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 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 management 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 1-1/2 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 thermostatic 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 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 1-1/2 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 turn-on 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 1/4 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 supply 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 1-1/2-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 1-1/2-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 could 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 pressures 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 unnecessary 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	4-1/2 hours
Water	5-1/2 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.

Determinations

(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 reentry battery 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 RCS 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 timeline 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

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 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 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.

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