At the same hearing, I reported to you the actions Dr. Low and I had taken to assure a prompt, thorough, and objective investigation of the accident. These included:

REVIEWS ACTIONS FOLLOWING ACCIDENT

(1) The establishment of the Apollo 13 Review Board, with Mr. Edgar M. Cortright, Director of the Langley Research Center, as Chairman.

(2) The instruction to NASA's Aerospace Safety Advisory Panel to review the procedures and findings of the Apollo 13 Review Board and to submit its independent report within 10 days of the Review Board's report, and

(3) The instruction to Dr. Dale Myers, NASA's Associate Administrator for Manned Space Flight, to provide necessary support to the Apollo 13 Review Board and to make recommendations, also with-

in 10 days of the Review Board's report, on plans for eliminating the problems encountered in Apollo 13 in order to proceed with Apollo 14 and future manned space missions.

REVIEWS RESULTS OF ACTIONS

Today we are here to review with you the results of these actions and the resulting future program actions which Dr. Low and I am now taking to preclude a recurrence of such accidents and to move ahead with the Nation's manned space flight program. In summary:

The report of the Apollo 13 Review Board was presented to us by Mr. Cortright on June 15 and made available to the committee on the same day. Dr. Low and I have now had an opportunity to study the report in detail and to review carefully its recommendations. In our view it is an excellent report based on a thorough and objective investigation and highly competent analysis. It clearly pinpoints the causes of the Apollo 13 accident and sets forth a comprehensive set of recommendations to guide our efforts to prevent the occurrence of similar accidents in the future.

The Aerospace Safety Advisory Panel submitted its report to NASA management at a meeting in Washington June 25, 1970. With your permission, Mr. Chairman, I would like to place its report which is in the form of a letter from its Chairman, Dr. Charles D. Harrington, in the record.

The CHAIRMAN. Without objection, that will be done.

(For the letter referred to see p. 56.)

Dr. PAINE. Dr. Harrington is here this morning to respond to any questions you may have. At this point I would like to read the key portions of his letter report summarizing the Safety Panel's appraisal of the job done by the Apollo 13 Review Board. He says:

> The Panel found that the Board' procedures and scope of inquiry proved effective in their task. The Review Board has performed a thorough and technically competent analysis in the reconstruction of the factors contributing to the Apollo 13 abort. We found no evidence and no reason to doubt the technical validity of their determination and findings.

This independent evaluation provides substantial additional confidence to Dr. Low and to me that our favorable appraisal of the report is correct.

Dr. Myers, Dr. Petrone, and the Office of Manned Space Flight have also completed extensive experiments, tests, studies, reviews, redesign work and program rescheduling activities, and have presented recommendations on the required corrective measures and program adaptations. Last Thursday Dr. Low and I held an extensive review at which Dr. Myers, Dr. Petrone, Colonel McDivitt and other officials of the Apollo program discussed in detail the technical problems and alternatives with the senior officials of NASA. Also present were Mr. Cortright and members of the Review Board, Dr. Harrington and members of the Aerospace Safety Advisory Panel, Mr. William A. Anders, Executive Secretary of the National Aeronautics and Space Council, and the Directors of NASA's Manned Space Flight centers: Dr. Robert R. Gilruth, Dr. Kurt H. Debus, and Dr. Eberhard Rees. Based on the discussions at this review and at followup meetings extending over the next 2 days, Dr. Myers has formally submitted to me with his endorsement the final recommendations of Dr. Petrone, the Apollo Program Director. These are embodied in Dr. Petrone's memorandum to me of June 27, 1970, which has been made available to the committee, and which I would like to place in this record, with your permission, Mr. Chairman.

The CHAIRMAN. Without objection: that will be done.

(For the memorandum referred to see p. 57.)

Dr. PAINE. On the basis of the reports and recommendations before us and detailed discussions with responsible and knowledgeable experts in NASA, Dr. Low and I have approved the following actions to implement the recommendations of the Apollo 13 Review Board and to carry out the steps recommended by Dr. Petrone and Dr. Myers to prepare for the Apollo 14 mission. In summary, these actions are:

APOLLO 14 POSTPONED TO EARLY 1971

First, the recommendations of the Apollo 13 Review Board will be implemented before the Apollo 14 mission is approved for launch. This will require postponing the launch date to no earlier than January 31, 1971. Command Service Module systems will be modified along the recommended lines to eliminate potential combustion hazards in high pressure oxygen of the type revealed by the Apollo 13 accident. Unsealed fan motors will be removed from the oxygen tanks and an additional oxygen tank added to the service module of Apollo 14. Electrical wiring within high pressure oxygen systems which might provide an ignition spark if damaged will be limited to stainless steel sheathed wires. Teflon, aluminum, and other potentially reactive materials in the presence of high pressure oxygen will be used as little as possible and kept away from possible ignition sources. For example, the quantity probe will be stainless steel instead of aluminum and the fuel cell oxygen supply valve which now has Teflon-insulated wires in high pressure oxygen will be redesigned to eliminate this hazard. Warning systems on board the spacecraft and at mission control will be modified consistent with the Board's recommendations to provide more immediate and visible warnings of system anomalies. A comprehensive review of spacecraft emergency equipment and procedures and use of command service modules and lunar modules in "lifeboat" modes is now underway at the Manned Spacecraft Center in Houston. Dr. Petrone will outline for you the specific actions we plan to take in response to the first six recommendations of the Board, and Dr. Myers will discuss his specific plans for critically reassessing all Apollo spacecraft subsystems in response to recommendation No. 9 of the Board.

NASA REVIEW OF APOLLO 13 REPORT

Secondly, the associate administrators in charge of the Offices of Space Science and Applications, Manned Space Flight, and Advanced Research and Technology, have been directed to review the Apollo 13 review board report to apply throughout NASA the lessons learned in their areas of responsibility. They have been instructed to take action with respect to recommendation No. 6 (concerning anomalies in critical subsystems prior to flight), recommendation No. 7 (calling for a thorough reexamination of all spacecraft, launch vehicle and ground systems which contain strong oxidizers to evaluate potential hazards) and recommendation No. 9 (concerning the design, manufacture, test, and operation of spacecraft subsystems). I have requested a written report by August 25 on their assessment and the actions taken or proposed.

In addition, we will take steps to disseminate widely throughout the industry and the technical community the lessons of Apollo 13 to prevent recurrences in other areas. You might be interested to know in this connection that I have forwarded to Academician Keldysh of the Soviet Academy of Sciences a copy of the complete Apollo 13 Review Board report so that lessons which might be learned from our accident can be applied to prevent a similar hazard to Soviet cosmonauts.

Third, the Aerospace Safety Research and Data Institute (ASRDI) at the NASA Lewis Research Center has been directed to conduct additional research on materials compatibility, ignition, and combustion at various gravity levels, and on the characteristics of supercritical fluids, as recommended by the Apollo 13 Review Board. This will expand a review already begun by ASRDI on oxygen handling in aerospace programs. In this effort, the Lewis Research Center will be supported by other elements of the NASA organization. This research will be of direct long-term benefit to NASA in carrying out its future programs, and will help other sectors of the economy.

AEROSPACE SAFETY ADVISORY PANEL

Fourth, I have requested that the Aerospace Safety Advisory Panel conduct a review of the management processes utilized by NASA in implementing the recommendations of the Apollo 13 Review Board and report to me their views no later than the Apollo 14 flight readiness review. This will again give us the benefit of the panel's valuable independent insight when future decisions are made. I have also asked Mr. Cortright to reconvene the Apollo 13 Review Board later this year, as he suggested, to review the results of continuing tests to determine whether any modifications to the board's findings, determinations, or recommendations are necessary in light of additional evidence which may become available.

JANUARY LAUNCH OF APOLLO 14 POSSIBLE

The assessment of the Office of Manned Space Flight, in which Dr. Low and I concur, is that the reasonable time required for the design, fabrication, and qualification testing of the modifications to the Apollo system we have determined to be necessary, and for the other actions outlined above which must be taken before the next Apollo mission, will permit us to launch Apollo 14 to the Fra Mauro region of the moon at the January 31, 1971, launch opportunity. This will also move the planned launch date for Apollo 15 several months to July or August 1971, maintaining the approximate 6-month interval between launches on which our operations in the Apollo program are now based. However, we will not launch Apollo 14 or any other flight unless and until we are confident that we have done everything necessary to eliminate the conditions that caused or contributed to the problems we encountered on Apollo 13 and are ready in all other respects. One of our prime concerns will be to maintain the efficiency and high standard of performance required of our launch and ground support teams during the extended periods of reduced activity entailed by the revised mission schedule and by the substantial cutbacks which have been made necessary by the overall reductions in the Nation's space program.

MODIFICATION COSTS ESTIMATED AT $15 MILLION

It is too early to present to you our detailed estimates of the costs and budgetary impact of the spacecraft modifications and program changes that we are now making. Our best current estimate is that the modifications and changes related to the actions resulting from the Apollo 13 accident will be in the range of $10 to $15 million of increased costs, which we plan to handle within our total Apollo budget.

Before turning to Dr. Myers and Dr. Petrone, I would like to comment briefly on the lessons to be learned from Apollo 13. The Review Board found "that the accident was not the result of a chance malfunction in a statistical sense, but rather resulted from an unusual combination of mistakes, coupled with a somewhat deficient and unforgiving design." The presence of inadequate thermostatic switches in the heater circuits of the oxygen tanks, the loose fill tube assembly probably caused by a buildup of "worst case" tolerances and the "shelf dropping" incident, the improvised detanking procedure employed in preparing for launch, and the resulting damaged Teflon-insulated fan motor wiring caused by overheating which later provided the ignition spark—together all of these elements combined to cause the accident. In the absence of any one of these links in the chain of events, oxygen bottle No. 2 would not have failed.

NASA's actions in response to the Board's recommendations will, in my view, avoid those specific things which led or contributed to the Apollo 13 accident; and the reviews and research we have undertaken will help us avoid future potential hazards throughout our programs. But in a larger context, we at NASA must be concerned with the fact that despite the rigorous management controls in effect and, from all the evidence, adhered to, a hazardous condition existed that was not identified and corrected. In fact, the presence of the inadequate thermostatic switches in the tank and the resultant baking of the wires at temperatures as high as 1000° F. during detanking were not discovered until actual full-scale tests were conducted for the Review Board in which wires were damaged, leading to a reexamination of the data recorded at Kennedy Space Center during the detanking and the switch specifications.

REVIEW OF SPACECRAFT CONTRACTS

With regard to our contracts with North American Rockwell and Grumman for the spacecraft involved in the Apollo 13 mission, we have underway a review of the incentive provisions in their contracts to determine what steps should be taken by NASA in light of the accident. In accordance with our contract with North American Rockwell we will take the service module oxygen system failure into account in determining the amount of the 1970 award fees to be paid. That fee will be determined in view of all activities during 1970, and thus will be based not only on the Apollo 13 accident but also on the effectiveness of the redesign and rebuilding activities during the months following the accident in preparation for Apollo 14.

In the case of the Grumman lunar module contract the fee provisions are phrased only in terms of performance during an actual lunar landing mission. However, since in performing as it did in the "lifeboat" mode the lunar module "Aquarius" clearly demonstrated its ability to have successfully performed most of the operations of an actual landing, we are performing a technical assessment of the Apollo 13 mission as it was flown to establish what portion of the performance was demonstrated and, therefore, what portion of the incentive fee should be paid now.

In a program as large and complex as Apollo, involving thousands of people throughout the country, we must obviously depend on a rigorous documentation system to record and convey program management information. What we must always guard against, however, is the possibility of permitting this flow of careful documentation to substitute for the meaningful exchange of information. No matter how thorough and careful we are, we ultimately depend on incisive and informed problem analysis by competent people who make the key decisions on the basis of their thorough understanding of the underlying actualities which are recorded in the documentation.

We cannot in the case of Apollo 13, point to one individual or group of individuals or organization and say that they caused the accident. Nor have we or the Review Board been able to formulate—even with all the advantages of hindsight—a management procedure which, had it been in effect for Apollo 13, would have guaranteed that such an accident could never happen. The excellent recommendations of the Board in the areas of management and procedures can further strengthen Apollo and other NASA programs. But in the last analysis, we must depend upon the thoroughness and detailed understanding of all those in responsible positions in the NASA-industry hierarchy throughout every phase of design, manufacture, test and flight operations. I have the utmost confidence that the NASA team can fix the Apollo 13 problem and strengthen its operations to minimize the chances of future problems. We realize, however—and the members of this committee realize—that the exploration of space is a demanding and hazardous enterprise in which man is probing the unknown. NASA men and women are doing many things for the first time. Any deficiencies in our ability to look ahead and foresee difficulties, any inattention to detail will be exposed in the harsh environments in which our work is tested. In my opinion, no finer or more dedicated group of people has ever worked together more effectively than this Nation's space team, and I am confident of their continuing future success.

Mr. Chairman, this concludes my statement, and I would now like to ask Mr. Myers and Dr. Petrone to summarize in detail for you our proposed actions in response to the recommendations of the Apollo 13 Review Board.

(The letter and memorandum referred to on page 51 are as follows:)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
OFFICE OF THE ADMINISTRATOR,
Washington, D.C., June 25, 1970.

Dr. T. O. PAINE,
Administrator, National Aeronautics and Space Administration,
Washington, D.C.

DEAR DR. PAINE: This letter is in response to your request that the Aerospace Safety Advisory Panel review and comment on the procedures and findings of the Apollo 13 Review Board.

With the backgorund of the Panel's earlier review of the Apollo program management and risk assessment system, we met in working sessions with Mr. Cortright and his panel chairmen as well as with members of the Apollo 13 Investigation Team. Thus we have been able to review the evolving process of inquiry and to observe much of the evidence as it was developed. Our participation in the Board's deliberations provided a timely forum for both their consideration of our comments and our understanding of their determination and findings.

The Panel found that the Board's procedures and scope of inquiry proved effective in their task. The Review Board has performed a thorough and technically competent analysis in the reconstruction of the factors contributing to the Apollo 13 abort. We found no evidence or suggestion that significant data or events were not pursued with diligence and no reason to doubt the technical validity of their determination and findings.

Recommendations made for the redesign of the system should improve the manufacturability and minimize the failure modes of the system under abnormal conditions. The recomendations for improvements in the analysis and validation of nonstandard situations are certainly necessary and should be implemented immediately. The efficacy of the other recommendations for continuing research, assessment and engineering organization review will depend upon the manner in which they are implemented. There must now be provisions for the performance of these recommendations in a manner satisfactory and visible to you.

While there is no need for us to file a separate lengthy report, we would like to emphasize certain points.

The total Apollo system, both hardware and software, possesses a considerable degree of inherent redundancy and reliability. Successful return to earth after a major system failure was possible because many alternate systems, modified procedures and non-standard operations were available to the ground and flight crew.

Almost all of the special actions and procedures required for a successful recovery had been thought out and developed in the premission period. This says much for the thoroughness of mission planning.

The mission control group responded to the unusual and critical events in a very effective manner. Their high degree of skill and knowledge, and the discipline to make it effective in a timely fashion, were as critical as the crew response in achieving the recovery of Apollo 13.

The elaborate technical management control system created in Apollo has, in our experience, achieved a high degree of maturity and definition. In this case, the acceptance of the design and manufacturability risks, the lack of understanding of thermal switch performance and the informal system in the evaluation of the test procedure change reflect more a failure of human judgment than a failure in the requirements of the technical management system.

Such an incident brings into prominence the question of management control and risk acceptability. This incident should not call into question the basic credibility of the technical management system. The system now in existence has significantly reduced the possibility of errors in human judgment. The phasedown of personnel has been achieved in a manner to maximize skill retention, and the flights of prior Apollo Saturn Systems have been eminently successful. The problem now is to sustain human motivation and assure working familiarity with the subsystems and their hazards. Finally erosion in engineering support and launch operations manpower and untimely delays in resuming the launch schedule could only serve to degrade the capability to service and launch the Apollo Saturn System and thus introduce unknown risks.

In summary, the Panel commends the integrity of effort of the Board and its associates and now awaits the implementation of its recommendations.

Sincerely yours,

CHARLES D. HARRINGTON,
Chairman, Aerospace Safety Advisory Panel.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
Washington, D.C., June 27, 1970.

To: A/Administrator.
Through: M/Associate Administrator for Manned Space Flight.
From: MA/Apollo Program Director.
Subject: Proposed Actions in the Apollo Program in Response to the Apollo 13 Review Board Report.

The OMSF response to the Apollo 13 Review Board Report was presented to the Administrator at a meeting on June 25, 1970. Based on discussions which took place at that meeting, we have done additional analysis and testing. Results of these efforts, which have been discussed at several meetings, have led me to recommend the following actions:

1. Oxygen tank modifications
   (a) Replacement of all Teflon coated wires by stainless steel sheathed wires
   (b) Removal of unsealed fan motors
   (c) Modification of heater configuration from two 75-watt heaters powered from a single bus to three 50-watt heaters powered from two independent buses.
   (d) Modification of quantity probe from aluminum to stainless steel
   (e) Addition of temperature sensor to heater probe
   (f) Elimination of heater thermal switches
   (g) Modification of tank cap to preclude need for rotation of quantity probe during assembly
2. Addition of third oxygen tank to avoid operation in low quantity regime on Apollo 14 & 15 thereby permitting removal of unsealed fan motors; and review the oxygen subsystem requirments for Apollo 16 and subsequent missions.
3. Modification of fuel cell oxygen reactant valve to separate Teflon coated wires from oxygen environment.
4. Caution and warning system modifications
   (a) Modification of caution and warning system to provide an audio and light alarm for single fuel cell reactant valve closure
   (b) Installation of talkback indication for single fuel cell reactant valve closure
   (c) Installation of existing modification kit to adjust, where appropriate, the hydrogen caution and warning trip level.
5. Addition of second-level limits sensing in the Mission Control Center as recomended by the Review Board.
6. Completion of the comprehensive review now under way of the consumables and emergency equipment in the Lunar Module and Command Module in accordance with recommendation #4 of the Review Board Report.
7. Completion of the special tests and analyses now under way in accordance with recommendation #5 of the Review Board Report.
8. Respond prior to August 25th to your directions with regard to recommendation #6, 7, and 9 of the Board Report in so far as they apply to the Apollo Program.

Based on the estimated time required for the design, fabrication and qualification testing for the modifications outlined above, and for the other actions set forth, I propose the Apollo 14 mission be scheduled for launch to the Fra Mauro region of the moon no earlier than the 31 January 1971 launch opportunity. This proposed schedule will move the planned launch date for Apollo 15 to July or August 1971, maintaining our approximate six-month interval between launches on which the Apollo operations are now based.

Our best current estimate, which may change as we proceed with the actions outlined above, is that the modifications to the Apollo hardware which we now have identified will cost in the range of $10 to $15 million.

I request approval of these actions at the earliest possible time.

ROCCO A. PETRONE,
Apollo Program Director.

Concurrence:

DALE D. MYERS,
Associate Administrator for Manned Space Flight.

Approved:

THOMAS O. PAINE, *Administrator.*

The CHAIRMAN. Dr. Myers.

STATEMENT OF DR. MYERS

Dr. MYERS. Mr. Chairman, members of the committee, I appreciate the opportunity to present to you the response of the Office of Manned Space Flight to the Cortright Board report. I believe the Board's recommendations are sound, and you will find that we concur with each recommendation and are responding to each. Dr. Paine has discussed recommendations 6, 7, and 8, which deal with NASA-wide implementation, for both manned and unmanned activities. Dr. Petrone will cover recommendations 1 through 6, which deal specifically with the Apollo program. I would like to speak to recommendation 9, which, although directed toward Apollo, I believe has important implications for our other manned programs, including Skylab and our future programs such as the shuttle and space station.

Let me first read the recommendation:

> The Manned Spacecraft Center should reassess all Apollo spacecraft subsystems, and the engineering organizations responsible for them at MSC and at its prime contractors, to insure adequate understanding and control of the engineering and manufacturing details of these subsystems at the subcontractor and vendor level. Where necessary, organizational elements should be strengthened and indepth reviews conducted on selected subsystems with emphasis on soundness of design, quality of manufacturing, adequacy of test, and operational experience.

First, we will expand the review to cover the three manned spaceflight centers—Manned Spacecraft Center, Kennedy Space Center, and Marshall Space Flight Center, for all Apollo subsystems, including the command module, the lunar module, the launch vehicle and the ground support equipment.

Second, we will expand the review to include Skylab, and will use the results of these two studies and actions to set requirements for future programs.

The reassessment of subsystems will be managed by the headquarters Office of Manned Space Flight and will include participation of Center top management and technical personnel most familiar with the subsystems. Additional personnel familiar with quality of manufacturing, engineering design and control systems, test and operations, and subcontractor management will be involved.

Although the history of Apollo mission performance has been outstanding, we will review for each subsystem significant failure history trends, evaluate hazards to hardware in manufacturing, checkout or in flight, and will reevaluate possible "sympathetic failures" where redundant systems may lose their redundancy due to the failure of one element affecting the performance of the second element, as occurred in the case of Apollo 13. Of course, in such a study we recognize fully that pressure vessels must not fail, because of their serious impact.

Reviews will result in a report and presentation on each subsystem, a screening process, a further review indepth on selected subsystems, and a final presentation given to an Office of Manned Space Flight here in Washington.

Throughout the review and presentation process, we will evaluate the adequacy of our engineering team at the centers, at the prime contractors, and at the subcontractor level.

A report on actions taken and those remaining on recommendation 9, as well as our actions on recommendations 6 and 7 will be presented to the Administrator by August 25.

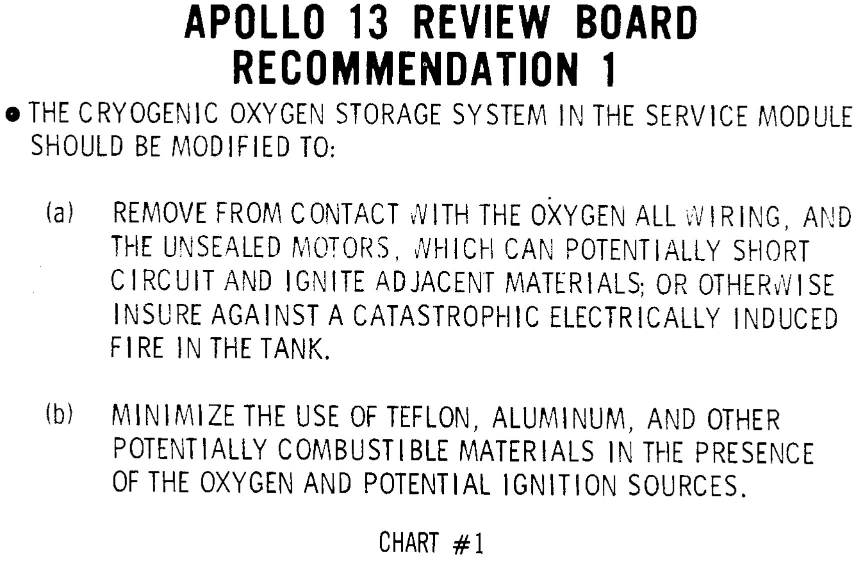
I believe that such a review will be extremely valuable in refining and developing a new level of understanding for Apollo and for our future programs.

I would now like to call on Dr. Petrone, Director of the Apollo program for the Office of Manned Space Flight, to describe the actions to be taken by him relative to the recommendations 1 through 6, which deal specifically with the Apollo program.

STATEMENT BY DR. PETRONE

Dr. PETRONE. Thank you, Mr. Chairman.

May I have chart 1 (fig. 21), please? This shows recommendation No. 1 of the Apollo 13 Review Board. It addresses itself to removing from contact with oxygen all wiring and the unsealed motors which can potentially short circuit, and ignite adjacent materials or otherwise insure against a catastrophic electrically induced fire in the tank.



APOLLO 13 REVIEW BOARD RECOMMENDATION 1

- THE CRYOGENIC OXYGEN STORAGE SYSTEM IN THE SERVICE MODULE SHOULD BE MODIFIED TO:

(a) REMOVE FROM CONTACT WITH THE OXYGEN ALL WIRING, AND THE UNSEALED MOTORS, WHICH CAN POTENTIALLY SHORT CIRCUIT AND IGNITE ADJACENT MATERIALS; OR OTHERWISE INSURE AGAINST A CATASTROPHIC ELECTRICALLY INDUCED FIRE IN THE TANK.

(b) MINIMIZE THE USE OF TEFLON, ALUMINUM, AND OTHER POTENTIALLY COMBUSTIBLE MATERIALS IN THE PRESENCE OF THE OXYGEN AND POTENTIAL IGNITION SOURCES.

CHART #1

FIGURE 21

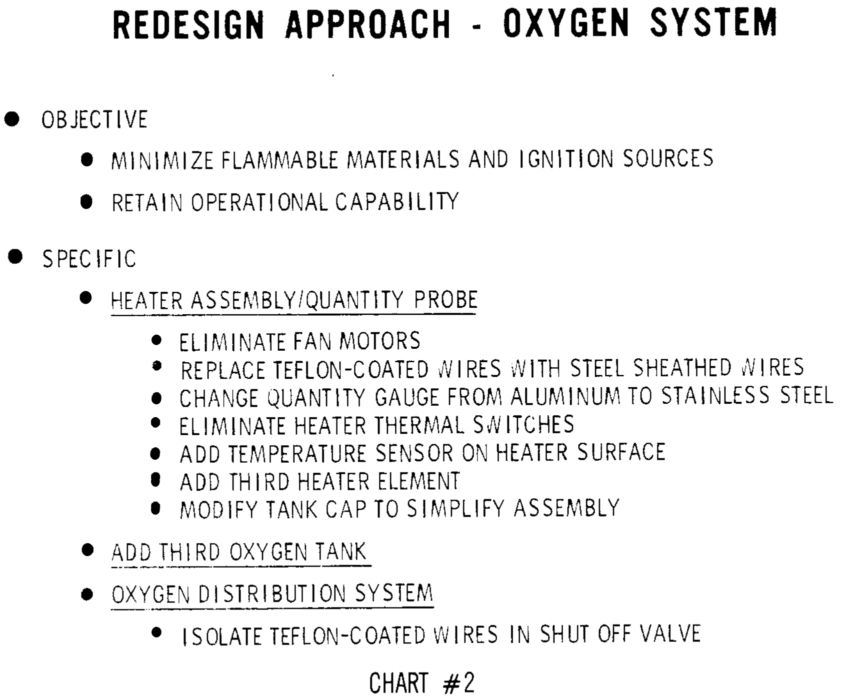
The second part of that recommendation was to minimize the use of Teflon, aluminum, and other potentially combustible materials in the presence of the oxygen and potential ignition sources.

Chart 2 (fig. 22), please. On this chart we show our redesign approach to the oxygen system. Our objective is first to minimize flammable materials and ignition sources, and second, to retain our operational capability.

Now, specifically the modifications we will make are in the heater assembly-quantity probe. We will eliminate the unsealed fan motors. We will replace the Teflon-coated wires with steel-sheathed wires. We will change the quantity gage from aluminum to stainless steel. We will eliminate heater thermal switches. To give us an understanding, however, of the temperature on the heater elements, we will add a temperature sensor on that heater element. To improve redundancy in the tank once we take out the unsealed fan motor we will add a third heater element. We also will modify the tank cap to simplify the basic assembly.

We must also add a third oxygen tank to the service module to allow us to operate in the low-density regime, once we remove the unsealed fans.

This design was already in work as a requirement for the Apollo 16 and subsequent missions. Now, we can take that third tank, modify it as noted above, and introduce that into the service module. This will meet our requirements for Apollo 14 and 15 in the low-density regime. However, for Apollo 16 and subsequent missions where we have



REDESIGN APPROACH - OXYGEN SYSTEM

- OBJECTIVE
  - MINIMIZE FLAMMABLE MATERIALS AND IGNITION SOURCES
  - RETAIN OPERATIONAL CAPABILITY
- SPECIFIC
  - HEATER ASSEMBLY/QUANTITY PROBE
    - ELIMINATE FAN MOTORS
    - REPLACE TEFLON-COATED WIRES WITH STEEL SHEATHED WIRES
    - CHANGE QUANTITY GAUGE FROM ALUMINUM TO STAINLESS STEEL
    - ELIMINATE HEATER THERMAL SWITCHES
    - ADD TEMPERATURE SENSOR ON HEATER SURFACE
    - ADD THIRD HEATER ELEMENT
    - MODIFY TANK CAP TO SIMPLIFY ASSEMBLY
  - ADD THIRD OXYGEN TANK
  - OXYGEN DISTRIBUTION SYSTEM
    - ISOLATE TEFLON-COATED WIRES IN SHUT OFF VALVE

CHART #2

FIGURE 22

higher oxygen requirements, we will have to review our oxygen subsystem to insure we can meet those requirements.

Mr. GEHRIG. Dr. Petrone, will you eliminate the fans altogether or will you just take them out of the tank?

Dr. PETRONE. In the module we are discussing for Apollo 14 and 15 we will eliminate them entirely.

Mr. GEHRIG. There will be no fans?

Dr. PETRONE. None on Apollo 14 and 15.

Mr. GEHRIG. How will you keep the—how will you get rid of the bubble in the tank formed by the heater?

Dr. PETRONE. We have operated down to the regime of 35 percent and have operated for periods of approximately 50 hours without the fan. This is a specific regime we have experienced. But since we have not operated below 35 percent and since we could have the difficulty you are referring to, we put in a third tank to keep us out of the regime in which we do not have experience. However, on this flight we would expect to get that experience which requires zero "g" for a prolonged period of time. The only way we are going to get that experience is through flight testing. But I do note that for Apollo 16, where our demands are even higher than Apollo 14 and 15, we will have to review the need for circulation and it may be necessary to introduce some other elements.

However, we will not use unsealed fan motors.

Senator GOLDWATER. Dr. Petrone, I notice on your next chart you call for unsealed fan motors, yet you do not show them.

Dr. PETRONE. Those are to be removed. I have those as notes to myself. The basic chart would eliminate the unsealed fan motor.

In the oxygen distribution system, we will isolate the Teflon-coated wires in the shutoff valve. Here we found Teflon also in the high oxygen pressure area.

On chart 3 (fig. 23), I show a basic drawing of what the tank would look like schematically with our modifications. The items on the left are notes which would say, one, we are going to remove the unsealed fan motors. We will use sheathed wires. The quantity probe, which we have to retain will be changed from aluminum to stainless steel. The thermal switches will have been removed. The temperature sensor, the second one will have been added. As I mentioned, we will add a third heater element for redundancy. The tank cap will be modified to simplify the basic installation of the heater probe assembly.

Senator GOLDWATER. How can you keep this oxygen in a supercritical stage without some circulation?

Dr. PETRONE. Sir, we will do that by the heater. We will keep our pressure up to the 900-pounds-per-square-inch regime and in the high density areas, high density being the regime down to approximately 35 percent, we feel we will get enough heat transfer due to conduction. There will be no convection because you are in zero "g." and we feel that will give us proper distribution. It is in a regime below 35 percent that we have concern, that we have no experience, and for that reason we are adding a third tank for Apollo 14.

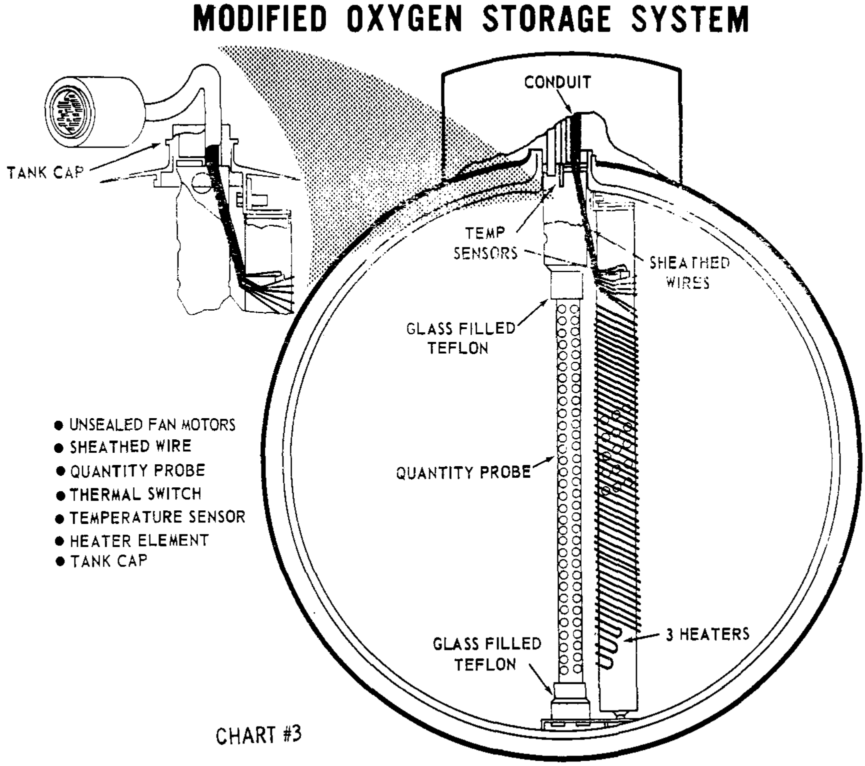
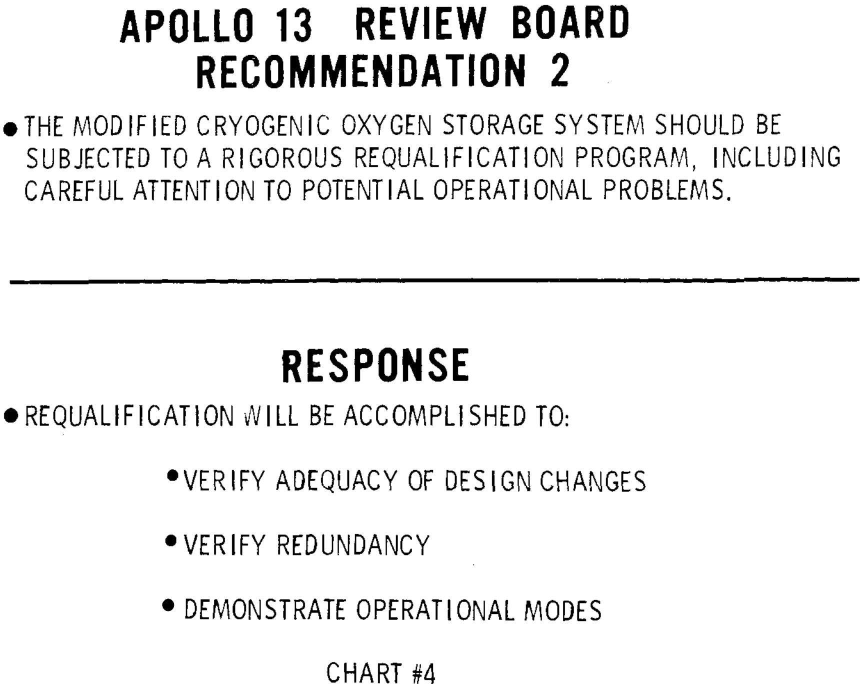


Figure 23

Senator Goldwater. What happens in minus "g." conditions with the supercritical oxygen? It used to be circulated by fans but now you are depending on heat and you are not going to get it—you do not want too much heat in it. How are you going to keep it moving?

Dr. Petrone. Sir, the concern comes in zero "g.", in other words, the forces, negative or positive "g." forces, are in your interest. They will help circulation. However, for zero gravity, the heat transfer due to conduction at the higher density regime will give us a distribution of heat and we can remove the fan as long as we are willing to add a third tank, to avoid the low-density regime. This is an area of the unknown. There are studies which would indicate to us we could go without that. However, we do not feel we want to take just theoretical studies. We want to see the performance of that at least in the Apollo 14 flight.



APOLLO 13 REVIEW BOARD RECOMMENDATION 2

- THE MODIFIED CRYOGENIC OXYGEN STORAGE SYSTEM SHOULD BE SUBJECTED TO A RIGOROUS REQUALIFICATION PROGRAM, INCLUDING CAREFUL ATTENTION TO POTENTIAL OPERATIONAL PROBLEMS.

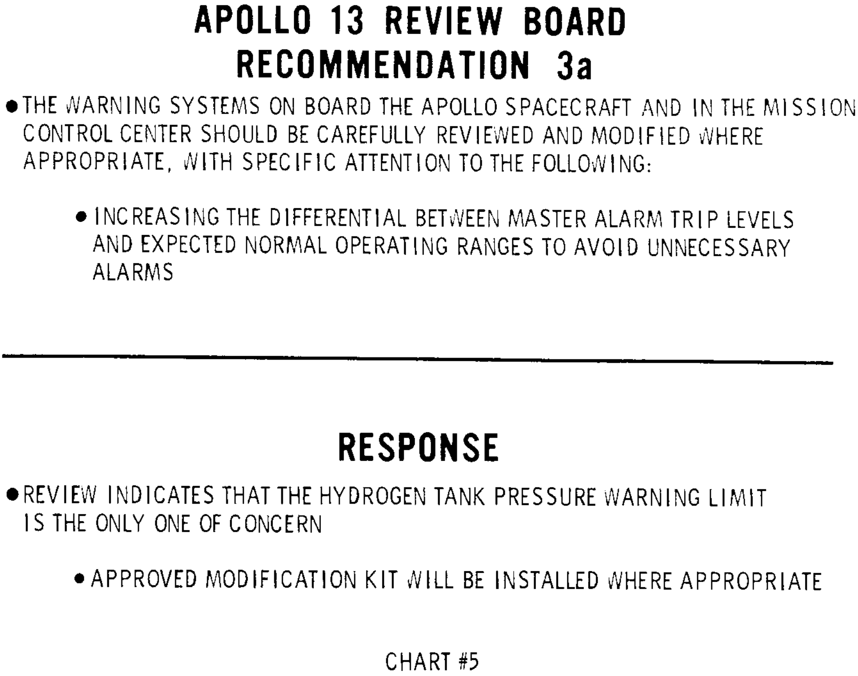
RESPONSE

- REQUALIFICATION WILL BE ACCOMPLISHED TO:
  - VERIFY ADEQUACY OF DESIGN CHANGES
  - VERIFY REDUNDANCY
  - DEMONSTRATE OPERATIONAL MODES

CHART #4

FIGURE 24

Chart 4 (fig. 24), please. This refers to recommendation 2 of the Apollo 13 Review Board, that the modified tank should be subjected to a rigorous requalification program. I might state that in the Apollo program we have a specific set of ground rules that we must meet on the ground, in our requalification. We will requalify to verify adequacy of design changes, verify we do have adequate redundancy and demonstrate operational modes, working over many parts of the regime.



APOLLO 13 REVIEW BOARD RECOMMENDATION 3a

- THE WARNING SYSTEMS ON BOARD THE APOLLO SPACECRAFT AND IN THE MISSION CONTROL CENTER SHOULD BE CAREFULLY REVIEWED AND MODIFIED WHERE APPROPRIATE, WITH SPECIFIC ATTENTION TO THE FOLLOWING:
  - INCREASING THE DIFFERENTIAL BETWEEN MASTER ALARM TRIP LEVELS AND EXPECTED NORMAL OPERATING RANGES TO AVOID UNNECESSARY ALARMS

RESPONSE

- REVIEW INDICATES THAT THE HYDROGEN TANK PRESSURE WARNING LIMIT IS THE ONLY ONE OF CONCERN
  - APPROVED MODIFICATION KIT WILL BE INSTALLED WHERE APPROPRIATE

CHART #5

FIGURE 25

Chart 5 (fig. 25), please. Here we come to a recommendation of the Review Board that has four sections to it. I will have a chart for each section. It basically addressed itself to the warming systems on board the Apollo spacecraft and in the Mission Control Center. It said these systems should be carefully reviewed and modified where appropriate.

The first one addressed itself to looking at the differential that existed between master alarm trip levels and expected normal operating ranges. We have done that.

Our review indicates that the hydrogen tank pressure warning limit is the only one of concern. There we have an approved modification kit to be installed in spacecraft where appropriate, to give us this wider range.

APOLLO 13 REVIEW BOARD RECOMMENDATION 3b

- THE WARNING SYSTEMS ON BOARD THE APOLLO SPACECRAFT AND IN THE MISSION CONTROL CENTER SHOULD BE CAREFULLY REVIEWED AND MODIFIED WHERE APPROPRIATE, WITH SPECIFIC ATTENTION TO THE FOLLOWING:
  - CHANGING THE CAUTION AND WARNING SYSTEM LOGIC TO PREVENT AN OUT-OF-LIMITS ALARM FROM BLOCKING ANOTHER ALARM WHEN A SECOND QUANTITY IN THE SAME SUBSYSTEM GOES OUT OF LIMITS

RESPONSE

- BLOCKING OF CRITICAL SYSTEM PARAMETERS MINIMIZED BY PROVIDING SECOND LEVEL SENSING ON GROUND

CHART #6

FIGURE 26

Chart 6 (fig. 26), please. Recommendation 3–B, here, referred to changing the caution and warning system logic to prevent an out-of-limits alarm from blocking another alarm when a second quantity in the same subsystem goes out of limits.

Here we have had to resort to providing the second-level sensing on the ground in the Mission Control Center at Houston to minimize the effect of blocking of the critical system parameters.

APOLLO 13 REVIEW BOARD RECOMMENDATION 3c

- THE WARNING SYSTEMS ON BOARD THE APOLLO SPACECRAFT AND IN THE MISSION CONTROL CENTER SHOULD BE CAREFULLY REVIEWED AND MODIFIED WHERE APPROPRIATE, WITH SPECIFIC ATTENTION TO THE FOLLOWING:
  - ESTABLISHING A SECOND LEVEL OF LIMIT SENSING IN MISSION CONTROL ON CRITICAL QUANTITIES WITH A VISUAL OR AUDIBLE ALARM WHICH CANNOT BE EASILY OVERLOOKED

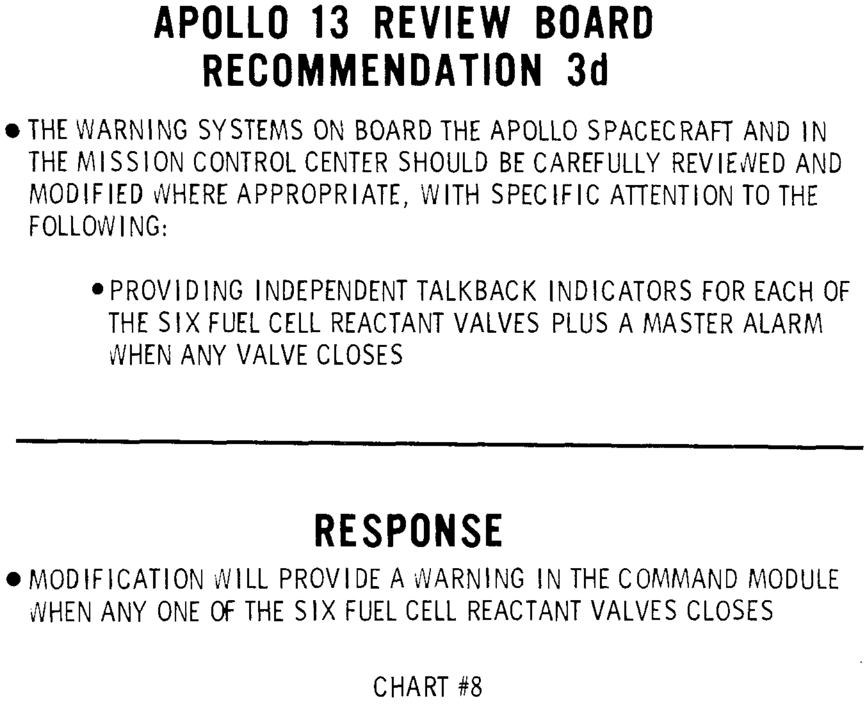
RESPONSE

- THE CAPABILITY FOR SECOND LEVEL SENSING IS BEING IMPLEMENTED
- A MASTER ALARM LIGHT IN ADDITION TO THE PRESENT INDIVIDUAL WARNING LIGHTS IS BEING ADDED

CHART #7

FIGURE 27

Chart 7 (fig. 27), please. Recommendation 3–C. This specifically talked of establishing a second-level sensing on the ground on critical quantities with a visual or audible alarm which could not be easily overlooked. That capability for second-level sensing is being implemented and we will have a master alarm light in addition to the present individual warning lights.



APOLLO 13 REVIEW BOARD RECOMMENDATION 3d

- THE WARNING SYSTEMS ON BOARD THE APOLLO SPACECRAFT AND IN THE MISSION CONTROL CENTER SHOULD BE CAREFULLY REVIEWED AND MODIFIED WHERE APPROPRIATE, WITH SPECIFIC ATTENTION TO THE FOLLOWING:
    - PROVIDING INDEPENDENT TALKBACK INDICATORS FOR EACH OF THE SIX FUEL CELL REACTANT VALVES PLUS A MASTER ALARM WHEN ANY VALVE CLOSES

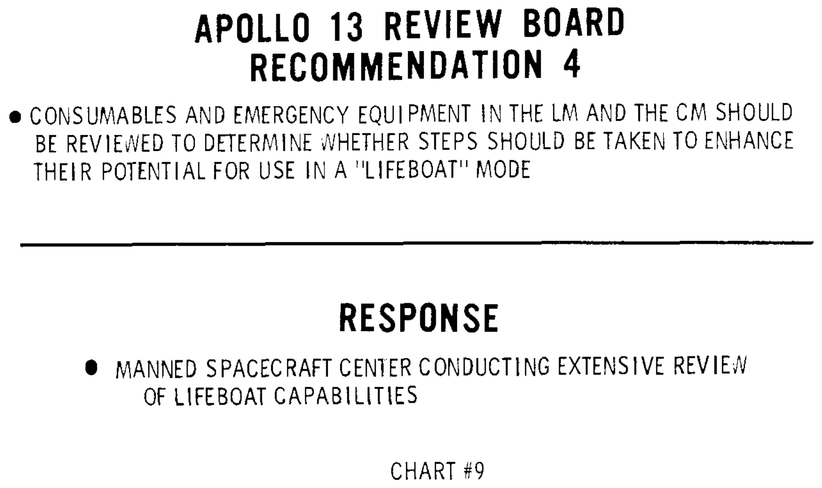
RESPONSE

- MODIFICATION WILL PROVIDE A WARNING IN THE COMMAND MODULE WHEN ANY ONE OF THE SIX FUEL CELL REACTANT VALVES CLOSES

CHART #8

FIGURE 28

Chart 8 (fig. 28). Recommendation 3–D. This addressed itself to providing independent talkback indicators for each of the six fuel cell reactant valves plus a master alarm when any valve closes. We will make a modification and provide a warning in the command module when any one of the six fuel cell reactant valves closes.



APOLLO 13 REVIEW BOARD RECOMMENDATION 4

- CONSUMABLES AND EMERGENCY EQUIPMENT IN THE LM AND THE CM SHOULD BE REVIEWED TO DETERMINE WHETHER STEPS SHOULD BE TAKEN TO ENHANCE THEIR POTENTIAL FOR USE IN A "LIFEBOAT" MODE

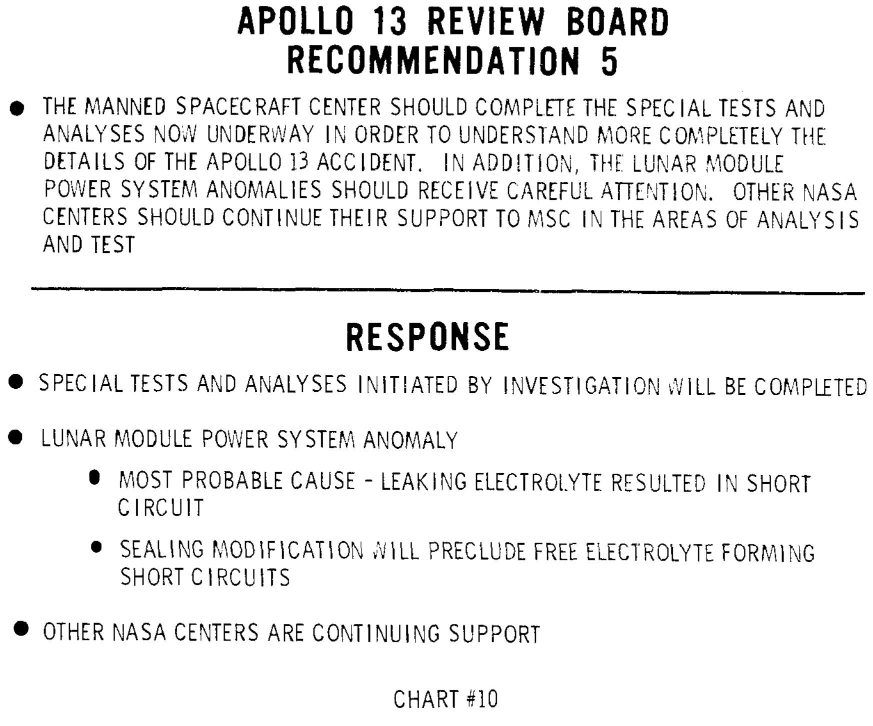
RESPONSE

- MANNED SPACECRAFT CENTER CONDUCTING EXTENSIVE REVIEW OF LIFEBOAT CAPABILITIES

CHART #9

FIGURE 29

Chart 9 (fig. 29). Recommendation 4. This addressed itself to reviewing the consummables and emergency equipment in the lunar module and command module to enhance their potential for use in a "lifeboat" mode. This review is underway. We have a very extensive review going on and we will be getting reports within the coming weeks on what we can do in addition to what we were able to do on Apollo 13.



APOLLO 13 REVIEW BOARD RECOMMENDATION 5

- THE MANNED SPACECRAFT CENTER SHOULD COMPLETE THE SPECIAL TESTS AND ANALYSES NOW UNDERWAY IN ORDER TO UNDERSTAND MORE COMPLETELY THE DETAILS OF THE APOLLO 13 ACCIDENT. IN ADDITION, THE LUNAR MODULE POWER SYSTEM ANOMALIES SHOULD RECEIVE CAREFUL ATTENTION. OTHER NASA CENTERS SHOULD CONTINUE THEIR SUPPORT TO MSC IN THE AREAS OF ANALYSIS AND TEST

RESPONSE

- SPECIAL TESTS AND ANALYSES INITIATED BY INVESTIGATION WILL BE COMPLETED
- LUNAR MODULE POWER SYSTEM ANOMALY
  - MOST PROBABLE CAUSE - LEAKING ELECTROLYTE RESULTED IN SHORT CIRCUIT
  - SEALING MODIFICATION WILL PRECLUDE FREE ELECTROLYTE FORMING SHORT CIRCUITS
- OTHER NASA CENTERS ARE CONTINUING SUPPORT

CHART #10

FIGURE 30

Chart 10 (fig. 30) recommendation 5. This addressed itself to completing the special tests and the analyses now underway. Our response there is those special tests and analyses initiated by the investigation will be completed.

The second part of the recommendation addressed itself to the lunar module power system anomaly, saying that it should receive careful attention. The lunar module batteries which were powering Apollo 13 on the way home, did indicate a short circuit at approximately 97 hours into the mission, for a very short period of time 1 to 2 seconds. We have done a detailed analysis of the telemetry data that we had for that period of time and we have identified the most probable cause being leaking electrolyte which resulted in a short circuit. We plan to fix this by a sealing modification which will preclude free electrolyte from forming short circuits.

The last part of that recommendation addressed itself to the other NASA centers which have given a very high level of support to the Manned Spacecraft Center in this area, to continue this support. Those centers will continue their support.

Mr. Gehrig. Dr. Petrone, the fix on the lunar module anomaly which is reported in the Board's finding No. 47, this will not have any significant cost or schedule impact on the program, then?

Dr. Petrone. We do not see this as a large fix. It is a matter of adding potting compound to areas that were exposed to possible electrolyte shorts and thereby sealing it. That would not be a high cost fix.

APOLLO 13 REVIEW BOARD RECOMMENDATION 6

- WHENEVER SIGNIFICANT ANOMALIES OCCUR IN CRITICAL SUBSYSTEMS DURING FINAL PREPARATION FOR LAUNCH, STANDARD PROCEDURES SHOULD REQUIRE A PRESENTATION OF ALL PRIOR ANOMALIES ON THAT PARTICULAR PIECE OF EQUIPMENT, INCLUDING THOSE WHICH HAVE PREVIOUSLY BEEN CORRECTED OR EXPLAINED. FURTHERMORE, CRITICAL DECISIONS INVOLVING THE FLIGHT-WORTHINESS OF SUBSYSTEMS SHOULD REQUIRE THE PRESENCE AND FULL PARTICIPATION OF AN EXPERT WHO IS INTIMATELY FAMILIAR WITH THE DETAILS OF THAT SUBSYSTEM

RESPONSE

- PRESENT PROCEDURE
  - IN RESOLVING ANY ANOMALY RELIABILITY AND QUALITY ASSURANCE PERSONNEL REVIEW HARDWARE HISTORY FOR PRIOR ANOMALIES
- AUGMENTATION OF PRESENT PROCEDURES
  - HARDWARE HISTORIES WILL ALSO BE REVIEWED BY TEST ENGINEERS
  - FINDINGS WILL BE PRESENTED TO PROJECT ENGINEER
  - START PRESENT SYSTEM FOR RESOLVING IN-FLIGHT PROBLEMS EARLIER
  - EXPERTS RELOCATED AS REQUIRED

CHART #11

Figure 31

Now, we will go to Chart 11 (fig. 31) recommendation 6. This recommendation addressed itself to insuring that whenever significant anomalies occur in a critical subsystem during final preparation for launch, standard procedures should require the presentation of all prior anomalies on that particular piece of equipment, including those which have been previously corrected or explained. Furthermore, critical decisions involving the flight worthiness of subsystems should require the presence and full participation of an expert who is intimately familiar with the details of that subsystem.

In our present procedure, in resolving any anomaly, reliability and quality assurance engineers review the hardware history for prior anomalies. We are going to augment our present procedures by requiring in addition to the reliability quality assurances personnel, that the test engineer also review the hardware history and make a presentation of his findings to the project engineer. We presently have a system for resolving in-flight anomalies which starts with the final countdown. This is a grouping of cross-expertise in support of the Mission Control Center at Houston. We are now going to activate that system approximately 6 weeks before launch which will include all of the final launch preparations. This will bring together the cross-expertise that is needed in solving any one problem.

Senator CURTIS. May I ask a question?

The CHAIRMAN. Senator Curtis.

SUMMARY OF DESIGN PHILOSOPHY FOR FIRE PREVENTION

Senator CURTIS. There is something I would like to have somebody comment on. When the fire occurred 3 years ago, the 204 fire, extensive modifications of the Apollo hardware were made after that fire. Yet the Apollo 13 Review Board found "A hazardous combination of materials and potential ignition sources in the oxygen tanks."

I would like to have you comment on that particularly as to any connection with the earlier studies of the fire.

Dr. PETRONE. Sir, I would state that the review after the 204 fire concentrated on the cabin of the command module and the lunar module. The review came up with specifications that in effect, had to assume the fire would start or a spark would start, that it would be impossible to totally rule it out in a thing as large as the cabin, and then come up with materials specifications that would extinguish the fire in the 5 pound per square inch pure oxygen that we have in space.

The basic ground rule was to assume the fact that a fire would start, and determine how to contain it. Through the use of Teflon, which was the best material available, any fire that started in 5 pounds per square inch zero "G," would smolder out.

In addition, specifications and rules were arrived at on having firebreaks so that an ignition started in one place and maybe smoldering as it was going out would not set off other material nearby by having prescribed amounts that could be located in specific places.

In this tank we have a different condition now. Instead of low pressure, we have this much higher pressure of a thousand pounds per square inch. In the design, the assessment was made that once we have the harness in and the cable in the sealed container, and have checked it out at a high voltage and see no short, then we will have no ignition. So that was the error, the abuse unknown at that time of overheating this wire, as we did in the improvised detanking procedure we did set up the potential then, of these arcs. Once you obtain ignition with the Teflon at this high pressure, there was no containing it as there would be in a cabin.

Mr. GEHRIG. Dr. Petrone, I would like to follow that up with a question. After the Apollo 204 accident why were not all these subsystems reviewed, particularly where they involved an oxygen environment and where they had not been subjected to prior formal design review by NASA or North American Rockwell?

Dr. PETRONE. I believe I can say the tank was reviewed. It was reviewed in the summer of 1967 by a group that NASA put in residence with North American to review all systems and I believe the basic error was made within the final criteria which assumed you could have an ignition source and then in the cabin it would snuff out. In the tank, the testing of the harness at the higher voltage was taken as proof that you would not have ignition.

Mr. GEHRIG. As I understand it, you did not test to see if Teflon would burn in a high density, high pressure oxygen environment.

Dr. PETRONE. Well, there were tests made I believe at 20 pounds per square inch and there——

Mr. GEHRIG. Did it burn at 20 pounds per square inch?

Dr. PETRONE. At 20 pounds per square inch it would smolder. It would not go out. And the conclusion was that at higher pressures, the rate of combustion would not vary greatly. So, the knowledge that Teflon would burn in the higher pressures was acknowledged and is in our basic design specifications. The denial of an ignition source, that there would not be a way of setting it off in that tank, is the key failure.

Mr. GEHRIG. Well, what bothers me about that is that that is precisely what the initial design concept was when they designed the command module. They said you have to have three things for a fire, an ignition source, oxygen and fuel and the way they were going to prevent fires in that pure oxygen environment was to prevent ignition sources. They did not prevent ignition sources and I thought that had taught everybody a lesson, yet here we have another case where we have a tank with a pure oxygen environment, we have fuel in the tank, and we do have ignition sources.

I still do not understand why NASA or the contractors did not test the Teflon under this high pressure oxygen and test for ignition sources. As I understand it from the Board's report, the way that most of the testing is done is by striking and here the ignition source, and the ignition source was thought to be in the Apollo 204 accident, an electric arc which I understand concentrates the heat energy. Could you comment on that, please?

Dr. PETRONE. Yes. The testing is done on that harness in a sealed container and as such, understood not to get further wear or abuse by movement as it would in a cabin. The test after it was assembled was considered to give us assurance we would not have an ignition source. Now, through the abuse of overheating the wire we, in effect, set up an ignition source, and that is the error.

Mr. GEHRIG. But this then is the same basic error that was made prior to the Apollo 204 fire.

Dr. PETRONE. I do not believe I would consider it to be the same basic error.

Mr. GEHRIG. Well, the same philosophy, design philosophy, was followed in the design of the command module prior to the 204 fire. The way to eliminate fires in a pure oxygen environment, as the testimony before the committee shows, was to eliminate ignition sources. As a matter of fact, they got pretty careless about what kind of material they put in the command module because they were so sure they did not have ignition sources.

Dr. PETRONE. I referred here to the design in the tank, tested at a high enough voltage, revealed no ignition source. Now, when the equipment is abused there is no way you can design it to know what it can be abused for. The unknown abuse set off a series of conditions which gave us the fire.

(Additional information submitted for the record follows:)

The following is a summary of the design philosophy adopted to prevent fire in Apollo following the Apollo 204 accident.

FIRE PREVENTION IN APOLLO

Following the Apollo 204 fire in January 1967, possible causes for spacecraft fires, and means of fire prevention were re-examined.

Three things must be present to start and sustain a fire: an oxidizer, a fuel and an ignition source.

In manned spacecraft, an oxidizer (oxygen) must always be present to sustain life. Therefore, one look toward minimizing possible fuel sources, or toward eliminating ignition sources, in order to prevent a fire. Two different approaches were used to minimize the fire hazard in the cabin and in the oxygen tank, because the environment in these two locations is entirely different.

Fire Prevention in the Cabin: The detailed examination of the Apollo spacecraft cabin after the 204 fire soon revealed that it would not be possible to assure the elimination of all ignition sources. There are miles of wiring in the cabin; there are hundreds of switches and connectors. And the potential for damaging these during checkout, or even during flight, always exists. A damaged piece of wire, a scraped piece of insulation, or a damaged connector can become a source of ignition.

Therefore, the approach adopted for design and testing had to consist of eliminating as much combustible material as possible consistent with operation requirements; protecting remaining combustibles against fires; and arranging combustibles so that any accidental fire would be self-limiting and of limited magnitude in the test, launch and flight atmospheres. In a low pressure oxygen atmosphere, many non-metallic materials become potential fuel sources; however, metals will not burn. But some non-metals can also be found that will not burn at the 5 psi cabin atmosphere. Only Teflon wire insulation was permitted. Space suit covers were changed from Nyon to Fiberglass cloth (Beta-cloth). New potting compounds that do not burn were invented. All nylon and polyurethane plastics were ruled out, and were generally replaced with fluorine-based compounds that will not burn in this atmosphere.

Then tests were made. In these tests, provocative ignition was deliberately attempted all over the spacecraft. And it was demonstrated that in the 5 psi cabin atmosphere the spacecraft fire could not be sustained; it always self-extinguished.

It was also found that the same materials that were safe in the 5 psi (space) cabin atmosphere would burn at 16 psi in pure oxygen—the atmosphere that had been planned for the launching pad. We therefore changed from a pure oxygen atmosphere to one that contained 60% oxygen and 40% nitrogen on the launching pad. Tests again demonstrated that fire would not propagate in the newly rebuilt spacecraft in this atmosphere, even at 16 psi.

The oxygen storage tank: Inside the oxygen storage tank, the pressure is 900 psi. The materials that were found to be safe in the cabin would still burn in this atmosphere. Even metals, aluminum, steel and inconel, can be ignited. Therefore, it was not possible to remove all the "fuel"; instead, the ignition source would have to be eliminated.

Inside the tank, the situation is far more restricted than in the cabin: there is only a small amount of wire, and a few electrical components. These could conceivably become an ignition source through overheating, or through arcing. The possibility of overheating was eliminated by installing fuses in the circuit. This left only arcing as the potential igniton source.

It was known that a damaged wire or damaged insulation would be needed to strike an arc. And It was reasoned that if it was demonstated, after the tank was assembled, that the wiring was not damaged, no damage could occur later on because the tank was sealed. The wiring was checked after assembly—through the use of a dielectric strength test—and found to be undamaged.

Of course, we now know that one important factor was overlooked in this reasoning: the wiring inside the *sealed* tank could be subsequently damaged through exteral sources. This is just what happened during the special de-tanking procedure prior to launch. The wiring was damaged, a potential ignition source was created, and the Teflon insulation was ignited when the arc occurred in flight.

For future flights, potential ignition sources for the materials as located within the tanks are being eliminated by encasing all wire in stainless steel and by removing the fan motors from the tank.

Senator HOLLAND. Mr. Chairman——

The CHAIRMAN. Senator Holland.

OXYGEN TANKS

Senator HOLLAND. I have several questions. First, why was the second oxygen tank a casualty after the accident had happened in the first tank?

Why was that sequence apparently unavoidable?

Dr. PETRONE. I do not believe we fully have explained that. The analyses have considered failure of the second tank. It took about an hour and a half to lose its pressure. I do not believe we fully understand exactly how the first one caused the second one to lose pressure.

I wonder if Mr. Cortright might care to comment on that from the Board's standpoint.

Senator HOLLAND. It seems to me this is one of the critical points. You had two tanks in order to have one available if there was an accident on the first, and yet the accident on the first was communicated to the second so as to take it out of usefulness; and my question is why?

Mr. CORTRIGHT. Senator, there are at least two possibilities here. There was a severe shock or jolt at the time the first tank which actually was tank No. 2, ruptured. This rapid expulsion of oxygen built up a pressure in the bay that exceeded 20 pounds per square inch and blew a rather strong structural panel off in a few thousandths of a second. The resulting jolt was sufficient that it might have jolted open the relief valve to oxygen tank No. 1 and that may have failed to reseat properly, in which event the tank would slowly leak down as it did.

Another possibility is that the metal elements, primarily the tubing in the cap to the top of the oxygen tank No. 2, could have been thrown violently aside when the top of the tank ruptured, struck a line to oxygen tank No. 1 and caused a small leak in that line. It would take only a small leak to deplete the oxygen in the time it was depleted.

Now, we found no way to prove by testing which of those two, if either, was the cause. Virtually all other known or observed events were demonstrated in subsequent tests.

Senator HOLLAND. What additional precautions are you taking now to do away with any possibility of a similar communication between tanks one and two or even to tank three, which you propose to add?

Dr. MYERS. We are going to review all of the possible sympathetic damage conditions in the Apollo spacecraft and its launch vehicle, but it is very clear that the protection against damage from an exploding tank or rupturing tank to another tank close by is one that we just cannot design against. We must keep from having tank ruptures. That is a fundamental premise of design that we must follow in these designs. So, we are going to review other systems to see whether there are other elements other than tank failures that could give us this interaction from one redundant system to another, but it is clear that in the tank area we just have to protect against tank failures.

Senator HOLLAND. Why does the addition of a third tank, as you now propose, obviate any possibility of just such an accident affecting all three tanks?

Dr. MYERS. Of course, we are here removing all Teflon coated wiring, any of the kinds of materials that could give us difficulty, from these tanks and we are designing now with every precaution that has come out of our Board's report to be sure we do not have a tank rupture.

Senator HOLLAND. Does the addition of a third tank bring on any space problems within the confines of the vehicle?

Dr. PETRONE. No; it does not, Senator Holland. As I mentioned, we had planned to put a third tank in Apollo 16. We have an area called bay 1 wherein with Apollo 16 and subsequent, we will add also a third hydrogen tank and a scientific instrument module base. We will not have a problem on weight or space as far as adding a third tank for Apollo 14.

WIRE COVERING

Senator HOLLAND. If I understood your testimony correctly, you said you would obviate the possibility of the fire hazard in certain parts of the wiring by using stainless steel covering for your wiring. But you still are continuing teflon covering for some of the wiring. Why the difference?

Dr. PETRONE. I do not believe we have any Teflon-covered wires. They will all have been removed. The stainless steel sheathed wires will be used for any wires that have to go into that tank.

Senator HOLLAND. I understood some earlier testimony to indicate that certain parts of the wiring would remain Teflon-covered. Was I mistaken?

Dr. MYERS. Senator, this wiring, for example, that goes into the tank and down inside the oxygen probe will all be removed, all that Teflon-covered wiring will be removed and we will use only the stainless steel sheathed wire.

Senator HOLLAND. Where will the teflon wiring continue to be used?

Dr. MYERS. There will be no Teflon wiring used in the tank at all. The remaining pieces of Teflon are insulators that insulate the capacitance gage from the grounding of the outside of the tank. These pieces of Teflon are inert and since these wires are all removed, there are no ignition sources anywhere near them. We are continuing to review the possibility of removing those Teflon pieces but since there are no—since all the electrical sources inside the tank now will be covered with stainless steel, we believe that through our testing we will be able to prove to ourselves that that piece of Teflon is satisfactory.

Senator HOLLAND. Well, why retain any Teflon wiring if you know that that is flammable——

Dr. MYERS. Not Teflon——

Senator HOLLAND (continuing). And that the stainless steel-covered wiring is not flammable?

Dr. MYERS. I am sorry. We will not have any Teflon-covered wiring inside the tank. There is a Teflon insulator for this capacitance gage, here and here. Those are the only remaining pieces of Teflon in the tank but not Teflon-covered wiring.

Senator HOLLAND. Well, it will be flammable wherever it is; will it not?

Dr. MYERS. Yes. The problem in this capacitance gaging system is that we have a balanced dielectric insulator between the ground of this tank and this inner capacitance gaging system, and although we are looking at possible other materials for that capacitance gage system we have not found one that is satisfactory. Since we have removed all electrical wiring from the oxygen source, we believe we can continue with this design of the capacitance gaging system.

COUNTDOWN PROCEDURE

Senator HOLLAND. My next question is this: Will your countdown procedure include new tests applicable to the oxygen tanks which have not been used heretofore?

Dr. PETRONE. I guess I would like to address that—you say new tests. There will be new procedures in terms of the new design that we are going to have. With the modified design, we will bring it up to pressure differently. However, the use of the higher voltage which was done to shorten the time required to pressurize, we still, and this is part of the review, may have to continue that. It is a matter of some 3 to 4 hours of extra time that we would have to weigh. We do not count the higher voltage to have been the problem except on this improvised detanking procedure. That, of course, was a procedure that did cause the difficulty. It was not the tanking procedure. It was when we ran into trouble detanking that an improvised procedure did allow the higher voltage to be used with the inadequate thermal switch which did not open up when the limit of approximately 80° was reached.

Senator HOLLAND. Well, my question I will renew. Are you going to have new procedures involved in the countdown which will guard against a recurrence of that kind?

Dr. PETRONE. Yes, we will. We will have new procedures based on the new design. We will.

APOLLO FUNDING IN RELATION TO NEW SCHEDULE

Senator HOLLAND. I have two practical questions. The House reduced the fiscal year 1971 appropriation for research and development by $106.1 million below your request, indicating that the cut should be taken in the Apollo program. In fact, the House Appropriations Committee in its report, recommends that the Apollo 14 flight be deferred until after the first of calendar year 1971 and states: "The funds recommended will provide for one Apollo flight instead of two flights in fiscal year 1971."

Your decision, now announced to this committee, not to launch Apollo 14 until at least January 31, 1971, which moves the planned launch date for Apollo 15 to July or August 1971 at the earliest, agrees with the House recommendation. Will this reduce the cost of the Apollo program for fiscal year 1971?

Dr. MYERS. Our estimate is that change in the schedule would save approximately $20 million rather than the $106 million.

Senator HOLLAND. Why the difference between the figure that is stated by the House report and action and at the figure now stated by you?

Dr. MYERS. I think the problem probably is in the degree of operations at the Cape that are involved and the degree of support from the contractors. We all are dealing with that problem now of how to retain the capability of top systems engineers in support of our programs at the Cape, system engineers within our centers, and the people that really understand these systems at the contractors. When we look at delays in schedules it is difficult to estimate what kind of capablity we must maintain in support of these launch operations.

Senator HOLLAND. Let us see if I understand what you have said. You are suggesting something different from the House, that instead of the reduction made by the House of $106.1 million, their reason given that they expect only one Apollo flight instead of two flights in fiscal 1971, what reduction do you now recommend?

Dr. MYERS. We believe that you could save approximately $20 million on that move of the schedule but as we testified here today, the changes to the tank itself, we believe, will cost something of the order of $10 to $15 million. So, it really is a kind of tradeoff as far as the funding is concerned and, as we testified, we believe we can absorb these changes within the Apollo budget for this year.

Senator HOLLAND. And the reason that you can absorb them is due in part to the fact that you are slowing down the Apollo launches, is that correct?

Dr. MYERS. Yes, sir. That does trade off, approximately even.

Senator HOLLAND. These questions are going to be very troublesome questions in the appropriations process and perhaps particularly so in the conference and as I now understand it, you think that about $20 million is the maximum saving that would result and that $10 to $15 million of that would necessarily be used in making these changes.

Dr. MEYERS. Yes, sir.

Senator HOLLAND. To avert any possible recurrence of trouble with the oxygen tank.

Dr. MEYERS. Yes, sir. I think there is another point, Senator, that might be added here. In my testimony I discussed the further thorough investigation of our engineering teams and the capability of those teams to respond and to be on site properly and to understand in depth the kind of details that we really find we must understand in these systems. As the Apollo program schedule is either delayed or stretched, the challenges that we have for top technical people is something we must continue to reinforce to be sure that we have the proper support to these flights. And as a result of this review, one of the indications might be that we may want to reinforce the capabilities of some of our subsystem activities to be sure that we are properly supporting these flights. If that were the case, it would perhaps make it even tighter for Apollo problems for this coming year.

EFFECTIVENESS OF COUNTDOWN AT TWO LOCATIONS

Senator HOLLAND. Now, my last question is one which comes to me from various of the personnel in the Kennedy Space Center complex. Is there any reduction in the effectiveness of the countdown due to the fact that the countdown takes place at the Kennedy Space Center whereas the Manned Space Center is over at Houston?

Dr. MEYERS. No, sir, I do not believe so. I have seen tremendous communications carried on between those two centers and from what I have seen of the balance of effort between the two centers, it has turned out to be a very fine reinforcing kind of an activity. The testers in the field questioning at times the people who technically were involved in the development of the equipment has given us a balance of discussion that has been good as far as understanding these systems.

Senator HOLLAND. Well, I think you can understand why there is still skepticism on this question present among some of the people stationed at the Kennedy Space Center. They have never felt that removal so far apart of the Manned Spaceflight Center—the mission control center—at Houston from the launch operations center at Kennedy Space Center was a wise thing and could possibly result in the degree of efficiency that would have prevailed if the two centers had remained at the same location.

Thank you, Mr. Chairman.

The CHAIRMAN. Go ahead. Have you finished your statement?

Dr. PAINE. I believe our statement is concluded, Mr. Chairman. We will be happy to respond to any further questions.

The CHAIRMAN. Senator Goldwater?

FIREPROOF MATERIALS

Senator GOLDWATER. Yes.

Dr. Petrone, on chart 10 (see fig. 30) you indicate that short circuits have been caused by free electrolyte forming. How could that happen in that atmosphere?

Dr. PETRONE. These batteries have electrolyte in them as a process of charging. We also have to vent batteries to allow hydrogen gas which forms as part of the current forming process to escape. In this venting mechanism there is the potential for free electrolytes to escape and form in a globule. Despite the fact that we are in weightless condition at that time, some of the pressure that could build up could also expel some of the electrolytes, then letting it go into the terminal area where one then could get these short circuits.

Senator GOLDWATER. Are these cadmium batteries?

Dr. PETRONE I believe they are similar.

Senator GOLDWATER. The reason I am interested, I recall one day landing just behind another jet and that jet blew up because a cadmium battery blew up. I believe it had been allowed to get dry and I imagine the same process took place. I was very interested to ask that question because I am acquainted with electrolysis but I never heard of this but it certainly could happen.

Dr. Paine, we hear a lot about materials that will not burn and they are called fireproof and then they do burn and they are not fireproof; for example, Teflon. Now, I could have told you a long time ago that Teflon burns because my wife tells me every time I use a frying pan I burn it. What do you mean by "burning" and "fireproof"?

Dr. Paine. That is a very good comment, Senator Goldwater. The burning process, of course, is what you really fundamentally call in simplistic terms an oxidation. It is important to realize that every place in which a strong oxidizer is stored in any material, there is the possibility of two chemicals being in contact and reacting with each other.

In the case of Teflon the great resistance of this material to oxidation is perhaps best demonstrated by the fact that we did keep it for a substantial number of hours at Cape Kennedy during this detanking procedure at a heater temperature of 1,000° in contact with very high pressure oxygen without igniting it at that time. We degraded the Teflon badly and damaged it sufficiently so that we set up this later sparking ignition. Teflon below about 1,200° will not ignite even at a thousand p.s.i. oxygen, although once ignited Teflon in any pressure above about 20 p.s.i. will continue to oxidize, to burn in pure oxygen, as was brought out in the questioning of Mr. Gehrig.

What we have to do in the case of a spacecraft obviously, is to contain strong oxidizers and strong reducing agents within materials in such a way that we sufficiently minimize the chance of any reaction. But if the temperatures are raised high enough, of course, then they will ignite. Almost any time you get two dissimilar materials in contact they will begin to react against themselves.

Senator Goldwater. Did you know this before the tank accident?

Dr. Paine. Yes; as a result of the followup of 204 fire extensive tests were made of many materials. We found down at the five p.s.i. pressure at which we operate our cabins, there is a good deal of safety and with Teflon we can extinguish and block and have an opportunity to contain any ignition even if it begins. We found above 20 p.s.i. we get the opposite effect. The Teflon then continues to burn. And the high p.s.i. as we have in the tank, Teflon and even metals like iron and steel and aluminum, will burn, once ignited.

Senator Goldwater. I have heard that NASA is switching flight suits made of Nomex, whatever that is, to flight suits made of durette. Would you explain what Nomex is and will it burn?

Dr. Paine. Those particular terms are not familiar to me.

Senator Goldwater. They are not in your dictionary either?

Dr. Paine. Perhaps Dr. Low will comment on that.

Dr. Low. Senator, Nomex is a nylon-type fabric that has a high temperature resistance property in air. It will not burn, only char, while nylon will melt at a much lower temperature.

Senator Goldwater. At about what temperature?

Dr. Low. Nomex will char at 840° F. but nylon will melt at 482° F.

Seantor Goldwater. Is this the same material that race drivers wear today?

Dr. Low. Yes, sir.

Senator Goldwater. Will it withstand gasoline fire temperatures?

Dr. Low. No, sir.

Senator Goldwater. It will for a short period of time.

Dr. Low. Yes; for a few seconds but a better material has been developed, that has a higher flame-resistant temperature than Nomex. We are now using the material for the astronauts' aircraft flight coveralls and investigating its use for firefighting uniforms.

Senator Goldwater. Is that what you call durette?

Dr. Low. Yes.

Senator Goldwater. We saw some demonstrations in this room of the material that you developed at NASA that prevents burning. None would burn under even the—I think the temperature was 3,000°.

Dr. Low. The best material we have in the space suits are made out of what is a beta cloth which is a fiberglass made in a special way so that the glass fibers themselves will not irritate the skin. However, that beta cloth fiber does not wear very well. It wears out quite quickly. The Teflon materials and the astronauts' space-flight coveralls made out of Teflon material are not quite as fireproof but will not burn ordinarily in the air and this Teflon material does have much better wear capability than the beta cloth.

Senator Goldwater. Thank you very much.

Mr. Cortright, in your testimony before the House you said:

> I think we ran into a new phenomena that was not widely recognized before and that is that Teflon can be ignited rather easily if an electric arc is the igniting mechanism, and we ran tests to show that these small amounts of electrical energy were sufficient if they were in the form of an electric arc which concentrates the heat very locally in the material, and we ran additional tests to show that even through the one amp relatively quick low fuse that was on the line to protect it, you could get energy ten to 100 times in excess of what was required to ignite the wire insulation.

Am I right in saying that the ignition temperature of Teflon is 1,300, about 1,300°?

Mr. Cortright. I think that is about right, Senator Goldwater.

Senator Goldwater. And you can get that temperature out of 1-amp arc?

Mr. Cortright. Yes, sir, in a very local region you can get higher temperatures than that. The arc itself generates extremely high temperatures and it requires that the heat is so concentrated that it requires little total energy.

Senator Goldwater. What is the voltage used on that particular system?

Mr. Cortright. The voltage used in the spacecraft is 28 volt D.C.

Senator Goldwater. All through it? All systems?

Mr. Cortright. On the motors it is 115 a.c., pardon me. The basic power supply in the spacecraft is 28 volt D.C. But the fan motors were the higher A.C. voltage.

Senator Goldwater. Are there any special conditions needed to get a concentration of energy in an arc or will it always occur?

Mr. Cortright. Well, I am not sure how special they have to be. I can tell you the sort of arcs that we struck in order to get this to ignite. For example, if you skin the insulation on a wire to where it is just exposed to wire and carried a single strand of a multistrand wire into that skinned portion and then struck the arc by first melting that little piece of wire and then having the arc strike across the ionized gap, that would start it very well.

On other occasions we created the short by means of a pointed screwdriver which probably or definitely would not melt and ionize as readily as the single filament of wire and that also started the fire. So, I think what you really need is a point contact in the presence of a very thin shaving of insulation such as you get in a skinned area. And that was sufficient to start ignitions with less than 5 joules of energy.

Senator Goldwater. I imagine the fuse blew out in that system.

Mr. CORTRIGHT. Yes.

Senator GOLDWATER. It did?

Mr. CORTRIGHT. The fuses blew after the short.

Senator GOLDWATER. How fast a fuse do you have?

Mr. CORTRIGHT. Well, it is a quick blow fuse but it was, I believe, at the slow end of the quick blow range. I cannot give you the time but it was sufficient to pass—excuse me. Dr. Clark remembers that it took about 30 milliseconds of 3 amps to blow and we know that this could pass at least 20 joules of energy and perhaps as much as over 100.

Senator GOLDWATER. Was there any way that that could have been discovered during the Apollo 204 investigation?

Mr. CORTRIGHT. Had someone thought to run that particular type of ignition test, it would have been discovered, yes, sir, because that was not a highly complicated test to run. It was merely a matter of suspecting that this could occur.

Senator GOLDWATER. In your statement you say that one series of tests demonstrated electrical ignition of teflon insulation in supercritical oxygen under zero "G" and one "G," and provided data on ignition energy and burning rates.

Did you run similar tests on 5 p.s.i. pure oxygen atmosphere under one and zero "G" conditions?

Mr. CORTRIGHT. Not as part of these investigations, but I believe those tests were run after the Apollo 204 fire.

SUPERCRITICAL FLUID

Senator GOLDWATER. Just one more question. Maybe two more questions. You talk about supercritical state of oxygen. For the record, could you—could someone define what you mean by supercritical?

Mr. CORTRIGHT. Supercritical fluid is a single phase fluid. Normally, for example, a container of water, if I had a top on that, you would have liquid water and water vapor above it with a plane of separation. This is two-phase. Liquid oxygen in a container would look like that also but with liquid oxygen here and gaseous oxygen above it but in a certain regime of pressure-temperature combination that parting plane would disappear and the fluid would totally fill the tank in a single phase condition and it is maintained that way throughout the Apollo mission.

Senator GOLDWATER. It would not then be really a fluid, would it?

Mr. CORTRIGHT. Yes, it is a fluid.

Senator GOLDWATER. With gas——

Mr. CORTRIGHT. Well, Senator, you can have some very interesting discussions on whether it is more liquid or more gas and we never quite did resolve that. It is more like a very, very heavy gas that is more dense than liquid or as dense as liquid or a liquid that behaves like a gas. You can take your choice.

Dr. PAINE. A very stable fog would be another way of putting it.

Senator GOLDWATER. A very what?

Dr. PAINE. A very stable fog that would completely fill the container.

Senator GOLDWATER. Would the term "cryogenics" be compatible with supercritical?

Dr. PAINE. In order for oxygen to be supercritical it does require cryogenic temperatures, so that is a part of it.

Senator GOLDWATER. Dr. Petrone, on figure 28 you talk about providing independent talkback indicators for each of the six fuel cell reactant valves. I thought all of the spaceships had recorders that the command pilot could see or that could be reported to earth.

Dr. PETRONE. In the particular case of the fuel cell valves, the indicator system was so wired that both the oxygen and the hydrogen valve had to close before an indication was given. This is what we have modified or are in the process of modifying now so that a warning will occur if either one or the other should close as happened here due to shock. There was in this particular flight not much that could be done because we had lost the oxygen supply, but in the future we would want to know that if either one of the oxygen or the hydrogen valves closes—he will get a light and a horn to warn him.

Senator GOLDWATER. I am rather surprised that you did not have this before. One light for hydrogen would not be of much use in trying to tell which one you lost.

Dr. PETRONE. It turns out the way it is wired up, when you actuate a single switch you energize both valves. It is tied into the way you bring the system up. A single switch command will give both valves the command to open. That was the way that the indication came out, but we have changed that as a result of the review that we made after the Apollo 13.

Senator GOLDWATER. Was it a single switch, a single double-throw switch for two instruments, was it just a single switch for one instrument on two valves, it that correct?

Dr. PETRONE. Yes, sir. Normally in flight you would never have to throw that valve. You would never want to bring the fuel cell down. You have lost it then. So, it was a type of a switch that on the ground was needed to bring the fuel cells up and get them operating properly, and in flight one would never want to close that.

Dr. PAINE. An analogy that would be very familiar to you, Senator Goldwater, is that we had the indications essentially as you have with both wheels up in an aircraft, and what happened was that essentially in this case we had one wheel down and we did not get an indication of which was which. We will now have an indication such that we can see either valve being opened.

Senator GOLDWATER. Thank you.

Thank you very much, Mr. Chairman.

The CHAIRMAN. Senator Smith?

Senator SMITH of Illinois. No questions.

The CHAIRMAN. Senator Holland?

Senator HOLLAND. No further questions Mr. Chairman.

The CHAIRMAN. Mr. Gehrig.

THERMOSTATIC SWITCH

Mr. GEHRIG. Thank you, Mr. Chairman. Mr. Cortright, you have said—in testimony before the House committee—that the thermostatic switch discrepancy was not detected by NASA, North American Rockwell, or Beech in their review of documentation nor did tests identify the incompatabilty of the switches with the ground support equipment at the Kennedy Space Center since neither qualification nor acceptance testing required switch cycling under load as should have been done. It was a serious oversight in which all parties shared.

When and how did the Board detect the thermostatic switch discrepancy?

Mr. CORTRIGHT. There were tests being conducted to determine what damage might have occurred to the wiring which ran through the tank due to the extended heater operation.

Now, this test was first run with the switches wired closed, in other words, wired out of the circuit, assuming that the switches might have failed closed, although we did not really hypothesize at the time how this might have happened, and this showed that the wiring was damaged as mentioned in the Board's report.

Subsequently, then, it was reasoned that, well, the history of the switches was such that they had a tendency to fail to open; that was the chronic problem with them. Therefore, we decided to put the switches back in the circuit and determine whether or not the wires would be damaged even if the switches were in for this extended operation. And it was at that point in time that the switches failed. In other words, it was not a test specifically to test the switches, but rather a test in which the switches were used and failed; this was how we discovered the switch discrepancy. I think that answers your question.

Mr. GEHRIG. Yes. Do I understand that people did not realize that the switches were rated for 30-volt, direct current, and that there were 65 volts on the line?

Mr. CORTRIGHT. That is correct.

Mr. GEHRIG. Is that correct?

Mr. CORTRIGHT. Yes.

Mr. GEHRIG. Who designed the tank?

Mr. CORTRIGHT. Beech.

Mr. GEHRIG. Beech designed it. Now, Beech, as I understand it from your report or from your testimony before the House, uses 65 volts, alternate current, at their plant to test.

Mr. CORTRIGHT. That is correct.

Mr. GEHRIG. Would not the engineers recognize that they had 28 volt switches and that might cause a problem?

Mr. CORTRIGHT. It turns out that the switches were quite capable of operating at 65 volts alternate current in the manner in which Beech used it.

Mr. GEHRIG. I see. And they did not know that there were 65 volts direct current down at the cape?

Mr. CORTRIGHT. Well, they were notified that there was in the specification written by North American Rockwell.

Mr. GEHRIG. But they did not connect this with the 30-volt switches actually, as I understand it.

Mr. CORTRIGHT. That seems to be the case.

IGNITION SOURCES

Mr. GEHRIG. Dr. Petrone, going back to the discussion we were having before, there is an awful lot of oxygen on the Apollo command and service modules, on the lunar module, and on the Saturn V booster. Is NASA now going to take a look at all of these oxygen sources, look for ignition sources and combustible materials in the vicinity to make sure that they eliminate this hazard?

Dr. PETRONE. Yes, we are. We have those tests now underway and the thing we want to assure ourselves is that the materials that are there are tested under the conditions which they see. In other words, there are many types of tests that they call impact sensitivity tests, many different ways to qualify material to go into a lox tank. For example, we now, as a result of the Apollo 13 experience, review all our criteria to assure not only that we meet certain specifications but we meet all the conditions that exist in that tank. That activity is now underway.

Mr. GEHRIG. And are these people going to look at ignition from electric arcs rather than just from impacts and things like that?

Dr. PETRONE. Yes, we are.

Mr. GEHRIG. Because this is very similar, it seems to me—I looked back at the testimony before the committee on the Apollo 204 accident and it reads very similar to what we have today. Testimony at that time was: "The approach to fire prevention is to prevent the ignition of combustion by attempting to remove all possible sources of ignition." That was the design philosophy before the 204 fire.

FURTHER TESTS

Mr. Cortright, on page 5–1 of the report of the Apollo 13 Review Board, it is stated that, "Further tests and analysis which will be carried out under the overall direction of the Manned Spacecraft Center will continue to generate new information relative to this accident. It is possible that this evidence may lead to conclusions differing in detail from those which can be drawn now." Are these tests and analyses complete and if so, has any evidence developed that might lead to different conclusions than those presented in the report?

Mr. CORTRIGHT. Mr. Gehrig, the tests and analyses are not yet complete but as yet have not led to any different conclusions. I can tell you briefly at least two of them that are still underway. For example, at Beech Aircraft Corp. there is essentially a duplication of the detanking procedure on a flight quality tank which is going on for the second time. The first time the switches failed in a little different manner and hence, it is being repeated with the switches closed and actually the switches are out of the circuits, thereby simulating the manner in which is failed at the Cape.

Currently it is not possible to insure that the switches will fail closed because one of them, for example, melted out the contact points and they dropped out and it failed open, although we know that the two at the Cape failed close.

That is one test that is being completed this week.

Another series of tests and analyses is to further refine our understanding of the manner in which the panel ruptured and blew out. The first series of tests that were run were conducted with panels without cutouts in them and now we are attempting to account for the presence of cutouts in the panel which were present in the actual flight hardware and this may bring our experimental analyses and test data into better agreement with what we know happened in space.

TANK TEMPERATURE

Mr. GEHRIG. Why was the tank temperature not identified on the test specifications or checkout sheets as an item to be observed during ground testing at the Kennedy Space Center?

Mr. CORTRIGHT. I do not know the answer to that.

Mr. GEHRIG. Well, the tank temperature was monitored at the Control Center and it was off normal but nobody noticed it. Why do they record it if they do not monitor it?

Dr. PETRONE. May I attempt to answer that? The tank temperature was being observed on a scope. It was being recorded on tape. When I use the words observed on scope, he is reading a set of numbers and it was observed to go up from the range of about minus 300 to plus 80.

In the judgment of the people observing that rising temperature, when it hit 80 and then leveled—did not go any higher—they assumed it was at a safe temperature. That was incorrect because that particular gage, or that temperature sensor, has a maximum limit in the 80° range. Here was a sensor in effect pegged out but is reading 80. We now know the temperature was higher than that.

The temperature sensor, I might add, is not directly on this heating element. It is slightly displaced. It is on the quantity probe but even so, the trace will show temperature increase. As we plotted later, it went from minus 300 to plus 80 in about 3 hours and then leveled off at plus 80 but that leveling off was in the temperature sensor. It is the upper limits of the gage. The actual temperature was higher.

Mr. GEHRIG. Somewhere in the report, Mr. Cortright, it seems to me I remember reading that there is an alarm, a local alarm on this temperature reading and that nobody knows whether or not the alarm went off or not. Am I correct in that?

Mr. CORTRIGHT. What you may be recalling is reference to an alarm in Mission Control Center——

Mr. GEHRIG. That is right.

Mr. CORTRIGHT. When the pressures of the tank went above limit in the short period before the tank ruptured. There was a light that in all probability came on——

Mr. GEHRIG. That is what I remember.

Mr. CORTRIGHT. And indicated that and then went off again when the tank ruptured and the pressure dropped down. This was not noticed.

Mr. GEHRIG. I see.

AEROSPACE SAFETY ADVISORY PANEL

Dr. Harrington, who are the members of the Aerospace Safety Advisory Panel?

Dr. HARRINGTON. At the present time we have seven members, with myself as Chairman. Mr. Frank DiLuzio, Gen. Carroll Dunn, Dr. Henry Reining, Dr. John Hornheck, Dr. Harold Agnew, and Mr. Bruce Lundin. I think I have named all seven.

Mr. GEHRIG. Would you provide for the record, a brief biography of the members of the Panel, please?

Dr. HARRINGTON. Yes; I will provide that for the record.

(The material submitted for the record follows:)

DR. HAROLD M. AGNEW

(Weapons Division Leader, University of California, Los Alamos Scientific Laboratory, Los Alamos, N. Mex.)

Birthplace and Date: Denver, Colorado, March 28, 1921.

Educational Background: BA, University of Denver, 1942; MS, University of Chicago, 1948; PhD, (Physics), University of Chicago, 1949.

Career Highlights: Employment with the Metallurgical Laboratory, University of Chicago from 1942–1943; joined the Los Alamos Scientific Laboratory as a Staff member from 1943 to 1946 and 1949 to 1950, appointed Assistant to Technical Associate Director from 1951 to 1953 and from 1954 to 1961 was Alternate Division Leader. On leave from the University of California, Los Alamos Scientific Laboratory from 1962 to 1964 to become the Scientific Advisor, Supreme Allied Commander, Europe. Returned to Los Alamos Scientific Laboratory as Weapons Division Leader. Traveled in Europe, Japan, Korea, Taiwan, and Philippines. Member of CP–1 group (first nuclear chain reaction, Chicago, 1942). Flew with 509th Bombardment Group to Hiroshima with first nuclear weapon. Received the Ernest Orlando Lawrence Award in 1966.

Memberships: Chairman, Army Scientific Advisory Panel, 1965–present; Member, Aircraft Panel, President's Scientific Advisory Committee, 1965–present; Member, Defense Science Board, 1966–present; Member, NASA Aerospace Safety Advisory Panel, 1968–present; Chairman, U.S. Army Combat Developments Command Scientific Advisory Group, 1965; Member, U.S. Air Force Scientific Advisory Board, 1957–1968; Member, USAF Minuteman Planning Committee, 1961; Member, Von Karman Study Group, 1960; Consultant to the U.S. Army in 1944; Fellow, American Physical Society; New Mexico State Senate, 1955–1961; Los Alamos Board of Educational Trustees, 1950–1955 (President, 1955); Chairman, New Mexico Senate Corporation Committee, 1957–1961; Secretary, New Mexico Legislative Council, 1957–1961; Member, Governor's Radiation Advisory Council, 1959–1961; Phi Beta Kappa; Sigma Xi; Omicron Delta Kappa.

Will become Director, Los Alamos Scientific Laboratory on September 1, 1970.

PERSONAL HISTORY RESUME—FRANK C. DI LUZIO

Date of Birth: September 2, 1914, Rome, Italy.

Marital Status: Married, two children.

Height: 5′6″.

Weight: 150.

Education: B.S. (CE), Fenn College, Cleveland, Ohio 1938, Case Institute of Technology, Cleveland, Ohio; Cleveland Institute of Technology.

Additional Training: War Department, Washington, D.C.; War Manpower Commission, Contract Negotiation and Renegotiation School, Property Management, Property Disposal and Evaluation, Harvard AMP 32 Graduate School of Business Administration, Cambridge, Mass., AEC sponsored.

Experience: January 1, 1970—Present.—President Ecological Systems Analysis Corporation. The purposes for which this corporation is formed are to study and prepare ecological systems analyses and recommend courses of action; to prevent or abate pollution of air, water and land resources; to recommend institutional changes and funding methods to implement recommended courses of action; to provide management services to assist in setting up institutions and operating procedures to manage anti pollution facilities and services, and to engage in any other legal activity.

January 1, 1970—Present.—Consultant to E.G. & G. on Environment, Ecology and government relations.

January 2, 1968–January 1, 1970.—Vice President, EG&G, Inc.—EG&G is a multi-element company with broad technical capabilities and business interests. Research and development, instrumentation system design, engineering service work and manufacturing, encompass the fields of physics, electronics, optics, the nuclear sciences, scientific photography, oceanography and geophysics, the environmental sciences, and computer sciences. In the nonscientific business areas, EG&G companies are engaged in the fabrication of standard and custom metal products and in large-scale scientific nuclear test support service and peaceful applications of nuclear energy.

President, Reynolds Electrical & Engineering Co., Inc.—An EG&G subsidiary, REECo is the support services contractor to the Atomic Engery Commission at the Nevada Test Site and is responsible for base construction, housing and feeding, utilities, tunneling and mining, large-hole drilling, medical services, transportation, architect-engineering, etc., and employs approximately 5,000 people. The commercial electrical construction division headquartered in Tempe, Arizona, consists of three regional offices across the United States with projects in 37 of the 50 states, as well as Guam, Puerto Rico, and Japan.

August 1966 to January 2, 1968.—Assistant Secretary for Water Pollution Control, U.S. Department of the Interior—Acted for the Secretary of the Interior in coordinating the national pollution efforts under the water pollution acts of 1965 and 1966; administered Executive Order 11288 which places in the Secretary the responsibility for insuring that federal activities comply with the intent of the water pollution acts; implemented the establishment of state standards in compliance with the water pollution act of 1965 as amended in 1966, and developed criteria for establishing state water quality standards. In addition, retained the Secretary's responsibility for the Office of Saline Water, and performed such other functions as the Secretary assigned. Participated in and directed pollution control studies for Italy, West Germany, France, Israel, Japan, England, and Mexico; was Department of the Interior coordinator and representative for the Interagency committees on air, land, and solid wastes.

January 1965 to August 1966.—Director, Office of Saline Water, U.S. Department of the Interior—Completed formulation of and placed into effect an aggressive and accelerated program for economically feasible means of desalting sea and brackish waters. Instituted short, medium, and long-range programs leading to increased emphasis in engineering for practical application of desalting techniques. Participated in and directed water resource development programs including surface and ground water development, desalting and waste water recovery for Saudi Arabia, Egypt, Iran, Israel, Spain and Italy at the request of the U.S. State Department. Implemented the administration's commitment to make U.S. water resource technology available to all nations of the world.

April 20, 1963 to January 25, 1965.—Staff Director, Committee on Aeronautical and Space Sciences, U.S. Senate—Responsible for preparing program papers for the Committee and making special studies for the various committees of the U.S. Senate involved in or interested in both the U.S. Air Force and NASA space programs; made recommendations to the Senate Committee on National Space Budgets.

October 15, 1962 to April 20, 1963.—Vice President & Director, Fairbanks, Morse & Co., Hydraulic and Special Projects Division—In charge of engineering design, applications egineering, sales, and project administration. Responsible for the management and coordination of English Electric and Vickers-Armstrong, London, England, license agreements covering their hydraulic products; served as member of R&D committee, and management committees of both Fairbanks, Morse & Co., and Fairbanks Whitney Corporation.

October 1, 1961 to October 15, 1962.—Vice President, Engineering, Fairbanks, Morse & Co., Beloit Division.—In charge of all product and special engineering, reporting to Vice President Group Executive. Products consisted of motors, diesel engines, pumps, magnetos, compressors, etc. Engineering organization had a staff of approximately 325 profesional and sub-professional people.

January 1, 1961 to October 1, 1961.—General Manager, Albuquerque Research Center, Fairbanks, Morse & Co.—Reported to Vice President-Government Products. In addition, was also assigned as Assistant for Research and Development to President of Fairbanks, Morse & Co. Coordinated research and development corporation-wide, served as Chairman of R&D Committee, and evaluated engineering proposals related to national defense programs.

May 19, 1957 to January 1, 1961.—Deputy Manager, Albuquerque Operations Office, U.S. Atomic Energy Commission—Assisted Manager in performance of executive duties covering all functions assigned to ALO. Directly responsible for the evaluation, coordination, and appropriate action regarding performance of functions assigned to the operating divisions in the areas of research, development, manufacturing, and quality assurance on atomic ordnance. Directed activities related to storage operations, nuclear materials, management and security administration. Upon special assignment from the Atomic Energy Commission, Washington, D.C., executed programs for AEC Headquarters organizations other than the Division of Military Application. Coordinated for the AEC Division of Military Application, the exchange of weapon technology between the United States and the United Kingdom Atomic Energy establishments at Aldermaston and Harwell, England.

January 15, 1956 to May 19, 1957.—Assistant Manager for Manufacturing, Albuquerque Operations Office, U.S. Atomic Energy Commission—Directed and coordinated Albuquerque Operations Office development and production complex in design, development, and manufacture of nuclear and non-nuclear weapons and weapons components. Developed from broad DMA directives detailed ALO directives and planning schedules, allocating responsibility and establishing delivery requirements, time schedules, and procurement authorizations for the several contractors involved. Coordinated plans for all major changes in existing or new development or manufacturing facilities and equipment resulting from mission or programmatic changes. Planned and directed the execution of ALO programs and policies designed to effectively coordinate design activities with the manufacturing processes; planned and coordinated program reporting needs of the Manager and the preparation of periodic consolidated progress summaries and program statistics. Coordinated weapons development, testing and production with Armed Forces Special Weapons Command—Defense Atomic Support Agency for military weapons input.

August 1952 to January 1956.—Manager, Los Alamos Area Office, U.S. Atomic Energy Commission—Administered assigned programs in the field of research and development of atomic weapons and in this capacity administered AEC's contract with the Los Alamos Scientific Laboratory. Planned and executed a comprehensive program for construction and maintenance of technical and other project facilities. Provided supervision of all contract operations, including architect-engineering and construction and supply contracts.

April 1950 to August 1952.—Director, Community Management Division, U.S. Atomic Energy Commission, Los Alamos—Participated as a member of Area Manager's staff in the continuous review of the assigned Los Alamos Office program.

September 1940 to October 1941.—Engineer, U.S. Bureau of Reclamation, Parker Dam, California—Field inspection of power plant (one shift), checked field changes in construction, steel setting, construction details and procedures.

March 1938 to September 1940.—Jr. Engineer, U.S. Bureau of Reclamation—Assigned to Coulee Dam, Washington. Field engineer inspection of placing of concrete, setting reinforcing steel, and installation of power plant equipment and drum gate mechanism.

PROFESSIONAL ORGANIZATIONAL MEMBERSHIP

International Association for Hydraulic Research; Association for Applied Solar Energy, Scientific Member, Tempe, Arizona; National Society of Professional Engineers; Professional Engineer, New Mexico, Registration No. 3252; Professional Engineer, Alaska, Registration No. 859–E; Professional Engineer, Nevada 2969; American Geophysical Union, National Academy of Sciences, Washington, D. C.; Seismological Society of America; American Society of Civil Engineers.

SELECTIVE MEMBERSHIP

President's Commission on Marine Science, Engineering and Resources

Presidential appointment, January 1967. Established by the June 1966 Marine Resources and Engineering Development Act to examine the Nation's stake in the development, utilization, and preservation of our marine environment; to review all current and contemplated marine activities and to assess their adequacy to achieve the national goals set forth in the Act; to formulate a comprehensive, long-term, national program for marine affairs designed to meet present and future national needs in the most effective possible manner; to recommend a plan of government organization best adapted to the support of the program.

NASA Aerospace Safety Advisory Panel

Congressional Appointment, May 1968. Established by the National Aeronautics and Space Administration Authorization Act, 1968, the Panel reviews safety studies and operations plans referred to it and makes reports thereon; advises the Administrator with respect to the hazards of proposed or existing facilities and proposed space missions and program operations and with respect to the adequacy of proposed or existing mission modes and safety standards; and performs such other duties as the Administrator may require.

National Water Commission

Presidential Appointment, October 1968. Established by the National Water Commission Act, Congress has directed the Commission to review present and anticipated national water resource problems, assess the nation's future water needs and identify alternative ways to meet them; to give consideration to conservation, more efficient use of existing supplies, reduction of pollution, innovations to encourage the highest economic use of water, interbasin transfers, and technological advances. The technology includes but is not limited to desalting, weather modification and purification and reuse of waste water. Congress has directed that the Commission consider not only the best technology, but also the economic, social, and aesthetic consequences of water resource development.

MAJ. GEN. CARROLL HILTON DUNN

Carroll H. Dunn was born in Lake Village, Arkansas August 11, 1916. He graduated from the University of Illinois, Urbana, Illinois, with a Bachelor of Science degree (Mechanical Engineering) in 1938. His military career began 1 July 1938 when he was commissioned a Second Lieutenant in the Regular Army by professional examination. His first assignment was at Laredo, Texas with the Eighth Engineer Squadron, First Cavalry Division. In February 1941 he was assigned to the Engineer Replacement Training Center, Fort Leonard Wood, Missouri.

In November 1942 he was assigned to the 30th Infantry Division as Division Engineer and concurrently Commanding Officer, 105th Engineer Combat Battalion. He remained assigned to this Division through training at Camp Blanding, Florida; Camp Forest, Tennessee; Camp Atterbury, Indiana, and moved overseas with the Division to England. From June 1944 to May 1945 he participated with the 30th Division in combat in Europe, going from the Omaha Beach to Magdaburg, Germany. During this period he was wounded by an enemy mine during the attack on Saint Lo, and spent two months in the hospital in England, returning to join his unit for the final drive into Germany.

In July 1945 he was assigned to the Second Infantry Division as Assistant Chief of Staff, G–4, a position which he held until May 1946, when he was ordered by the Army to the State University of Iowa, Iowa City, Iowa, to take graduate engineering study. He graduated in June 1947 with a Master of Science degree in Civil Engineering, following which he was assigned to the Engineer School, Fort Belvoir, Virginia, as Instructor in combat engineer activities.

From October 1949 to August 1952 he was assigned to the Engineer Section GHQ Far East Command, where his principal duties concerned staff supervision of the construction activities of that Command.

He returned to the United States in August 1952 and was assigned as Director, U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, a principal research activity of the Corps of Engineers in the field of hydraulics, soils, and concrete. He continued in this assignment until July 1955, when he was ordered to Washington, D.C. to become Executive Officer to the Chief of Engineers, United States Army, an assignment held until August 1958, when he was selected for attendance at the Industrial College of the Armed Forces, Washington, D.C.

Upon graduation from the Industrial College, he was assigned to Thule, Greenland as Area Engineer and was responsible for construction of facilities for the Nation's first Ballistic Missile Early Warning System. Upon return to the United States in July 1960, he was assigned to the newly organized Corps of Engineers Ballistic Missile Construction Office at Los Angeles, with the dual position of Deputy Commander and Director of Titan II Missile System construction.

With his nomination for promotion to Brigadier General on 18 January 1962, he was reassigned as Division Engineer, U.S. Army Engineer Division, Southwestern, Dallas, Texas, effective 1 March 1962. In this assignment he was responsible for a construction program exceeding 300 million dollars per year. Among the many construction projects under his supervision were the Manned Spacecraft Center at Houston and the 1.2 billion dollar program to improve the Arkansas River for navigation, flood control, water supply, and power.

On 1 August 1964 he was assigned to the Eighth U.S. Army in Korea as Deputy Chief of Staff. He held that assignment until 17 January 1966, when he was reassigned to Vietnam to assume directive control of all Department of Defense construction programs in Vietnam. He served as Director of Construction, United States Military Assistance Command, Vietnam, until 30 June 1966.

On 1 July he was reassigned as Assistant Chief of Staff for Logistics (J–4), United States Military Assistance Command, Vietnam. In this assignment, he was responsible for coordination of all logistics support for the U.S. and Free World Forces in Vietnam, essentially assuring that the material, equipment and transportation, needed to support combat operations, were available. He continued to hold this position until 15 September 1967.

On 16 October 1967 he was assigned as Director of Military Construction, Office of the Chief of Engineers, Washington, D.C. In this position he was responsible for military construction within the Army, and for construction and design work performed for the Air Force and the National Aeronautics and Space Administration, and other Government Agencies as assigned. He was also responsible for the Army Nuclear Power Program and specialized fallout shelter engineering support for Civil Defense. The dollar value of work assigned to the directorate totals approximately one billion a year.

General Dunn was appointed Deputy Chief of Engineers on 1 August 1969.

PERSONAL DATA:

Born: August 11, 1916, Lake Village, Arkansas.

Father: William L. Dunn, Sr., Mother: Ruth Dewey Dunn. Both reside in Lake Village, Arkansas.

Married Letha E. Jantz 11 November 1939 at Moline, Illinois.

Children: Carolyn J. (Mrs. Douglas L. Caldwell, Apt T–1, Seminary Forest Apts., 2200 No. Pickett Street, Alexandria, Virginia 22304).

Capt. Carroll Hilton, Jr., Quarters 552A, Pope Road, Ft. Belvoir, Va. 23060.

Official Address: %The Adjutant General, Department of the Army, Washington, D.C. 20310.

EDUCATION

University of Illinois (BS in Mechanical Engineering)—1938; Command and General Staff School, Seventh General Staff Class—1942; State University of Iowa (MS in Civil Engineering)—1947; Industrial College of the Armed Forces—1959.

CHRONOLOGICAL LIST OF PROMOTIONS

Rank	Temporary (AUS)	Permanent (RA)
2d Lieutenant		July 1, 1938
1st Lieutenant	Sept. 9, 1940	July 1, 1941
Captain	Oct. 11, 1941	----------
Major	June 27, 1942	July 1, 1948
Lt. Colonel	Apr. 30, 1943	July 1, 1954
Colonel	Aug. 13, 1952	July 1, 1963
Brigadier General	Apr. 10, 1962	June 13, 1966[2]
Major General	Aug. 1, 1966[1]	Apr. 17, 1968[3]

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[1] DOR July 1, 1961.
[2] DOR Jan. 29, 1966.
[3] DOR Nov. 25, 1967.

CHRONOLOGICAL LIST OF ASSIGNMENTS

Assignments	From	To
8th Engineer Squadron, Fort McIntoch, Tex	July 1938	Feb. 1941.
Engineer Replacement Training Center, Ft. Leonard Wood, Mo	Feb. 1941	July 1942.
303d Engineer Combat Battalion, Camp Butler, N.C	July 1942	Nov. 1942.
Division engineer, 30th Infantry Division and commanding officer, 105th Engineer Combat Battalion, Camp Blanding, Fla., Camp Forest, Tenn., Camp Atterbury, Ind., England, and Continental Europe	Nov. 1942	May 1945.
Commanding officer, 1153d Engineer Combat Group, Le Havre, France	May 1945	July 1945.
Assistant chief of staff, G-4, 2d Infantry Division, Camp Swift, Tex. and Fort Lewis, Wash	July 1945	May 1946.
Graduate student, State University of Iowa, Iowa City, Iowa	May 1946	June 1947.
Engineer school instructor, Fort Belvoir, Va	July 1947	July 1949.
Engineer section GHQ, Far East Command, Tokyo, Japan	Sep. 1949	Aug. 1952.
Director, U.S. Army Waterways Experiment Station, Vicksburg, Miss	Sep. 1952	June 1955.
Executive officer to the chief of engineers, U.S. Army, Washington, D.C	July 1955	Aug. 1958.
Student, Industrial College of the Armed Forces, Washington, D.C	Aug. 1958	June 1959.
Area engineer, Thule, Greenland	July 1959	July 1960.
Deputy commander, Corps of Engineers Ballistic Missile Construction Office, and Director, Titan II construction	Aug. 1960	Feb. 1962.
Division engineer, U.S. Army Engineer Division, Southwestern, Dallas, Tex	Mar. 1962	July 1964.
Deputy Chief of Staff, 8 U.S. Army, Seoul, Korea	Aug. 1964	Jan. 1966.
Director of construction, U.S. Military Assistance Command, Vietnam, Saigon, Vietnam	Feb. 1966	June 1966.
Assistant Chief of Staff for Logistics, J-4, U.S. Military Assistance Command, Vietnam, Saigon, Vietnam	July 1966	Sep. 1967.
Director of military construction, Office of the Chief of Engineers, Washington, D.C	Oct. 1967	July 1969.
Deputy Chief of Engineers, Washington, D.C	Aug. 1969	

LIST OF CITATIONS AND DECORATIONS

Distinguished Service Medal; Silver Star; Legion of Merit; Bronze Star Medal with two oak leaf clusters and "V" device; Army Commendation Medal with two oak leaf clusters; Air Force Commendation Medal with one oak leaf cluster; Purple Heart; French Croix de Guerre avec Palm; Belgian Fourragere.

SERVICE MEDALS

American Defense Service Medal; American Campaign Medal; World War II Victory Medal; Europe-Middle East Campaign Medal with five campaign stars; Korean Service Medal; UN Service Medal; Army of Occupation Medal, Germany; Army of Occupation Medal, Japan; National Defense Service Medal; Vietnam Service Medal with three campaign stars.

PERSONAL BACKGROUND MATERIAL

Interests and Hobbies.—Golf; Bowling; Spectator Sports; Photography (Color Slide).

CIVIC AND PROFESSIONAL ACTIVITIES

Registered Professional Engineer (District of Columbia and Texas); Fellow, American Society of Civil Engineers; Member, Society of American Military Engineers; Association of the U.S. Army; Member, NASA Aerospace Safety Advisory Panel.

RELIGION

Protestant (Baptist); Deacon, Sunday School Teacher; Active in Church in area to which assigned.

CHARLES D. HARRINGTON

Dr. Harrington was born July 22, 1910. He received his B.S. degree in Chemistry from Harvard College in 1937 and M.A. and Ph.D. degrees in Chemistry from Harvard University Graduate School in 1939 and 1941, respectively.

He joined the Mallinckrodt Chemical Works in 1941 as a Research Chemist and was assigned to work with the Manhattan Project in 1942 where he assisted in the development of the initial process used for uranium purification. In 1944 he became the Technical Director of Mallinckrodt's Uranium Division and in

1952 was appointed Manager of that division with responsibility for the direction of activities of the Destrehan Plant. In 1958 responsibility for the then new Weldon Spring Plant was assumed. Both of these plants were operated by Mallinckrodt for the Atomic Energy Commission. In 1960 he was elected a Vice President of Mallinckrodt and in May 1961, when the Nuclear Division of Mallinckrodt merged with the Nuclear Fuels Division of Olin and the Nuclear Development Corporation of America to form the United Nuclear Corporation, he became Vice President, Chemical Division and a member of the Board of Directors of the new corporation. In 1963 he became the Senior Vice President of United Nuclear Corporation.

In July 1965, Douglas United Nuclear, Inc. was formed as a subsidiary owned jointly by the Douglas Aircraft Company (now McDonnell Douglas Corporation) and United Nuclear Corporation, and Dr. Harrington became the President and General Manager of this new corporation. Douglas United Nuclear, Inc. was formed to carry out the joint activities of the two parent companies in the Tri-Cities, Washington area. These activities include the management of the production reactors and fuels fabrication facilities at Hanford for the Atomic Energy Commission and the furtherance of other commercial objectives in the nuclear energy field. As a complement to the development of the Tri-Cities area and as a base of commercial activities on the part of the several new contractor organizations engaged at Hanford, Douglas United Nuclear has been actively participating in the expansion of the Graduate Center in the area.

In addition to his current position as President and General Manager of Douglas United Nuclear, Dr. Harrington serves as a Director for the corporation and also as a Director and Vice President of United Nuclear Corporation. He is also a Director of the Tri-City Nuclear Industrial Council. He has served as a member of the Atomic Energy Labor-Management Advisory Council since its inception and in February 1968, was appointed to a six-year term as a member of the Aerospace Safety Advisory Panel, National Aeronautics and Space Administration, and is currently serving as Chairman of this Panel.

Dr. Harrington is co-author of "Uranium Production Technology" which was published in 1959 and has also published or delivered a number of papers, including those delivered at the Paris (1957) and Rome (1963) Conferences on Nuclear Energy. He was recipient of the 1960 Mid-West Award of the American Chemical Society for contributions to technology in the nuclear energy field.

Dr. Harrington is a member of the Bonneville Regional Advisory Council and a member of the Advisory Board, College of Engineering, Washington State University. He is a fellow of the American Nuclear Society and a member of the American Chemical Society, the National Space Club, the American Association for the Advancement of Science, the American Management Association and the Atomic Industrial Forum.

JOHN AUSTIN HORNBECK

J. A. Hornbeck is a vice president of the Western Electric Company and president of the Sandia Corporation, a nonprofit Western Electric subsidiary. Sandia Corporation operates Sandia Laboratory at Albuquerque, N.M., Livermore Laboratory at Livermore, Calif., and other smaller facilities for the Atomic Energy Commission. He is also a director and member of the executive committee on Sandia Corporation. His office is in Albuquerque.

He was born on November 4, 1918 in Northfield, Minn., and graduated from Central High School in Kalamazoo, Mich., in 1935. He received a Bachelor of Arts degree in physics from Oberlin College in Ohio in 1939 and a Doctorate in Physics from the Massachusetts Institute of Technology in 1946. While in college, he was a member of the soccer and debating teams and was captain of the tennis team during his senior year.

Following his graduation from Oberlin, he was a teaching fellow at M.I.T. for two years before joining the National Defense Research Committee as a technical aide. He returned to M.I.T. as a research assistant in 1943, becoming secretary of the N.D.R.C.'s Land and Mines Committee a year later.

Mr. Hornbeck began his Bell System career in 1946 as a research physicist in the physical electronics department of Bell Telephone Laboratories. Transferred to the transistor research department in 1951, he was placed in charge of the semiconductor physics department in 1952, becoming head of the solid state devices department the following year.

From 1955 to 1958, he was director of electron device development and from 1958 to 1962, he was executive director of the Semiconductor Device & Electron Tube Division. In 1962, he was named president and a director of Bellcomm, Inc. (jointly owned by American Telephone and Telegraph Company and Western Electric and located in Washington, D.C.).

Mr. Hornbeck was elected vice president of Western Electric Company, effective September 1, 1966. At that time, he also became vice president, a director, and a member of the executive committee of Sandia Corporation. He assumed his present position on October 1, 1966.

A fellow in the Institute of Electrical and Electronic Engineers and the American Physical Society, he is a member of the American Association for the Advancement of Science, Phi Beta Kappa, Sigma Xi, Delta Sigma Rho, the Cosmos Club (Washington, D.C.), and the Four Hills Country Club (Albuquerque, N.M.). He is a member of the Aerospace Safety Advisory Panel to NASA and serves as chairman of the Advisory Board, National Bureau of Standards Institute of Basic Standards. He has contributed articles to *Physical Review* and other professional journals.

Mr. Hornbeck is president of the Albuquerque United Community Fund and a director of the Albuquerque Symphony Orchestra and the Presbyterian Hospital Center Foundation.

He married Emily Elizabeth Aldrich on January 31, 1942 in Wauwatosa, Wisc. They have two daughters—(Mrs.) Joan Aldrich Smith and Deborah Ann—and three sons—Kirk Austin, John Frederick, and Christopher Wolfe—and live at 1516 Sagebrush Trail, S.E., Albuquerque 87123.

Mr. Hornbeck is active in Boy Scout activities and enjoys golf and bridge in his leisure time.

BRUCE T. LUNDIN, DIRECTOR, LEWIS RESEARCH CENTER, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Bruce T. Lundin, a native of Alameda, California and a graduate in Mechanical Engineering of the University of California in 1942, began his scientific career with the National Advisory Committee for Aeronautics in 1943 at the Lewis Research Center. He was initially engaged in heat transfer investigations and in improving the performance of our World War II aircraft engines. In 1946 he was placed in charge of the Jet Propulsion Research Section, which conducted some of this country's early research on turbojet engines.

In 1952 Mr. Lundin was appointed Chief of the Engine Research Division at the Center, and became responsible for the full-scale engine program. Work that he directed over the next several years contributed significantly to the performance and reliability of today's commercial transport and supersonic aircraft jet engines. He also pioneered in research on large-scale ramjet engines.

When NACA became the nucleus of the present National Aeronautics and Space Administration in October of 1958, Mr. Lundin was appointed an Assistant Director of the Center. In this capacity he directed much of the Center's expanded role in space propulsion and power generation. This role was further enlarged in December, 1961 when he was appointed Associate Director for Development. The responsibilities embraced development of turbojet engines, chemical rockets, electric thrusters for spacecraft propulsion, and electric power generating systems for spacecraft using chemical, solar and nuclear energy sources. He also directed the development and operation of NASA's Centaur and Agena launch vehicles for unmanned spacecraft and of spacecraft for investigating advanced methods of space propulsion.

In May 1968 Mr. Lundin went to NASA Headquarters as Deputy Associate Administrator for the Office of Advanced Research and Technology, and in March 1969 was named Acting Associate Administrator. On November 1, 1969 he was appointed Director of the Lewis Research Center.

Mr. Lundin is a member of Tau Beta Pi and Sigma Xi, an Associate Fellow of the American Institute of Aeronautics and Astronautics, and a Fellow of the Royal Aeronautical Society. He is also a member of several governmental advisory committees, including the NASA Aerospace Safety Advisory Panel, the Scientific Advisory Board of the U.S. Air Force, and the NASA Research Advisory Committee on Space Vehicles. In 1965, he received the NASA Medal for Outstanding Leadership.

HENRY REINING, JR.

Henry Reining, Jr. became the first dean of the newly constituted Von KleinSmid Center for International and Public Affairs in 1967. His administration includes three instructional components—the School of Politics and International Relations, with two departments, i.e. Political Science and International Relations, the School of Public Administration, and the Graduate Program of Urban and Regional Planning. His role as dean provides him with the opportunity to bring to bear all of the resources of the University which are devoted to governmental affairs.

A former president of the American Society for Public Administration, he has served government at all levels. He pioneered in the development of the National Institute of Public Affairs in Washington, D.C., serving as its first executive director. His activities at the national level have also included membership on a number of committees and commissions. He is presently a member of the National Aeronautics and Space Administration's Aerospace Safety Advisory Panel.

During World War II, he served as consultant to the United States National Resources Planning Board in the establishment of the National Roster of Scientific and Specialized Personnel, to the War Department, School of Administration, Port Washington, and to the United States Civil Service Commission for whom he conducted the first generalist examination for executives and administrators (in 1940) and assisted in the establishment of the Public Administration Examining Division. In 1943–44, he traveled to Brazil for the United States Coordinator of Inter-American Affairs to assist the Brazilian National Department of Administration.

He has been a consultant to the United States Commissioner of Indian Affairs on administrative matters, and was instrumental in the selection and training of superintendents of Indian reservations. He was consultant to the Secretary of the Interior for whom he made a survey of Boulder City, Nevada, which ultimately enabled it to become a self-governing community. He was a member of the U.S. Civil Service Commission's Regional Loyalty Board for a number of years, and of the national Loyalty Review Board.

He went to Brazil again in 1951–52, for the United Nations, to chair a multinational faculty team to set up South America's first School of Public Administration in Rio de Janeiro. In 1953, he journeyed to Turkey to represent the U.S.A. at an international congress at Istanbul, and to advise on the development of a regional public administration institute at the University of Ankara.

In 1954, Dean Reining made the survey in Iran which led during the next seven years to a joint effort with the University of Tehran to establish an Institute of Public and Business Administration, now a permanent institution.

During the summer of 1954, he went to the Philippines to assist the University of the Philippines in the development of its Institute of Public Administration, especially its in-service training program.

In 1957, he surveyed the training needs of the government of Pakistan, which effort led to the setting up of an executive development program at USC for groups of top civil servants, totaling almost 100 during the succeeding three year period.

Dean Reining moved the USC Pakistan program to Pakistan in 1960. At that time, he assisted in setting up a system of three institutes of public administration in two wings and at the center of that Government. He also assisted in establishing the curricula at two universities, the University of Dacca and the University of Punjab.

Dean Heining has also been active in state and local matters. He was a consultant to the California State Assembly in 1950, and made a study of the reorganization of the State Government. He was, during 1957–58, Chairman of the Los Angeles County Charter Commission, which presented a thorough revision to the County's Board of Supervisors. He is presently Chairman of the Los Angeles City Charter Commission which presented a new charter in July 1969 and has participated in the City Council's hearings held since that date.

Dean Reining began his academic career and his association with USC in 1932, as Assistant Professor, School of Public Administration.

During the period 1934–1936, he was a member of the Politics faculty at Princeton University and a Research Associate, Local Government Surveys; 1935–1945, Educational Director, National Institute of Public Affairs in Washington, D.C.; 1945–46, Management Consultant with the firm of Rogers, Slade and Hill, New York City; 1946–47, Assistant Executive Director, Port of New York Authority, New York City.

In 1947, Dr. Reining returned to USC as Professor of Political Science and Public Administration. In 1953, he became Dean of the School of Public Administration and in 1967, Dean of the Von KleinSmid Center for International and Public Affairs.

His professional associations have included: American Society for Public Administration (national president, 1957–58); Council on Graduate Education for Public Administration (chairman, 1964–66); Pi Sigma Alpha (national vice-president, 1958–1960); American Political Science Association; Public Personnel Association; Western Governmental Research Association, (Board of Governors, 1958–1960); et al.

Dean Reining received his A.B. in Political Science in 1929 at the University of Akron; his A.M. in Politics at Princeton University in 1930, and his Ph.D. in Poiltics in 1932, also at Princeton University.

Dr. Reining is the author of a number of books, monographs, and articles for learned journals.

He was born September 15, 1907. He is married to Darline Diekmann Reining, and has four children: William Henry, Judith Ellen, Susan Elisabeth, and Richard Charles.

ADVISORY PANEL ACTIVITIES

Mr. GEHRIG. Where did the Panel meet to consider and review the work of the Apollo 13 Review Board?

Dr. HARRINGTON. We met at the Manned Spacecraft Center during the time that the Review Board was meeting there. I first went there at Mr. Cortright's invitation on April 29 and 30 to discuss the planned scope of the inquiry and to arrange for the Panel's review of the procedures. The Panel then met on May 6 in Houston with both the Apollo 13 Review Board and the MSC Apollo 13 Investigating Team to review the inquiry process, the evidence, and the determinations and findings to date. Then we met again on May 27 in working sessions with the Panel chairmen of the Apollo 13 Review Board. One of the Panel members and the Executive Secretary of the Panel made additional trips to review the continuing operations of the Board.

Mr. GEHRIG. How many times did the panel meet to discuss the Review Board's work?

Dr. HARRINGTON. The Panel met twice with, as I have just mentioned, at Houston, with the Board. Based on these meetings together with a review of the Board report itself, the Panel met on June 19 to prepare the report to the Administrator.

Mr. GEHRIG. Were the findings of the Panel unanimous or was there dissent?

Dr. HARRINGTON. There was no dissent.

Various members had various inputs into the report which were accepted by all the others.

Mr. GEHRIG. So the report is unanimous?

Dr. HARRINGTON. Yes.

Mr. GEHRIG. What was the Panel charter with respect to the Apollo 13 accident?

Dr. HARRINGTON. We had a specific directive from the Administrator, Dr. Paine, to review the procedures and findings of the Apollo 13 Review Board and report on those and report on the findings to the Administrator.

Mr. GEHRIG. Would you have that placed in the record, please?

Dr. HARRINGTON. Yes.

(The material submitted for the record follows:)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
OFFICE OF THE ADMINISTRATOR,
Washington, D.C., April 20, 1970.

To: Dr. Charles D. Harrington, Chairman, Aerospace Safety Advisory Panel.
Subject: Review of Procedures and Findings of Apollo 13 Review Board.
Attachment: (a) Memorandum dated April 17, 1970, to Mr. Edgar M. Cortright, subject: Establishment of Apollo 13 Review Board.
References: (a) Section 6 National Aeronautics and Space Administration Authorization Act, 1968; (b) NMI 1156.14—Aerospace Safety Advisory Panel.

1. In accordance with References (a) and (b), the Aerospace Safety Advisory Panel (hereafter referred to as the Panel) is requested to review the procedures and findings of the Apollo 13 Review Board (hereafter referred to as the Board) established by Attachment (a).

2. The procedures established by the Board will be made available to the Panel for review and comment as provided in paragraph 4(a) of Attachment (a).

3. As Chairman of the Panel, you are designated an Observer on the Board. In this capacity, you, or another member of the Panel designated by you, are authorized to be present at those regular meetings of the Board you desired to attend. You are also authorized to receive oral progress reports from the Chairman of the Board or his designee from time to time to enable you to keep the Panel fully informed on the work of the Board.

4. The final report and any interim reports of the Board will be made available promptly to the Panel for its review.

5. The Panel is requested to report to us on the procedures and findings of the Board at such times and in such form as you consider appropriate, but no later than 10 days after the submission to us of the final report of the Board.

T. O. PAINE,
Administrator.
GEORGE M. LOW,
Deputy Administrator.

Enclosure.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION,
OFFICE OF THE ADMINISTRATOR,
Washington, D.C., April 17, 1970.

To: Mr. Edgar M. Cortright.
Subject: Establishment of Apollo 13 Review Board.
References: (a) NMI 8621.1—Mission Failure Investigation Policy and Procedures; (b) NMI 1156.14—Aerospace Safety Advisory Panel.

1. It is NASA policy as stated in Reference (a) "to investigate and document the causes of all major mission failures which occur in the conduct of its space and aeronautical activities and to take appropriate corrective actions as a result of the findings and recommendations."

2. Because of the serious nature of the accident to the Apollo 13 spacecraft which jeopardized human life and caused failure of the Apollo 13 lunar mission, we hereby establish the Apollo 13 Review Board (hereinafter referred to as the Board) and appoint you Chairman. The members of the Board will be qualified senior individuals from NASA and other Government agencies. After consultation with you, we will:

(a) Appoint the members of the Board and make any subsequent changes necessary for the effective operation of the Board; and

(b) Arrange for timely release of information on the operations, findings, and recommendations of the Board to the Congress, and, through the NASA Office of Public Affairs, to the public. The Board will report its findings and recommendations directly to us.

3. The Board will:

(a) Review the circumstances surrounding the accident to the spacecraft which occurred during the flight of Apollo 13 and the subsequent flight and ground actions taken to recover, in order to establish the probable cause or causes of the accident and assess the effectiveness of the recovery actions.

(b) Review all factors relating to the accident and recovery actions the Board determines to be significant and relevant, including studies, findings, recommendations, and other actions that have been or may be undertaken by the program offices, field centers, and contractors involved.

(c) Direct such further specific investigations as may be necessary.

(d) Report as soon as possible its findings relating to the cause or causes of the accident and the effectiveness of the flight and ground recovery actions.

(e) Develop recommendations for corrective or other actions, based upon its findings and determinations or conclusions derived therefrom.

(f) Document its findings, determinations, and recommendations and submit a final report.

4. As Chairman of the Board you are delegated the following powers:

(a) To establish such procedures for the organization and operation of the Board as you find most effective; such procedures shall be part of the Board's records. The procedures shall be furnished the Aerospace Safety Advisory Panel for its review and comment.

(b) To establish procedures to assure the execution of your responsibilities in your absence.

(c) To designate such representatives, consultants, experts, liaison officers, observers, or other individuals as required to support the activities of the Board. You shall define their duties and responsibilities as part of the Board's records.

(d) To keep us advised periodically concerning the orgainzation, procedures, operations of the Board and its associated activities.

5. By separate action we are requesting the Aerospace Safety Advisory Panel established by Reference (b) to review both the procedures and findings of the Board and submit its independent report to us.

6. By separate action we are directing the Associate Administrator for Manned Space Flight to:

(a) Assure that all elements of the Office of Manned Space Flight cooperate fully with the Board and provide records, data, and technical support as requested.

(b) Undertake through the regular OMSF organization such reviews, studies, and supporting actions as are required to develop recommendations to us on corrective measures to be taken prior to the Apollo 14 mission with respect to hardware, operational procedures, and other aspects of the Apollo program.

7. All elements of NASA will cooperate with the Board and provide full support within their areas of responsibility.

T. O. Paine,
Administrator.
George M. Low,
Deputy Administrator.

Mr. Gehrig. Did the Panel have complete freedom to investigate anything they wanted with regard to the accident or with regard to the procedures used by the Review Board?

Dr. Harrington. Yes, we did. No problem.

PRIOR ACTIVITIES OF PANEL

Mr. Gehrig. Prior to the Apollo 13 accident, what did the activities of the Panel consist of?

Dr. Harrington. The Panel's first year was spent in a survey of the Apollo program management system and the system for hazard identification. The review involved staff and program elements at NASA Headquarters, the Manned Space Flight Centers, and the majority of principal contractors for the spacecraft, launch vehicle, and Apollo mission support. The Panel met in session 22 days.

Mr. Gehrig. Would you say that the Panel was well prepared for their review of the Apollo 13 Board's procedures, then, and to review the accident?

Dr. Harrington. Yes. In addition to this general program which I have outlined, we had further assignments from the Administrator such as a review of the investigation process involved in the LLRV and LLTV accidents review boards, and a review of the management process for the evaluation of risks inherent in reducing Saturn static testing and launch operations.

TECHNICAL MANAGEMENT

Mr. GEHRIG. Dr. Harrington, I have one more question in two parts that I will put in the record for you to answer, if that is satisfactory.

On the second page of your letter in the fifth paragraph you say, and I pick up the quote:

> . . . the lack of understanding of thermal switch performance and the informal system in the valuation of the test procedure change reflect more a failure of human judgment than a failure in the requirements of the technical management system."

What do you mean by that?

Further, As I understand it:

(1) There was no procedure for checking the switch design against the ground support system at the Kennedy Space Center (See pp. 5–9 and 5–18 Finding No. 16).

(2) The technical management system did not require that prior anomalies on a critical subsystem be brought to the attention of the decisionmakers when a significant anomaly occurred in that critical subsystem.

(3) There was no procedure requiring the ground support personnel at Kennedy Space Center to monitor the heater current readings on the oxygen tank heater control panel.

(4) The dimensioning on the oxygen storage tank fuel line was such that looseness to the point of incomplete connection was possible in the event of worse case tolerance buildup.

(5) The oxygen tanks contained a combination of oxidized combustible material and potential ignition sources which was precisely the problem of the Apollo 204 accident.

All of these seem to me to be failures of technical management; are they not?

(The answer supplied for the record follows:)

The Cortright Report called for redesign of the sub-system components and strengthening of the specific procedures appropriate to the situation and the Panel concurred in this. We stated that recommendations made for the redesign of the system must improve the manufacturability and minimize the failure modes of the system under out of tolerance conditions. We also said that recommendations for improvements in the analysis and validation of non-standard situations are certainly necessary and should be implemented immediately.

But to have said this is not to have said enough. Procedures are the consequence of human judgment and human judgment must knowledgeably implement them.

A series of individual judgments were made during the life cycle of the tank without complete awareness of the consequences or their possible interdependence and cumulative effect. If the cumulative situation had been recognized the procedures were in existence for an appropriate management response. Lack of continuity of engineering evaluation of the subsystem over an extended period of time further compounded the situation.

Thus, as we noted, the problem is also to sustain human motivation and assure working familiarity with the sub-systems and their hazards. The Panel, as did the Apollo 13 Review Board, recognized the significance of this variable; and we have further cited some of its implications for the future.

Mr. GEHRIG. Mr. Myers or Dr. Petrone, I have a number of questions that I will put in the record for you to answer.

(Additional questions submitted by Mr. Gehrig and answers supplied for the record are as follows:)

Question 1. In appendix D, p. 92, the Board stated that the comprehensive review initiated by the MSC Apollo 13 investigating team of all CSM and LM tanks, valves, and associated system elements in which oxygen or oxidizers are stored, controlled or distributed should be prosecuted vigorously.

What is the status of this review?

Answer. This review commenced immediately after the Apollo 13 mission and is still continuing with evaluation, tests and analyses to be completed prior to the time the Apollo 14 mission is flown. In this review, emphasis is being placed on oxygen and oxidizer systems and pressure vessels with electrical interfaces which operate at pressures greater than 20 psi. Lower pressure systems were placed outside the scope of this review since they had been thoroughly reviewed after the Apollo 204 incident and have been under rigorous control since then. Completion of some parts of this evaluation, such as the oxygen and oxidizer system components in the ground support equipment are contingent upon completion of certain tests which are still in process and a subsequent review of the test data.

Question 2. What determinations have been made to date and will any hardware changes be required as a result of this particular review?

Answer. As a direct response to Recommendation 1 of the Apollo 13 Accident Review Board, the following modifications have been approved:

a. Deletion of unsealed fans in the storage vessels.

b. Replacement of all Teflon-coated wiring in the storage vessel with wiring insulated with glass in a stainless steel sheath.

c. Modification of the storage vessel quantity probe from aluminum to stainless steel.

d. Modification of the tank cap to simplify assembly through elimination of the requirement to rotate the quantity probe during tank build up.

e. Removal of the storage vessel heater element thermal switches and addition of a heater assembly temperature sensor.

f. Other modifications which were necessitated by the removal of the unsealed fans; namely the installation of a third heater element in each storage vessel and addition of a third storage vessel.

The comprehensive review of system elements in which oxygen or oxidizers are stored, controlled or distributed has resulted in the following changes:

a. Isolation from oxygen of Teflon-coated wiring in the fuel cell oxygen reactant valves.

b. The material planned for use in the oxygen storage vessel of the advanced portable life support system was to be aged cryoform processed stainless steel. The review determined that in its failure mode this new material could be catastrophic, therefore, the steel used in the current system will not be changed.

Question 3. In appendix D a recommendation is made for the review and evaluation of the practice of co-location of redundant subsystems where failure of one can also fail its companion subsystem.

What action has been taken in this area and what decisions have been made with respect to any relocations?

Answer. An extensive review has been performed to investigate the damage which would be produced by the structure failure of pressurized vessels in the command and service module and the lunar module. Analyses and test results were used to develop damage assessments based on the expected failure modes, the stored energy of the tank and their proximity to essential equipment, crew or other pressurized vessels. The general conclusion of this investigation is that most of the pressure vessels of the spacecraft contain energy levels large enough to induce severe damage to other elements of the system and spacecraft. Damage to redundant systems in close proximity is possibly as well as other unacceptable results such as massive structural damage to the command module or lunar module resulting in cabin decompression or extensive damage to plumbing and wiring. The hazards identified in these findings are consistent with the knowledge which existed during original design of Apollo and which were accepted from the outset. The Apollo design objective has been to eliminate this type of failure through prudent design, effective safety devices, and proof testing of each pressure vessel as part of the acceptance requirement.

Question 4. The Board also indicated a need for the review and evaluation of a requirement for shock qualificateion testing of service module components or subsystems. What action is being taken on this suggestion?

Answer. A complete review of the service module is in process to evaluate the need for shock testing of components and subsystems. To date, the service module hydrogen reactant valve and reaction control system isolation valve have successfully completed shock testing. Also the service module oxygen storage vessel relief valve and the redesigned fuel cell oxygen reactant valve have been scheduled for such testing.

Question 5. In appendix D, p. 83, there is reference to a review of pressure vessels in the Apollo system wherein there was identified a direct electrical interface or exposed wiring in the media. Has the review of all such pressure vessels been completed?

Answer. The review referred to in this question has been completed. This has identified the need for certain tests to be conducted. Upon completion of testing we will undertake a thorough analysis and evaluation of the test results.

Question 6. Are there any cases in which hardware changes are deemed necessary prior to further flight operations?

Answer. It is assumed that the hardware changes referred to in this question are associated with the pressure vessels discussed in the previous question. No hardware changes have as yet been identified from the review, however, tests are still being conducted and final determination will await their completion and subsequent analysis of the test data.

AMES POLYMER RESEARCH LABORATORY

Mr. GEHRIG. Also a question for you, Dr. Paine.

The House reduced the construction of facilities by $16,325,000 below the request, denying funds for facilities at several centers. One of these is a Polymer Research Laboratory at the Ames Research Center. NASA testified before this committee that the main thrust of this laboratory will be directed toward polymeric materials to enhance aircraft and spacecraft safety.

How important is this laboratory to NASA's research into fireproof materials?

(The answer supplied for the record follows:)

The current main thrust of this proposed laboratory will be directed primarily toward materials which will enhance aircraft safety. The talents and interests of the scientists at the Ames Research Center are such that the proposed Polymer Research Laboratory will become a major focal point of NASA's research into ablative and fireproof materials.

The Polymer Chemistry Research group at Ames Research Center has made several outstanding contributions to the solution of fire safety problems of NASA and the nation. Modified urethane and isocyanurate foams are being tested for military and civil aircraft, as well as mine safety applications. Intumescent paint has demonstrated a great potential for increased fire safety during aircraft opertions aboard carriers. There are many other polymer chemistry applications which will develop in the future.

We have found that if we are to fulfill our role to enhance aircraft fire safety, we must maintain a competent and highly motivated in-house capability to effectively communicate with industry and manage our contract program.

The Polymer Chemistry Research group is presently located in scattered locations. To effectively manage this group and to enable it to achieve its leadership role, it is mandatory that it be appropriately housed in a more efficient and less hazardous environment. The proposed facility is essential to the fulfillment of our mission.

FURTHER LUNAR MISSIONS

Mr. GEHRIG. Mr. Chairman, Senator Smith has a question that she had hoped to be here to ask but she asked me to ask it in the event she did not get here. So, I will ask that question. Dr. Paine, you can reply now or reply for the record.

As you know, there has been a great deal of interest expressed in the Senate on the need for further lunar missions and I wonder if you would discuss the importance of further lunar missions covering such matters as (1) the opinions of the scientific community, (2) the expected benefits from further lunar missions, and (3) the availability of the hardware.

Dr. PAINE. Fine. I would be very happy to prepare a thoughtful response to that for the record. I would like to just say very briefly here in response to Senator Smith's question that the moon has taught the

United States how to become a space-faring nation and in accepting the challenge of landing on the moon within a decade, America really came of age.

In the process of doing this, I think it is important that we remember the successes that were achieved. Before the start of the Apollo program we had an ability to operate men in flight really very close to the earth. We were able to get up to several hundred miles altitude; but the Apollo program and trips to the moon forced us to develop technologies capable of carrying men a quarter of a million miles into space. We were forced to develop almost every part of science, technology, materials, flight operations, electronics; and the impact of this not only on America's aerospace program but in every part of American technology and indeed throughout American society, I think alone would have justified the reasons why we have chosen the moon as a goal.

The scientific values are another justification for this, and particularly for the continuing flight to the moon. The fact that the two more areas that we have already visited have shown such different results, different histories, and the fact that there are many very different regions of the moon that scientists will be able to study in future trips—all of these are things that I would like to put in my response.

Finally, I think it is very important that we look at the fact that the Apollo program to the moon has occupied a rather small percentage of the American budget, less than a couple of percent of our Federal activities, and yet this has given our scientists and technologists and engineers an enormously stimulating new frontier to learn about the kinds of things which really only a lunar program would have been able to teach us.

I think it is very important in these times that we extend the opportunities for scientists and engineers and young people in the United States to associate themselves with bold ventures to meet the very difficult challenge that you have heard my associates today describe to you as we press forward in space.

I would like to make all of these points in more detail in a prepared statement.

Mr. GEHRIG. Dr. Paine, do you think that anyone, particularly anyone in the scientific or technical community would be satisfied with or, thought that only a single trip to the lunar surface would provide all of the needed data and knowledge?

Dr. PAINE. Absolutely not. The surface of the moon is equal in area to all of North and South America combined. It contains a tremendously rich variety of features. It has mountains and valleys and hills and these flat desert type areas, a plethora of craters and scientists are convinced in order to untangle the history of the solar system and the history of the Earth-Moon system, that a number of trips will be required.

The question I think we have to answer, Mr. Gehrig, is how many of man's initial trips to the moon should be made utilizing the Apollo system and to what extent should we be making our plans for the expeditions in the 1980's with the far more advanced systems that will become available then based on new developments like the space shuttle and space station—how much should we be planning on the further exploration of the moon in this different time schedule.

These are receiving intensive reviews within NASA now and I will be very happy to comment on this for the record.

(Additional information supplied for the record follows:)

WHY CONTINUE LUNAR MISSIONS

For the past ten years we have pursued a vigorous program of lunar exploration. This effort has resulted in scientific and engineering progress on a broad front—from mapping Meteor Crater in Arizona to mapping the craters of the moon; from the early Ranger spacecraft to the vastly more complicated Apollo system. With the Apollo missions we have barely crossed the threshold of a whole new era in the history of mankind—an era that will extend man's domain beyond his earth. Today, we can give serious attention to the study of the benefits and the problems of establishing a permanent foothold on the moon.

The prime arguments for continuing Apollo missions to the moon can be summarized as follows:

TO BROADEN AND DEEPEN OUR BASE OF SCIENTIFIC KNOWLEDGE

We want to understand the origin, evolution, and present characteristics of the moon and its historical relationship to the earth and to the solar system. This understanding will lead materially to a better understanding of our own earth and its origin, history, and processes.

TO EVALUATE POTENTIAL UTILIZATION OF THE MOON

The moon is a natural space station in orbit around the earth. We want to assess its value as a platform for future scientific, technological, and operational use. We want to evaluate the moon's natural resources and the use they could be to us in the future. Information on these major points will enable us to make the proper decisions regarding the utility of a lunar base.

TO INCREASE OUR EXPERIENCE IN SPACE OPERATIONS

Each lunar mission contributes major increases in our knowledge of the capabilities and limitations of man as a planetary explorer. Our astronauts adapted to the lunar environment much easier than many had anticipated and the complexity of their surface tasks will be expanded in the future missions. The problems of Apollo 13 taught us important lessons to apply to future Apollo missions and to other programs. The moon is the first planetary body that we will explore. As such it is the training ground for future manned planetary exploration.

TO MAINTAIN INTERNATIONAL LEADERSHIP IN SPACE

The first manned landing on the moon had an inestimable prestige value to our nation. To maintain this demonstrated leadership, it is important to capitalize on the technology and hardware we have developed. The international interest in lunar science is tremendous, and we are continuing to broaden the international aspects of the Apollo program.

The above points will be amplified in addressing the three parts of the specific question.

Opinions of the Scientific Community

There is very strong support among the scientists for continuing lunar missions. There was an almost electric sense of excitement in January of this year as about 1,000 scientists of the world met to discuss the findings of the analyses of the first returned lunar material. We were witnessing the birth of what some have termed a whole new science. For the first time, man had in his hands material from a precisely known location in another world. No longer was it mere conjecture that the moon could provide information on the early history of the solar system. It had become a demonstrated fact. Following Apollo 12, material returned from a very similar appearing mare region was shown to be significantly different. The moon obviously has had a very complex history which cannot be unraveled in a similar manner.

These facts led the Lunar and Planetary Missions Board, consisting of 14 highly respected non-NASA scientists, to make the following statement in April 1970:

"The Apollo Lunar Program holds out the promise of giving an understanding of the origin of the moon and earth. This clearly would be a major milestone in man's understanding of his physical world. Such an understanding will come from the unraveling of many clues, some of which are now at hand. These indeed demonstrate the great age of the lunar surface and therefore, show the possibility of reading the record back to the period of formation of the earth. Each of the many clues brought back by each mission is important only insofar as it contributes to the painting of a coherent picture.

The number of missions and the time duration of the program as now planned is thought to be sufficient to reach a truly basic understanding. A severe curtailment, however, would jeopardize this, and there would be the risk of having many clues but still a great enigma at the program's end. If this situation arose, we could be accused of conducting expensive space programs for publicity purposes rather than for the permanent enrichment of man's knowledge."

Last September a study conducted by the Space Science Board of the National Academy of Sciences resulted in a strong recommendation to exploit existing Apollo technology for achievement of the scientific objectives of lunar exploration. Recently the Space Science Board was asked by the Senate Committee on Aeronautical and Space Sciences if the earlier recommendation was still valid after our two successful landings. In a meeting on June 22, 1970, the Space Science Board gave a strong reendorsement for continuing lunar missions.

Similar sentiment was expressed in a letter by Dr. John Rodgers, President of the Geological Society of America:

"Since the Apollo program represents our total foreseeable opportunity to explore the geology of the moon, we believe that every appropriate effort should be made to insure that the maximum scientific results are obtained from the remaining Apollo flights."

Many of the country's leading scientists have underscored the need for continuing the lunar missions beyond Apollo 12. At the December 1969 meeting of the American Association for Advancement of Science in Washington, D.C., Dr. Frank Press of the Massachusetts Institute of Technology, joined by others in attendance, stated "It would be tragic to cut off lunar exploration just as we begin to get the vital answers we seek."

Some excerpts from recent comments of other leading scientists on this subject follow:

Professor Thomas Gold, Cornell University:

"For many years to come, the moon will be the only planetary body, other than the earth, that we shall be able to investigate closely. Information this will provide is expected to have far-reaching consequences for our understanding of the earth and the entire solar system. Such an understanding would be of interest not just to the scientists now engaged in lunar researches, but it is expected to interest greatly and to affect materially almost all of humanity. . . .

The two successful Apollo landings have begun to give us clues in the story; but just as the geologic past of the earth would not be unraveled from a couple of visits to the middle of the Sahara Desert, so these missions, chiefly devoted to test the technology, cannot give us more than the first few intriguing clues. The later Apollo missions are designed to bring in much of the diverse information required. Longer staytime, greater mobility, pinpoint landing at difficult sites of intrinsically greater interest, the deployment of instruments whose design is based on the information so far obtained—all these factors will contribute toward building up the complete picture. The scientific advances that have resulted so far from the Apollo Program are already very great, much greater than it has been possible to publicize generally, because at this stage, one is still involved with detailed scientific facts and not yet with the major overall conclusions. In the later lunar missions of the U.S. space program, the overall conclusions will emerge that can be understood generally and that will lead to a better management of the resources of our own planet."

Dr. James R. Arnold, University of California at San Diego (La Jolla):

"The places where we have been on the moon so far are the smooth, relatively young places. Where we want to go on the moon are the more ancient parts in the highlands. From what we can guess from data that we have already, the highlands should contain material that was formed at nearly the same time as the sun, earth, and solar system were formed . . . and when we have such material, we can get a very good idea as to *how* the solar system was formed. This would be a very fundamental piece of information, basic to almost everything that we do here on earth, since it would be related to all that we know about the earth we live on. There are many important questions that we are only now beginning to know how to ask about the earth—Why are there continents? Why are there oceans? Why are there mountains? Why are there valleys? Why are there ore bodies in some places and not others? Why are there earthquakes on the earth and no moonquakes on the moon? Why are these volcanoes? The information we get from the moon can help us to answer these basic geological questions about the earth itself."

Dr. Brian Mason, Smithsonian Institution:

"It is extremely important to maximize the returns from the investment in the Apollo Program by fully utilizing our present capabilities, and extending their range as far as possible. The two sites so far visited are similar in their geological nature. If we are to obtain an adequate picture of the overall structure and composition of the moon, it is essential that landings be made on several sites of significantly different geological nature. This will ensure the determination of the mineral content, origin, and age of major lunar rock formations which have been mapped from telescopic and satellite observations. Deployment of geophysical instruments such as seismographs and heat probes at several widely separated sites will make possible the continuous monitoring of conditions on and within the moon, providing a steady flow of information that will vastly expand our understanding of the earth-moon system. The successful completion of the Apollo missions is vital for the continuing evolution of the space program."

Dr. Robert M. Walker, Washington University, St. Louis, Missouri:

"The Apollo 11 and 12 missions have demonstrated that the moon is an exceedingly important object for scientific study. As we had all hoped, parts of the moon's surface dates back to the very beginning of the solar system, thus providing the promise of solving the fundamental problems of the origin of the solar system. The lunar samples also preserve the past history of the sun's behavoir. Knowledge of the sun—the driving force for the entire solar system—is obviously important if we are to understand the past (and future) of our own planet. Scientists can realize these goals only if additional lunar flights are made. We now know that the moon is non-uniform, and we need to visit different parts of the moon, particularly the highland areas; we need to collect different kinds of samples, particularly from deeper depths below the surface: we need to carry additional experimental packages to the moon. With persistence, we can achieve a notable scientific payoff from the investments made to date in the men and machines of the Apollo program.

If history is the guide, such scientific knowledge will profoundly modify the everyday existence of future generations."

Dr. Clifford Frondel, Harvard University:

"At this point, contemplating what should be done in the way of immediate scientific exploration of the moon is rather like standing on Plymouth Rock and deciding what should be done next. Strike inland and determine the outline of a new continent? Reboard ship and go to some other distant and unknown place? Go home?

The initial landing on the moon provided answers only to some very broad questions: What was the general nature of the lunar rocks? Are life forms present? Is it possible to proceed further in lunar exploration? One brief landing on any part of the moon would have given the same information.

From a scientific point of view, the initial work to be done necessarily is somewhat larger in scope. The moon contains a limited number of fundamental features, such as the maria, the highlands, the rilles and volcanic structures. All of these must be examined, and geochemical and geophysical data obtained, before the first coherent account of the moon and its relation to earth can be given. Only this provides a sufficient inventory of lunar features on which to base a systematic and understanding program of exploration in the future."

Dr. G. J. Wasserburg, California Institute of Technology:

"I have on some occasions been asked by some of my colleagues what I will do when the lunar program is over. From a scientific point of view, I must hope that it is not over for a very long time because of the fact that so much basic and exciting science is coming and will come. With sufficient concentration on the scientific returns from the future Apollo missions and the proper operation of these missions, with adequate interaction between program officials and the scientific community, I am convinced that we will see a tremendous return. The returned lunar samples mark the foundation of a new science which will certainly develop with increasing importance.

"I have been invited to give numerous speeches on the Lunar Program to different scientific societies. At the end of every speech, the one thing that became eminently clear was that when members of the scientific community heard about the fantastic amount of science which is being done and can be done within the Lunar Program and the general space program, they are exceedingly enthusiastic. After my recent speech in Leningrad to the Committee on Space Research, I was convinced of the tremendous excitement and respect directed towards the engineers and scientists of this nation for the accomplishments so far attained. I hope that we can continue this natural development so that the big rockets and expensive hardware used for these missions do not stand for dead symbols like the pyramids, but will instead be incorporated and developed into the major intellectual achievements of mankind."

A clear indication of the broad international scientific interest in a continuing lunar program is in the fact that 241 proposals for surface and orbital experiments were submitted for Apollo 16 and subsequent. This is the largest number ever received by NASA for one program. As a result of our recent request for proposals for analysis of lunar samples to be returned on Apollo 14 and subsequent, over 360 proposals have been received already from scientific teams around the world representing 24 countries.

Expected Benefits of Lunar Exploration

With the successful accomplishment of the first manned landing, the objective of succeeding flights is to increase our knowledge of our natural satellite. Much of the fundamental, scientific information which we expect to recover from these missions and potential benefits have been discussed in the previous statements.

As in most basic science work, many things we will learn are not predictable at this time. It is from the surprises that we may also make beneficial gains. One early example is the rapid growth of certain plants in a soil mixture containing a small amount of lunar soil. The behavior of these plants is now undergoing extensive study in cooperation with the Department of Agriculture to determine what is causing the enhanced growth and if there is some direct application that can be made to terrestrial agriculture.

We can see that certain specific Apollo experiments may provide information of direct benefit to the earth's inhabitants. Laser ranging to the moon, done with extreme accuracy, is expected to make possible measurement of the subtle variations in the earth's rotation. Recent indications appear to signify that these variations in the wobble of the earth's axis are associated with major earthquakes. Eventually this experiment may contribute to our ability to predict earthquakes. It is planned to carry additional laser reflectors on later missions to improve the data which we presently receive from the reflector array carried by Apollo 11.

A tidewater gravimeter is now under development for one of the final Apollo missions. This experiment has as a prime objective the detection and measurement of gravity waves originating within the universe. Detection of such waves is believed to have been done on earth. From the knowledge we have gained of the moon's seismic activity, we know that the sensitivity of this instrument will be increased 1,000 fold on the moon. Conclusive experimental proof of the existence of gravity waves, first predicted by Einstein in 1919, would be a fundamental scientific discovery with potential applications to future space travel.

From the block of Apollo missions we expect to gain significant information on the utility of the moon as a large stable space platform in orbit about the earth. Because of its lack of an atmosphere, Sir Bernard Lovell has stated that a "major consequence of Apollo will be the initiation of the moon as a base for scientific research. The instantaneous benefit here will be to the astronomical sciences." Perhaps of more immediate interest today is the fact that large area synoptic views of the earth are potentially extremely important in understanding broad atmospheric changes and their relationship to pollution control. One major area of interest is the measurement of the earth's heat budget and its variations through time. The moon's low gravity and high vacuum may offer some day advantages in manufacture of very specialized components. Certainly the moon is an excellent location for laboratories for such disciplines as high energy physics.

Information thus far returned from the Apollo missions is encouraging for planning permanent stations on the moon. Oxygen can undoubtedly be recovered from lunar materials. Construction, utilizing lunar materials, excavation and mining all seem feasible. There seems little doubt among those engineers and scientists who have studied the problem that a lunar base can be a reality when we are ready to apply the necessary effort.

In the more distant future the moon, as our closest neighbor, will undoubtedly assume roles of greatly increased importance—an archives storage vault or even refuge against earth disaster, a way station, a training ground, a safe harbor for planetary quarantine, and many other applications unpredictable at this time.

Hardware Availability

With respect to the Apollo hardware presently on hand or under procurement we have the capability of sending a maximum of six more manned missions to the moon. The presently planned utilization of these missions has been formulated with the assistance of many of our best scientific minds in conjunction with the technical and operational expertise gained thus far in our program. In particular, each landing site is very carefully selected.

Starting with Apollo 16, changes are being incorporated into the basic Apollo system which will significantly improve our exploration capability. A number of high priority orbital experiments will be incorporated into the Service Module and the time in lunar orbit will be increased. These experiments will enable us to gather information over large areas of the moon where landings will not be possible for some time. They may be of great importance in determining where a future lunar base should be located.

Modifications to the lunar module will extend surface staytime well beyond that of Apollo 12. More than twice as many manhours will be spent on the lunar surface. The landed payload will increase by about 100%. The range and efficiency of surface operations will be significantly increased through improved suit mobility and changes to the life support system. A roving vehicle will be carried which will enable the astronauts to traverse much greater distances than they can on foot.

The vehicle will carry a television camera so that scientists concerned with the traverse operations and the rest of us can share the astronauts' experiences. New traverse experiments are planned. Improvements in the emplaced surface experiment package should enable it to send data back to earth for more than two years.

We are continually reviewing the number of missions required—how many of the remaining six—to make the maximum gains within the smallest number of flights and we will reexamine our need for additional flights after each succeeding flight.

Thus far we have barely scratched the surface in exploring the moon. To place our accomplishments in proper perspective, the moon is an area about the size of North and South America combined. On Apollo 11 we explored an area not a whole lot bigger than a basketball court; on Apollo 12 perhaps an area the size of a football stadium. Final missions as presently planned will attempt to explore regions as large as Zion National Park.

Future Apollo manned lunar landings will be spaced so as to maximize our scientific return from each mission, always providing, of course, for the safety of those who undertake these ventures. Our decisions about manned and unmanned lunar voyages beyond the Apollo program will be based on the results of these missions.

In the long term, there is no question that our nation will want to continue missions to the moon and eventually establish a permanent base. Today we ask how soon and in what evolutionary steps we should proceed. NASA must decide how much of the initial exploration can be accomplished prudently with the Apollo system and to what extent we should be making our plans for the expeditions in the 1980's at which time far more advanced systems will become available. We have this subject under active study at this time.

The CHAIRMAN. We will leave the record open in case there are additional questions that the committee might want to ask.

Thank you very much. Appreciate it a whole lot.

Dr. PAINE. Thank you very much.

(Whereupon, at 11:55 a.m., the hearing was concluded.)

(Biographical data of the witnesses are as follows:)

EDGAR M. CORTRIGHT, NASA LANGLEY RESEARCH CENTER

Edgar M. Cortright, 46, Director of the NASA Langley Research Center, Hampton, Virginia, is Chairman of the Apollo 13 Review Board.

Mr. Cortright has been an aerospace scientist and administrator for 22 years. He began his career at NASA's Lewis Research Center, Cleveland, Ohio, in 1948 and for the next 10 years specialized in research on high-speed aerodynamics there.

In October 1958, Mr. Cortright was named Chief of Advanced Technology Programs at NASA Headquarters, Washington, D.C., where he directed initial formulation of NASA's Meteorological Satellite Program. In 1960, he became Assistant Director for Lunar and Planetary Programs and directed the planning and implementation of such projects as Mariner, Ranger, and Surveyor.

Mr. Cortright became Deputy Director of the Office of Space Sciences in 1961, and Deputy Associate Administrator for Space Science and Applications in 1963, in which capacities he served as General Manager of NASA's space flight program using automated spacecraft. He joined the Office of Manned Space Flight as Deputy Associate Administrator in 1967 and served in a similar capacity until he was appointed Director of the Langley Research Center in 1968.

He is a Fellow of the American Institute of Aeronautics and Astronautics and of the American Astronautical Society. He has received the Arthur S. Fleming Award, the NASA Medal for Outstanding Leadership, and the NASA Medal for Distinguished Service.

Mr. Cortright is the author of numerous technical reports and articles, and compiled and edited the book, "Exploring Space With a Camera."

He is a native of Hastings, Pennsylvania, and served as a U.S. Navy officer in World War II. He received Bachelor and Master of Science degrees in aeronautical engineering from the Rensselaer Polytechnic Institute.

Mr. and Mrs. Cortright are the parents of two children.

CHARLES D. HARRINGTON, DOUGLAS UNITED NUCLEAR, INC.

Dr. Charles D. Harrington, 59, President and General Manager, Douglas United Nuclear, Inc., Richland, Washington, is an official observer of the Apollo 13 Review Board.

Dr. Harrington, who has been associated with all phases of the chemical and nuclear industrial fields since 1941, is Chairman of the Aerospace Safety Advisory Panel, a statutory body created by Congress.

From 1941 to 1961, he was employed by the Mallinckrodt Chemical Works, St. Louis, Missouri. Dr. Harrington started with the company as a research chemist and in 1960, after a procession of research and management positions, was appointed Vice President, Mallinckrodt Nuclear Corporation and Vice President, Mallinckrodt Chemical Works.

In 1961, when the fuel material processing plant of Mallinckrodt became the Chemicals Division of United Nuclear Corporation, Dr. Harrington was named Vice President of that division.

He became Senior Vice President, United Nuclear Corporation, Centreville, Maryland, in 1963.

In 1965, Dr. Harrington was appointed President and General Manager, Douglas United Nuclear, Inc. The company manages production reactors and fuels fabrication facilities at Hanford, Washington, for the Atomic Energy Commission.

He is the co-author of a book, "Uranium Production Technology," and has written numerous technical papers. He has received the Mid-West Award of the American Chemical Society for contributions to technology in the nuclear energy field.

He is director of several corporations, including United Nuclear, as well as professional councils and societies.

Dr. Harrington has M.S., M.A., and Ph. D. degrees in chemistry from Harvard University.

THOMAS O. PAINE, ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

(Appointed Mar. 5, 1969. Sworn in Apr. 3, 1969)

Dr. Thomas O. Paine was born in Berkeley, Calif., November 9, 1921, son of Commodore and Mrs. George T. Paine, USN (Ret.). He attended public schools in various cities and was graduated from Brown University in 1942 with an A.B. degree in engineering.

In World War II he served as a submarine officer in the Pacific and the Japanese occupation. He qualified in submarines and as a Navy deep-sea diver and was awarded the commendation medal and submarine combat insignia with stars.

In 1946–49 Dr. Paine attended Stanford University, receiving an M.S. degree in 1947 and Ph. D. in 1949 in Physical Metallurgy. In 1946 he married Barbara Helen Taunton Pearse of Perth, Western Australia. They have four children: Marguerite Ada, George Thomas, Judith Janet and Frank Taunton.

Dr. Paine worked as a research associate at Stanford University from 1947 to 1949, where he made basic studies of high-temperature alloys and liquid metals in support of naval nuclear reactor programs. He joined the General Electric Research Laboratory in Schenectady, New York, in 1949 as research associate, where he initiated research programs on magnetic and composite materials. This work led to the first demonstration of the shape anisotrophy effect in single-domain magnetic particles, and to the basic patents on "Lodex" permanent magnets. In 1951 he transferred to the Meter and Instrument Department, Lynn, Mass., as manager of materials development, and later as laboratory manager. Major projects ranged from development of photocells and non-arc-tracking organic insulation to solid-state nuclear reactor control systems and aircraft instrumentation. For the successful fine-particle magnet development program, Dr. Paine's laboratory received the 1956 Award for Outstanding Contribution to Industrial Science from the American Association for Advancement of Science.

From 1958 to 1962 Dr. Paine was research associate and manager of Engineering Applications at GE's Research and Development Center in Schenectady. This involved organizing and managing a new laboratory component engaged in technical-economic studies and development programs in lasers, medical, electronics, electric vehicles, and many other fields.

In 1963–68 he was manager of TEMPO, GE's Center for Advanced Studies in Santa Barbara, Calif. This 400-man, long-range planning and interdisciplinary study group conducted interdisciplinary research for federal, state and local governments, foreign nations, banks, and industry. These programs ranged from criteria for selection of model cities to the logistics support system for Polaris submarines and from computerized management information systems to economic development in Africa. About 15 percent of these studies were for top management of the parent company.

On January 31, 1968, President Johnson appointed Dr. Paine Deputy Administrator of NASA. Upon the retirement of Mr. James E. Webb on October 8, 1968, President Johnson named Dr. Paine Acting Administrator of NASA. His nomination as Administrator was announced by President Nixon on March 5, 1969; this was confirmed by the Senate on March 20, 1969. He was sworn in by Vice President Agnew on April 3, 1969.

Dr. Paine's professional activities have included chairmanship of the 1962 Engineering Research Foundation—Engineers Joint Council Conference on Science and Technology for Less Developed Nations; secretary and editor of the E.J.C. Engineering Research Committee on the Nation's Engineering Research Needs 1965–1985; member, Advisory Committee and local chairman, Joint American Physical Society—Institute of Electrical and Electronic Engineers International Conference on Magnetism and Magnetic Materials; chairman, Special Task Force for U.S. Department of Housing and Urban Development; lecturer, U.S. Army War College and American Management Association; Advisory Board, AIME *Journal of Metals;* member, Basic Science Committee of IEEE and the Research Committee, Instrument Society of America; Collier Trophy Award Committee.

Dr. Paine is a member of the Sigma Xi; the Army and Navy Club, the Cosmos Club, the National Aviation Club, Washington, D.C.; New York Academy of Sciences; American Physical Society; Institute of Electrical and Electronic Engineers; American Institute of Mining, Metallurgical and Petroleum Engineers; American Society of Metals; Institute of Metals (London); Submarine Veterans of World War II; Society for the History of Technology; Marine Historical Association; American Museum of Electricity; Newcomen Society (London); Naval Historical Foundation; American Association for the Advancement of Science; National Association for the Advancement of Colored People; U.S. Naval Institute; Navy League; Association of the U.S. Army; Instrument Society of America; Associate Fellow, American Institute of Aeronautics and Astronautics; National Space Club Board of Governors; American Astronautical Society Fellow.

Dr. Paine received an Honorary Doctor of Science degree from Brown University on June 2, 1969.

ROCCO A. PETRONE, DIRECTOR, APOLLO PROGRAM

Rocco A. Petrone became Program Director for the National Aeronautics and Space Administration on Sept. 1, 1969. As Director of the Apollo Program Office in Washington, D.C., Dr. Petrone has overall responsibility for the direction and management of the Apollo manned space flight program which has as its mission the manned exploration of the Moon.

Prior to assuming the duties of his present position, Dr. Petrone was Director of Launch Operations at the John F. Kennedy Space Center, Fla. In this office he was responsible for the management and technical direction of preflight operations and integration, test, checkout, and launch of all space vehicles, both manned and unmanned, for the Kennedy Space Center. Launch operations, the largest organizational element as KSC, was the key directorate for committing to lanuch the Apollo 11 which landed the first men on the surface of the Moon.

Dr. Petrone's extensive career in rocket development began in 1952 at the Army's Redstone Arsenal in Huntsville, Ala., where he participated in the development of the Redstone, the Nation's first ballistic missile. He was in the blockhouse at Cape Canaveral in August 1953 as a member of the Missile Firing Laboratory for the first launch of the Redstone. From 1956 to 1960 he was detailed to the Army General Staff, Pentagon, Washington, D.C., where he was assigned duties in the field of guided missiles before being loaned by the U.S. Army to NASA at Kennedy Space Center in July 1960. During his NASA assignments, Dr. Petrone has been directly involved in all 12 successful launches of the Saturn I vehicles.

As the Saturn Project Officer, responsible to the Kennedy Space Center Director, Dr. Kurt H. Debus, Dr. Petrone assured that all aspects of the Saturn Project fulfilled the Kennedy Space Center requirements. When in 1961 this nation established its goal to land men on the Moon by 1970, the Apollo Manned Lunar Landing Program was approved, and Dr. Petrone was assigned as Apollo Program Manager.

He was responsible for the planning, development, and activation of all launch facilities required for the Apollo Program, including Launch Complex 39, where the Apollo/Saturn space vehicles are launched. Dr. Petrone retired from the U.S. Army with the rank of Lieutenant Colonel in June 1966, after 20 years service, and at that time continued his career as Director of Launch Operations at Kennedy Space Center.

Dr. Petrone graduated from the U.S. Military Academy in 1946, and after serving overseas in Germany from 1947 to 1950, he resumed his studies at the Massachusetts Institute of Technology, to earn his Masters degree in mechanical engineering in 1951. A year later, he was awarded a Professional degree in mechanical engineering. His performance at MIT won him membership in Sigma Xi, the scientific honor fraternity.

In March 1968, the Canaveral Council of Technical Societies presented to Dr. Petrone the Fifth Space Congress Award for his outstanding contributions to the local Missile and Space Program during 1967. He received the NASA Exceptional Service Award in November 1968 for his direction of the successful checkout and launch of Apollo 7, the first three-man mission into space. Dr. Petrone also received the NASA Distinguished Service Medal, the Agency's highest award, in January 1969, for his direction of the checkout and launch of Apollo 8, the first manned mission to the Moon. In May 1969, he was awarded an Honorary Doctorate of Science degree from Rollins College, Winter Park, Fla. On Oct. 21, 1969, Dr. Petrone received his second NASA Distinguished Service Medal—this one for his direction of the checkout and launch of Apollo 11, the first manned lunar landing mission.

Dr. Petrone is a student of the Civil War and has an extensive library on the subject. He is also interested in athletics, and played for the West Point football teams during the era of All Americans Felix "Doc" Blanchard and Glen Davis.

Dr. Petrone and wife, Ruth, have three daughters, Teresa, Nancy, and Kathryn, and one son, Michael.

DALE D. MYERS, ASSOCIATE ADMINISTRATOR, OFFICE OF MANNED SPACE FLIGHT

Dale D. Myers is Associate Administrator for Manned Space Flight, National Aeronautics and Space Administration. He assumed direction of NASA's manned space flight program on January 12, 1970. In this capacity he is responsible for the planning, direction, execution, and evaluation of NASA's overall manned space flight program. These functions include management authority over the George C. Marshall Space Flight Center, Manned Spacecraft Center, and John F. Kennedy Space Center.

Myers was born in Kansas City, Mo., on January 8, 1922. He was graduated from the University of Washington, Seattle, Wash., in 1943 with a bachelor of science degree in aeronautical engineering.

He joined North American Aviation in June 1943 as an aeronautical engineer and was project aerodynamicist on the F–82, XSNJ, and XFJ–1 airplanes. He developed the basic methods used by the company for stability and control analyses, including the effects of aeroelasticity on both dynamic and static stability.

In 1946 he joined the Aerophysics department of North American, which was engaged in research and development of long-range supersonic guided missiles. He progressed through aerodynamics and flight test to Assistant Director of the Aerophysics Department in 1954. In 1956 he was named Chief Engineer of the newly formed Missile Division, and in 1957 became Program Manager for the Air Force Hound Dog missile. He was appointed Vice President and Program Manager of the Hound Dog program in 1960. In April 1964, after a short period of advanced design, he became Vice President and Program Manager of the Apollo Command and Service Modules activities at North American Rockwell Corp., the company's present name.

Myers is a member of the American Institute of Aeronautics and Astronautics and of the American Management Association. In February 1969 he was awarded the NASA Certificate of Appreciation for his contributions to the Apollo 8 Moon-orbiting flight and in September 1969 he received the NASA Public Service Award for his contributions to the success of the Apollo 11 lunar landing mission.

Myers is married to the former Marjorie Williams, of Seattle, and has two daughters.

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