APOLLO 13

The Seventh Mission: The Third Lunar Landing Attempt 11 April–17 April 1970

Background

Apollo 13 was planned as a Type H mission, a precision piloted lunar landing demonstration and systematic lunar exploration. It was, however, aborted during translunar flight because of the loss of all the oxygen stored in two tanks in the service module.

The primary objectives were:

- to perform selenological inspection, survey, and sampling of materials in a preselected region of the Fra Mauro formation;
- to deploy and activate an Apollo lunar surface experiments package;
- to further develop human capability to work in the lunar environment; and
- to obtain photographs of candidate exploration sites.

The crew members were Captain James Arthur Lovell, Jr. (USN), commander; John Leonard "Jack" Swigert, Jr. [SWY-girt], command module pilot; and Fred Wallace Haise, Jr., lunar module pilot. Swigert was backup command module pilot, but Lt. Commander Thomas Kenneth "Ken" Mattingly, II (USN), the prime command module pilot, had been exposed to rubella (German measles) by a member of the backup crew[1], eight days before the scheduled launch date, and results of his pre-mission physical examination revealed he had no immunity to the disease. Consequently, on April 10, the day prior to launch, after several days of intense training with the prime crew, Swigert was named to replace Mattingly.

Selected as an astronaut in 1962, Lovell was making his fourth spaceflight and second trip to the Moon, the first person ever to achieve those milestones. He had been pilot of Gemini 7, command pilot of Gemini 12, and command module pilot of Apollo 8, the first piloted mission to the Moon. Lovell was born 25 March 1928 in Cleveland, Ohio, and was 42 years old at the time of the Apollo 13 mission. He received a B.S. from the U.S. Naval Academy in 1952. His backup for the mission was Commander John Watts Young (USN).

The original command module pilot, Mattingly would have been making his first spaceflight. Born 17 March 1936 in Chicago, Illinois, he was 34 years old at the time of the Apollo 13 mission. He received a B.S. in aeronautical engineering from Auburn University in 1958, and was selected as an astronaut in 1966.

Swigert was making his first spaceflight. Born 30 August 1931 in Denver, Colorado, he was 38 years old at the time of Apollo 13. Swigert received a B.S. in mechanical engineering from the University of Colorado in 1953, an M.S. in aerospace science from Rensselaer Polytechnic Institute in 1965, and an M.B.A. from the University of Hartford in 1967. He was selected as an astronaut in 1966.[2],

Haise was also making his first spaceflight. Born in Biloxi, Mississippi, on 14 November 1933, he was 36 years old at the time of the Apollo 13 mission. Haise received a B.S. in aeronautical engineering from the University of Oklahoma in 1959, and was selected as an astronaut in 1966. His backup was Major Charles Moss Duke, Jr. (USAF).

The capsule communicators (CAPCOMs) for the mission were Commander Joseph Peter Kerwin (USN/M.D./M.C.), Vance DeVoe Brand, Major Jack Robert Lousma (USMC), Young, and Mattingly. The support crew were Lousma, Brand, and Major William Reid Pogue (USAF). The flight directors were Milton L. Windler (first shift), Gerald D. Griffin (second shift), Eugene F. Kranz (third shift), and Glynn S. Lunney (fourth shift).

The Apollo 13 launch vehicle was a Saturn V, designated SA-508. The mission also carried the designation Eastern Test Range #3381. The CSM was designated CSM-109, and had the call-sign "Odyssey." The lunar module was designated LM-7, and had the call-sign "Aquarius."

Launch Preparations

The terminal countdown was picked up at T-28 hours at 05:00:00 GMT on 10 April. Scheduled holds were 9 hours 13 minutes at T-9 hours and one hour duration at T-3 hours 30 minutes.

At launch time, a cold front extended from a low pressure cell in the North Atlantic, becoming stationary through northern Florida and along the Gulf Coast to a low pressure area located in southern Louisiana. The frontal intensity was weak in northern Florida but became stronger in the northwestern Gulf of Mexico/Louisiana area. Surface winds in the Kennedy Space Center area were light and variable. Generally, winds in the lower part of the troposphere were light, permitting the sea breeze to switch the surface wind to the east southeast by early afternoon. Altocumulus clouds covered 40 percent of the sky (base 19,000 feet) and cirrostratus 100 percent (base 26,000 feet), the temperature was 75.9° F, the relative humidity was 57 percent; and the barometric pressure was 14.676 lb/in^2. The winds, as measured by the anemometer on the light pole 60.0 feet above ground at the launch site measured 12.2 knots at 105° from true north.

Ascent Phase

Apollo 13 was launched from Kennedy Space Center Launch Complex 39, Pad A, at a Range Zero time of 19:13:00 GMT (02:13:00 p.m. EST) on 11 April 1970. The planned launch window extended to 22:36:00 GMT to take advantage of a sun elevation angle on the lunar surface of 10.0°.

Between 000:00:12.6 and 000:00:32.1, the vehicle rolled from a launch pad azimuth of 90° to a flight azimuth of 72.043°. The S-IC engine shut down at 000:02:43.6, followed by S-IC/S-II separation, and S-II engine ignition. Due to high amplitude oscillations in the propulsion/structural system, the S-II center engine shut down at 000:05:30.64, 132 seconds earlier than planned. The early shutdown caused considerable deviations from the planned trajectory. The altitude at shutdown was 10.7 n mi lower and the velocity was 5,685.3 ft/sec slower than expected.

The remaining S-II engines burned 34 seconds longer than planned and shut down at 000:09:52.64. After separation, the S-IVB ignited at 000:09:56.90 and burned 9 seconds longer than planned, shutting down at 000:12:29.83, only -1.9 ft/sec in velocity and +0.2 n mi in altitude from the planned trajectory.

The S-IC stage impacted the Atlantic Ocean at 000:09:06.9 at latitude 30.177° north and longitude 74.065° west, 355.3 n mi from the launch site. The S-II stage impacted the Atlantic Ocean at 000:20:58.1 at latitude 32.320° north and longitude 33.289° west, 2,452.6 n mi from the launch site.

The maximum wind conditions encountered during ascent were 108.13 knots at 252° from true north at 44,540 feet, with a maximum wind shear of 0.0166 sec^{-1} at 50,610 feet.

Despite the early shutdown of the S-II center engine, parking orbit conditions at insertion, 000:12:39.83 (S-IVB cutoff plus 10 seconds to account for engine tailoff and other transient effects), showed a nearly nominal apogee and perigee of 100.3 by 99.3 n mi, a period of 88.19 minutes, an inclination of 32.547°, and a velocity of 25,566.1 ft/sec. The apogee and perigee were based upon a spherical Earth with a radius of 3,443.934 n mi.

The international designation for the CSM upon achieving orbit was 1970-029A and the S-IVB was designated 1970-029B. After undocking prior to Earth entry, the LM would be designated 1970-029C.

After orbital insertion, all launch vehicle and spacecraft systems were verified and preparations were made for translunar injection. Onboard television was initiated at 001:35 for about five-and-a-half minutes.

The 350.85-second translunar injection maneuver (second S-IVB firing) was performed at 002:35:46.30. The S-IVB engine shut down at 002:41:37.15 and translunar injection occurred ten seconds later, after 1.5 Earth orbits lasting 2 hours 29 minutes 7.3 seconds, at a velocity of 35,538.4 ft/sec.

Translunar Phase

At 003:06:38.9, the CSM was separated from the S-IVB stage and onboard television was initiated at 003:09 for about 72 minutes to show the docking, ejection, and interior and exterior views of the CM. Transposition and docking with the LM occurred at

003:19:08.8. The docked spacecraft were ejected from the S-IVB at 004:01:00.8, and an 80.2-second separation maneuver was initiated by the S-IVB auxiliary propulsion system at 004:18:00.6.

On previous lunar missions, the S-IVB stage had been maneuvered by ground command into a trajectory such that it would pass by the Moon and go into a solar orbit. For Apollo 13, the S-IVB was targeted to hit the Moon so that the vibrations resulting from the impact could be sensed by the Apollo 12 seismic station and telemetered to Earth for study.

A 217.2-second lunar impact maneuver was made at 005:59:59.5. The S-IVB impacted the lunar surface at 077:56:40.0. The seismic signals lasted three hours 20 minutes, and were so strong that the Apollo 12 seismometer gain had to be reduced to keep the recording on the scale. The suprathermal ion detector recorded a jump in the number of ions from zero at impact to 2,500 and then back to zero. It was theorized that the impact drove particles from the lunar surface up to 200,000 feet above the moon, where they were ionized by sunlight. The impact point was latitude 2.75° south and longitude 27.86° west, 35.4 n mi from the target point and 73 n mi from the Apollo 12 seismometer. At impact, the S-IVB weighed 29,599 pounds and was traveling 8,465 ft/sec.

Good quality television coverage of the preparations and performance of the second midcourse correction burn was received for 49 minutes beginning at 030:13.

Photographs of Earth were taken during the early part of translunar coast to support an analysis of atmospheric winds. At 030:40:49.65, a 3.49-second midcourse correction lowered the closest point of spacecraft approach to the Moon to an altitude of 60 miles. Before this maneuver, the spacecraft had been on a free-return trajectory, in which the spacecraft would have looped around the Moon and returned to Earth without requiring a major maneuver.

Through the first 46 hours of the mission, telemetered data and crew observations indicated that the performance of oxygen tank 2 was normal. At 046:40:02, the crew routinely turned on the fans in oxygen tank 2. Within three seconds, the oxygen tank 2 quantity indication changed from a normal reading of about 82 percent full to an obviously incorrect "off-scale high" reading of over 100 percent. Analysis of the electrical wiring of the quantity gauge revealed that this erroneous reading could have been caused by either a short circuit or an open circuit in the gauge wiring or a short circuit between the gauge plates. Subsequent events indicated that a short was the more likely failure mode.

At 047:54:50 and at 051:07:44, the oxygen tank 2 fans were turned on again, with no apparent adverse effects. The quantity gauge continued to read off-scale high.

Following a rest period, the Apollo 13 crew began preparations for activating and powering up the LM for checkout. At 053:27, the commander and lunar module pilot were cleared to enter the LM to commence inflight inspection. A television transmission of the spacecraft interior started at 055:14 and ended at 055:46. The crew moved back into the CM and the LM hatch was closed at 055:50.

At 055:52:31, a master alarm on the CM caution and warning system alerted the crew to a low pressure indication 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. At 055:52:58, flight controllers requested the crew to turn on the cryogenic system fans and heaters.

The command module pilot acknowledged the fan cycle request at 55:53:06, and data indicated that current was applied to the oxygen tank 2 fan motors at 055:53:20, followed by a power transient in the stabilization control system.

About 90 seconds later, at 055:54:53.555, 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. At about the same time, the crew heard a loud "bang" and realized that a problem existed in the spacecraft.

When the crew heard the bang and got the master alarm for low DC main bus B voltage, the commander was in the lower equipment bay of the command module, stowing the television camera which had just been in use. The lunar module pilot was in the tunnel between the CSM and the LM, returning to the CSM. The command module pilot was in the left-hand couch, monitoring spacecraft performance. Because of the master alarm indicating low voltage, the command module pilot moved across to the right-hand couch where CSM voltages could be observed. He reported that voltages were "looking good" at 055:56:10 and also reported hearing "…a pretty good bang…" a few seconds before. At this time, DC main bus B had recovered and fuel cell 3 did not fail for another 90 seconds. He also reported fluctuations in the oxygen tank 2 quantity, followed by a return to the off-scale high position.

The commander reported, "…We're venting something…into space…" at 056:09:07, followed at 056:09:58 by the lunar module pilot's report that fuel cell 1 was off-line. Less than half an hour later, he reported that fuel cell 3 was also off-line.

When electrical output readings for fuel cells' 1 and 3 went to zero, the ground controllers could not be certain that the cells had not somehow been disconnected from their respective busses and were otherwise functioning normally. Attention continued to be focused on electrical problems.

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 powerdown to lower the load on the remaining fuel cell. Fuel cell 2 was shut down at 058:00, followed 10 minutes later by powerdown of the CM computer and platform.

Observing the rapid decay in oxygen tank 1 pressure, controllers asked the crew to switch power to the oxygen tank 2 instrumentation. When this was done, and it was realized that oxygen tank 2 had failed, the extreme seriousness of the situation became clear.

Several attempts were then made to save the remaining oxygen in oxygen tank 1, but the pressure continued to decrease. It was obvious by about 90 minutes after the accident that the oxygen tank 1 leak could not be stopped and that shortly it would be necessary to use the LM as a "lifeboat" for the remainder of the mission. The resultant loss of oxygen made the three fuel cells inoperative. This left the CM batteries, normally used only during reentry, as the sole power source. The only oxygen left was contained in a surge tank and repressurization packages used to repressurize the CM after cabin venting. The LM became the only source of sufficient electrical power and oxygen to permit a safe return to Earth, and led to the decision to abort the Apollo 13 mission. By 058:40, 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.

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 crew members for a relatively short duration, could support three crew members and serve as the actual control vehicle for the time required.

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 SM service propulsion system would be used for such maneuvers. However, because of the high electrical power requirements for 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 spacecraft was then maneuvered back into a free-return trajectory at 061:29:43.49 by firing the LM descent engine for 34.23 seconds. It then looped behind the Moon and was out of contact with the Earth tracking stations between 077:08:35 and 077:33:10, a total of 24 minutes 35 seconds.[3]

Flight controllers calculated that the minimum practical return time for Apollo 13 was 133 hours total mission time to the Atlantic Ocean, and the maximum was 152 hours to the Indian Ocean. Since recovery forces were deployed in the Pacific, a return path was selected for splashdown there at 142:40.

A 263.82-second transearth injection maneuver using the LM descent propulsion system was executed at 079:27:38.95 to speed up the return to Earth by 860.5 ft/sec after the docked spacecraft had swung around the far side of the Moon.

Guidance errors during the transearth injection maneuver necessitated a 14.0-second transearth midcourse correction of 7.8 ft/sec, using the descent propulsion system at 105:18:42.0 to bring the projected entry flight-path angle within the specified limits. During the transearth coast period, the docked spacecraft were maneuvered into a passive thermal control mode.

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 being needed for the rest of the mission; LM oxygen for breathing; and lithium hydroxide (LiOH) filter canisters used to remove carbon dioxide from the spacecraft cabin atmosphere.

These consumables, and in particular the water and LiOH canisters, appeared to be extremely marginal in quantity 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 improved greatly. Engineers in Houston also developed a method that allowed the crew to use materials on board to fashion a device allowing use of the CM LiOH canisters in the LM cabin atmosphere cleaning system. At splashdown, many hours of each consumable remained available.

The unprecedented powered-down state of the CM required several new procedures for entry. The CM was briefly powered up to assess the operational capability of critical systems. Also, the CM entry batteries were charged through the umbilical connectors that had supplied power from the LM while the CM was powered down.

Approximately six hours before entry, the passive thermal control mode was discontinued, and a final midcourse correction was made using the LM reaction control system to refine the flight-path angle slightly. The 21.5-second maneuver of 3.2 ft/sec was made at 137:40:13.00.

Less than half an hour later, at 138:01:48.0, the service module was jettisoned, which afforded the crew an opportunity to observe and photograph the damage caused by the failed oxygen tank.

The crew viewed the SM and reported that an entire panel was missing near the S-band high-gain antenna, the fuel cells on the shelf above the oxygen shelf were tilted, the high-gain antenna was damaged, and a great deal of debris was exposed.

The LM was retained until 141:30:00.2, about 70 minutes before entry, to minimize usage of CM electrical power. At undocking, normal tunnel pressure provided the necessary force to separate the two spacecraft. All other events were the same as a normal mission.

Recovery

The command module reentered the Earth's atmosphere (400,000 feet altitude) at 142:40:45.7 at a velocity of 36,210.6 ft/sec, following a transearth coast of 63 hours 8 minutes 42.9 seconds. Some pieces of the LM survived entry and projected trajectory data indicated that they struck the open sea between Samoa and New Zealand.

The parachute system effected splashdown of the CM in the Pacific Ocean at 18:07:41 GMT (01:07:41 p.m. EST) on 17 April. Mission duration was 142:54:41.

The impact point was about 1.0 n mi from the target point and 3.5 n mi from the recovery ship U.S.S. Iwo Jima. The splashdown site was at latitude 21.63° south and longitude 165.37° west. After splashdown, the CM assumed an apex-up flotation attitude. The crew was retrieved by helicopter and aboard the recovery 45 minutes after splashdown.

The CM was recovered 43 minutes later. The estimated CM weight at splashdown was 11,132.9 pounds, and the estimated distance traveled for the mission was 541,103 n mi.

The crew departed the Iwo Jima by aircraft at 18:20 GMT on 18 April and arrived in Houston 03:30 GMT on 20 April. The Iwo Jima arrived with the CM at Hawaii at 19:30 GMT on 24 April. Deactivation was completed on 26 April.

The CM was delivered to the North American Rockwell Space Division facility in Downey, California, for postflight analysis, arriving at 14:00 GMT on 27 April.

Conclusions

The Apollo 13 accident was nearly catastrophic. Only outstanding performances by the crew and ground support personnel, and the excellent performance of the LM systems made a safe return possible.

The following conclusions were made from an analysis of post-mission data:

1. The mission was aborted because of the total loss of primary oxygen in the service module. This loss resulted from an incompatibility between switch design and pre-mission procedures, a condition which, when combined with an abnormal pre-mission detanking procedure, caused an inflight shorting and a rapid oxidation within one of two redundant storage tanks. The oxidation then resulted in a loss of pressure integrity in the related tank and eventually in the remaining tank.

2. The concept of a backup crew was proven for the first time when, three days prior to launch, the backup command module pilot was substituted for his prime crew counterpart, who was exposed and found susceptible to rubella (German measles).

3. The performance of lunar module systems demonstrated an emergency operational capability. Lunar module systems supported the crew for a period twice the intended design lifetime.

4. The effectiveness of pre-mission crew training, especially in conjunction with ground personnel, was reflected in the skill and precision with which the crew responded to the emergency.

5. Although the mission was not a complete success, a lunar flyby mission, including three planned experiments (lightning phenomena, Earth photography, and S-IVB lunar impact), were completed and data were derived with respect to the capabilities of the lunar module.

Report of the Apollo 13 Review Board

On 17 April 1970, NASA Administrator Thomas O. Paine established the Apollo 13 Review Board, naming Edgar M. Cortright, director of the NASA Langley Research Center, as chairman. Cortright’s eight-member panel met for nearly two months, and submitted their final report on 15 June. Neil Armstrong, commander of the recent Apollo 11 mission, was the only astronaut on the board. William Anders, lunar module pilot of Apollo 8, and executive secretary of the National Aeronautics and Space Council, was one of three observers.

The evidence pointed strongly to an electrical short circuit with arcing as the initiating event. About 2.7 seconds after the fans were turned on in the SM oxygen tanks, an 11.1-ampere current spike and a simultaneously voltage-drop 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. The power to the heaters in the tanks was not on (the quantity gauge and temperature sensor were very low power devices). The next anomalous event recorded was the beginning of a pressure rise in oxygen tank 2 thirteen seconds later. Such a time lag was possible with low-level combustion at the time. These facts pointed to the likelihood that an electrical short circuit with arcing occurred in the fan motor or its wires to initiate the accident sequence. The energy available from the short circuit was probably 10 to 20 joules. Tests conducted during the investigation showed that this energy is more than adequate to ignite Teflon 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 abnormal tanking operations at KSC prior to launch.

Data were not adequate to determine precisely the way in which the oxygen tank 2 system lost its integrity. However, available information, analyses, and tests performed during this investigation indicate that most probably 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 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 the 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 lead immediately to pressurization of the tank dome, which is equipped with a rupture disc rated at about 75 psi. Rupture of this disc or of the entire dome would then release oxygen, accompanied by combustion products, into bay 4. Spacecraft accelerations recorded at this time were probably caused by this release.

Release of the oxygen then began to pressurize the oxygen shelf space of bay 4. If the holes 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 SM locations indicated that combustion external to the tank probably took place. The ejected panel then struck the high-gain antenna, disrupting communications from the spacecraft for the 1.8 seconds.

How the Problem Occurred

Following is a list of factors that led to the accident:

- After assembly and acceptance testing, oxygen tank 2, assigned to Apollo 13, was shipped from Beech Aircraft Corporation to North American Rockwell (NR) in apparently satisfactory condition.

- 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).

- 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 arc 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 KSC which almost certainly set the stage for the accident.

- Although Beech did not encounter any problem in detanking during acceptance tests, it was not possible to detank oxygen tank 2 using normal procedures at KSC. Tests and analyses indicated that this was due to gas leakage through the displaced fill tube assembly.

- 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 that governed the operation of the heaters at KSC.

- 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.

- 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 was 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.

- 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 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.

- 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.

- 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.

- As shown by subsequent tests, failure of the thermostatic switches probably permitted the temperature of the heater tube assembly to reach about 1,000° F in spots during the continuous eight-hour period of heater operation. Such heating was shown in 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, oxygen tank 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, short circuited and ignited its insulation by means of an electric arc. The resulting combustion in the oxygen tank probably overheated and caused a failure in the wiring conduit where it entered the tank, and possibly in a portion of the tank itself.

- 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 into bay 4 of the SM, caused a leak in the high-pressure system of oxygen tank 1, damaged the high-gain antenna, caused other miscellaneous damage, and aborted the mission.

[1] Major Charles Moss Duke, Jr. (USAF).

[2] Swigert died 27 December 1982 in Washington D.C. of complications from bone marrow cancer treatments, one week before being sworn in as a member of the U.S. House of Representatives. On 2 November, he had been elected to Colorado's new Sixth Congressional District, receiving 64% of the vote.

[3] The source of these lunar occultation times is unknown, but they appear to be more accurate expressions of times in Apollo 13 Mission Operations Report, p. III-26.

BACK NEXT

[4] 1992 Guinness Book of World Records, page 118, states that Apollo 13 holds the record for farthest distance traveled from Earth: 248,655 st mi at 1:21 a.m. British Daylight Time 15 April 1970 at 158 miles above the Moon, the equivalent of 216,075 n mi 00:21 GMT 15 April 1970 (08:21 p.m. EST, 14 April) at an

altitude of 137 n mi.