55:53:41.172	22.9-ampere "spike" recorded in fuel cell 3 current, followed by drop in current and rise in voltage typical of one fan motor -- indicating opening of another motor circuit.
55:54:00	Oxygen tank no. 2 pressure levels off at 954 psia.
55:54:15	Oxygen tank no. 2 pressure begins to rise again.
55:54:30	Oxygen tank no. 2 quantity gage reading drops from full scale (to which it had failed at 46:40 g.e.t.) to zero and then read 75-percent full. This behavior indicates the gage short circuit may have corrected itself.
55:54:31	Oxygen tank no. 2 temperature begins to rise rapidly.
55:54:45	Oxygen tank no. 2 pressure reading reaches maximum recorded value of 1008 psia.
55:54:52.763	Oxygen tank no. 2 pressure reading had dropped to 996 psia.

The available evidence points to a combustion process as the cause of the pressure and temperature increases recorded in oxygen tank no. 2. The pressure reading for oxygen tank no. 2 began to increase about 13 seconds after the first electrical spike, and about 55 seconds later the temperature began to increase. The temperature sensor reads local temperature, which need not represent bulk fluid temperature. Since the rate of pressure rise in the tank indicates a relatively slow propagation of burning, it is likely that the region immediately around the temperature sensor did not become heated until this time.

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

While the data available on the combustion of Teflon in supercritical oxygen in zero-g are extremely limited, those which are available indicate that the rate of combustion is generally consistent with these observations. The cause of the 15-second period of relatively constant pressure first indicated at 55:53:59.763 has not been precisely determined; it is believed to be associated with a change in reaction rate as combustion proceeded through various Teflon elements.

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

LOSS OF OXYGEN TANK NO. 2 SYSTEM INTEGRITY

Key Data

55:54:52	Last valid temperature indication (-151° F) from oxygen tank no. 2.
55:54:52.763	Last pressure reading from oxygen tank no. 2 before loss of data--996 psia.
55:54:53.182	Sudden accelerometer activity on X, Y, and Z axes.
55:54:53.220	Stabilization control system body rate changes begin.
55:54:53.555*	Loss of telemetry data begins.
55:54:55.35	Recovery of telemetry data.
55:54:56	Various temperature indications in SM begin slight rises.
55:54:56	Oxygen tank no. 2 temperature reads off-scale high.
55:54:56	Oxygen tank no. 2 pressure reads off-scale low.

After the relatively slow propagation process described above took place, there was a relatively abrupt loss of oxygen tank no. 2 integrity. About 69 seconds after the pressure began to rise, it reached the peak recorded, 1008 psia, the pressure at which the cryogenic oxygen tank relief valve is designed to be fully open. Pressure began a decrease for 8 seconds, dropping to 996 psia before readings were lost. Virtually

*Several bits of data have been obtained from this "loss of telemetry data" period.

all signals from the spacecraft were lost about 1.85 seconds after the last presumably valid reading from within the tank, a temperature reading, and 0.8 second after the last presumably valid pressure reading (which may or may not reflect the pressure within the tank itself since the pressure transducer is about 20 feet of tubing length distant). Abnormal spacecraft accelerations were recorded approximately 0.42 second after the last pressure reading and approximately 0.38 second before the loss of signal. These facts all point to a relatively sudden loss of integrity. At about this time, several solenoid valves, including the oxygen valves feeding two of the three fuel cells, were shocked to the closed position. The "bang" reported by the crew also probably occurred in this time period. Telemetry signals from Apollo 13 were lost for a period of 1.8 seconds. When signal was reacquired, all instrument indicators from oxygen tank no. 2 were off-scale, high or low. Temperatures recorded by sensors in several different locations in the SM showed slight increases in the several seconds following reacquisition of signal. Photographs taken later by the Apollo 13 crew as the SM was jettisoned show that the bay 4 panel was ejected, undoubtedly during this event.

Data are not adequate to determine precisely the way in which the oxygen tank no. 2 system lost its integrity. However, available information, analyses, and tests performed during this investigation indicate that most probably the combustion within the pressure vessel ultimately led to localized heating and failure at the pressure vessel closure. It is at this point, the upper end of the quantity probe, that the 1/2-inch Inconel conduit is located, through which the Teflon-insulated wires enter the pressure vessel. It is likely that the combustion progressed along the wire insulation and reached this location where all of the wires come together. This, possibly augmented by ignition of 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. The accelerations recorded were probably caused by this release.

Release of the oxygen then began to pressurize the oxygen shelf space of bay 4. If the hole formed in the pressure vessel were large enough and formed rapidly enough, the escaping oxygen alone would be adequate to blow off the bay 4 panel. However, it is also quite possible that the escape of oxygen was accompanied by combustion of Mylar and Kapton (used extensively as thermal insulation in the oxygen shelf compartment, figure 4-11, and in the tank dome) which would augment the

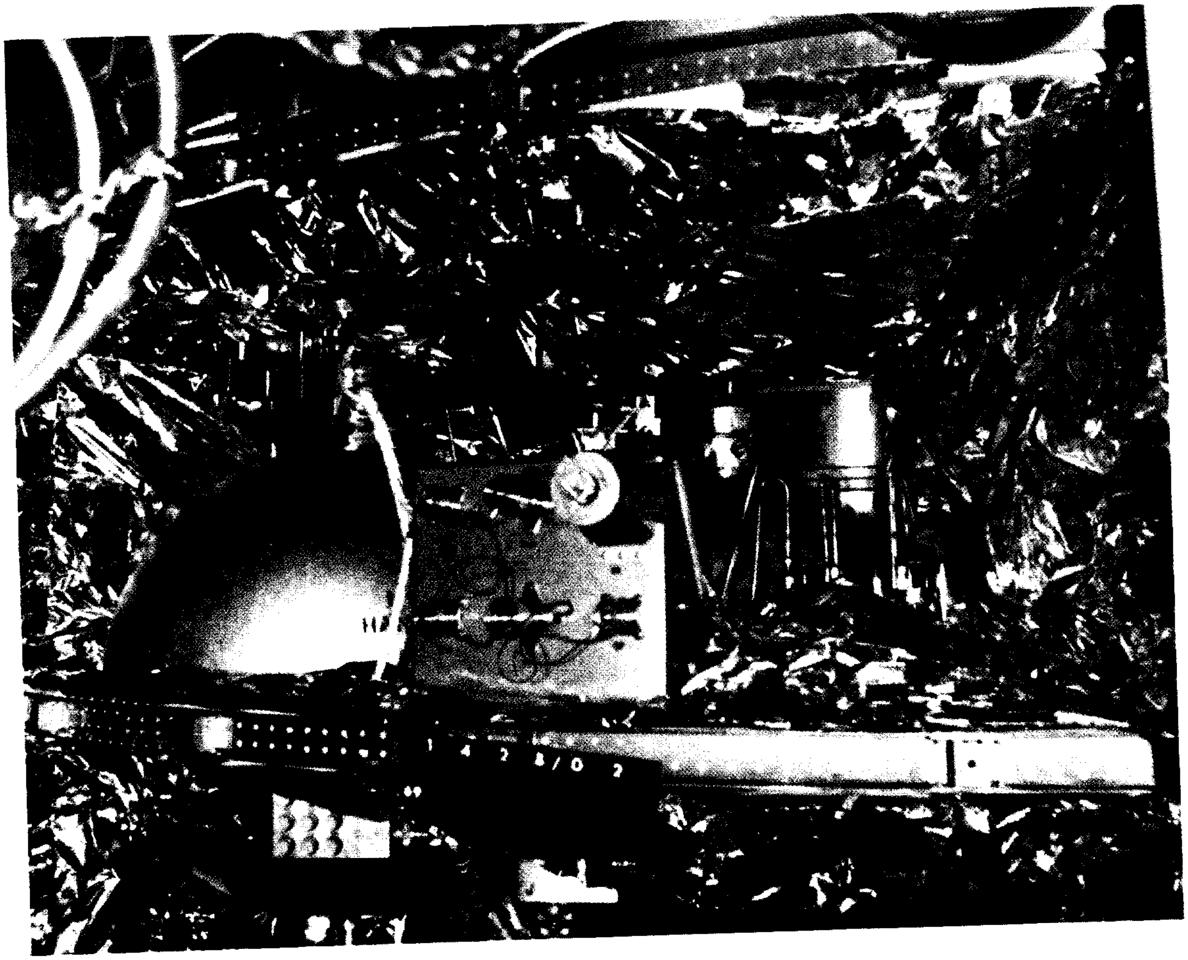


Figure 4-11.- Closeup view of oxygen tank shelf.

pressure caused by the oxygen itself. The slight temperature increases recorded at various SM locations indicate that combustion external to the tank probably took place. Further testing may shed additional light on the exact mechanism of panel ejection. The ejected panel then struck the high-gain antenna, disrupting communications from the spacecraft for the 1.8 seconds.

LOSS OF OXYGEN TANK NO. 1 INTEGRITY

Key Data

55:54:53.323	Oxygen tank no. 1 pressure drops 4 psia (from 883 psia to 879 psia).
55:54:53.555 to 55:54:55.35	Loss of telemetry data.
55:54:56	Oxygen tank no. 1 pressure reads 782 psia and drops steadily. Pressure drops over a period of 130 minutes to the point at which it was insufficient to sustain operation of fuel cell no. 2.

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

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

PART 5. APOLLO 13 RECOVERY

UNDERSTANDING THE PROBLEM

In the period immediately following the caution and warning alarm for main bus B undervoltage, and the associated "bang" reported by the crew, the cause of the difficulty and the degree of its seriousness were not apparent.

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

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

The failure of oxygen tank no. 2 and consequent removal of the bay 4 panel produced a shock which closed valves in the oxygen supply lines to fuel cells 1 and 3. These fuel cells ceased to provide power in about 3 minutes, when the supply of oxygen between the closed valves and the cells was depleted. Fuel cell 2 continued to power ac bus 1 through dc main bus A, but the failure of fuel cell 3 left dc main bus B and ac bus 2 unpowered (see fig. 4-12). The oxygen tank no. 2 temperature and quantity gages were connected to ac bus 2 at the time of the accident. Thus, these parameters could not be read once fuel cell 3 failed at 55:57:44 until power was applied to ac bus 2 from main bus A.

The crew was not alerted to closure of the oxygen feed valves to fuel cells 1 and 3 because the valve position indicators in the CM were arranged to give warning only if both the oxygen and hydrogen valves closed. The hydrogen valves remained open. The crew had not been alerted to the oxygen tank no. 2 pressure rise or to its subsequent drop because a hydrogen tank low pressure warning had blocked the cryogenic subsystem portion of the caution and warning system several minutes before the accident.

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 a television camera which had just been in use.

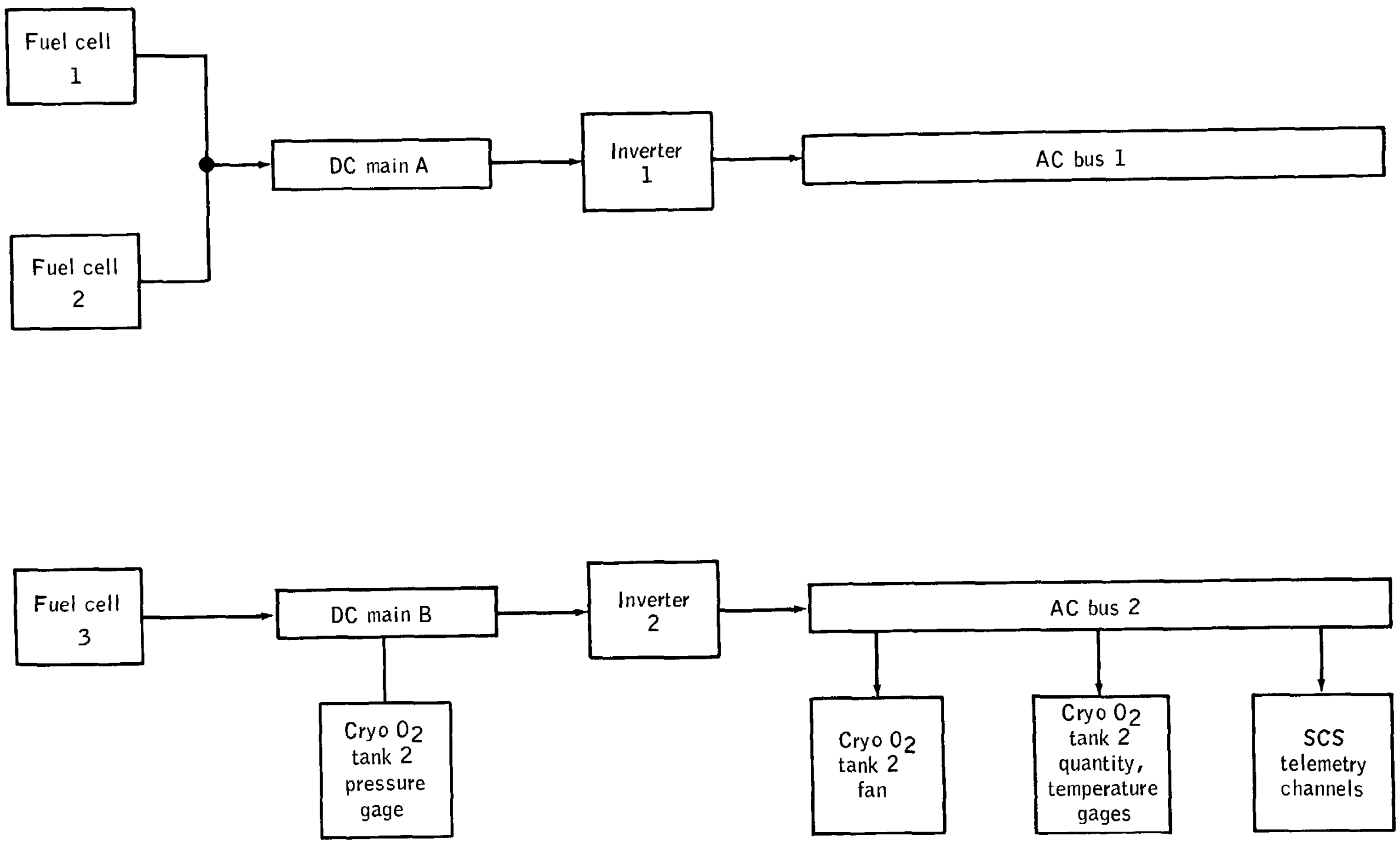


Figure 4-12.- Electrical configuration at 55:54:53 g.e.t.

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 CMP moved across to the right-hand couch where CSM voltages can be observed. He reported that voltages were "looking good" at 55:56:10. At this time, main bus B had recovered and fuel cell 3 did not fail for another 1-1/2 minutes. He also reported fluctuations in the oxygen tank no. 2 quantity, followed by a return to the off-scale high position. (See fig. 4-13 for CM panel arrangement).

When fuel cells 1 and 3 electrical output readings went to zero, the ground controllers could not be certain that the cells had not somehow been disconnected from their respective busses and were not otherwise all right. 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. Observing the rapid decay in oxygen tank no. 1 pressure, controllers asked the crew to switch power to the oxygen tank no. 2 instrumentation. When this was done, and it was realized that oxygen tank no. 2 had failed, the extreme seriousness of the situation became clear.

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

It was obvious by about 1-1/2 hours after the accident that the oxygen tank no. 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.

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

RETURN TO EARTH

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

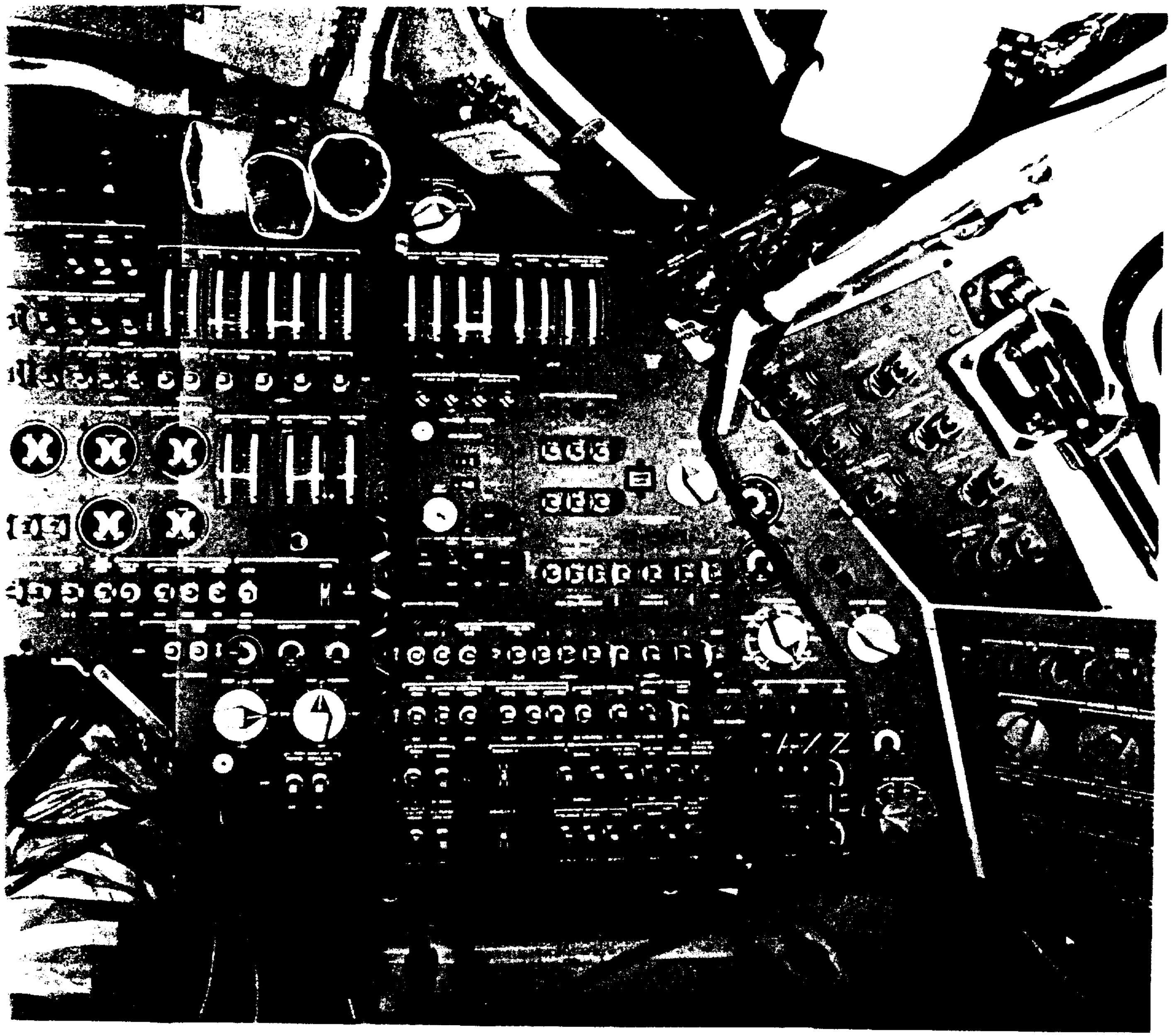
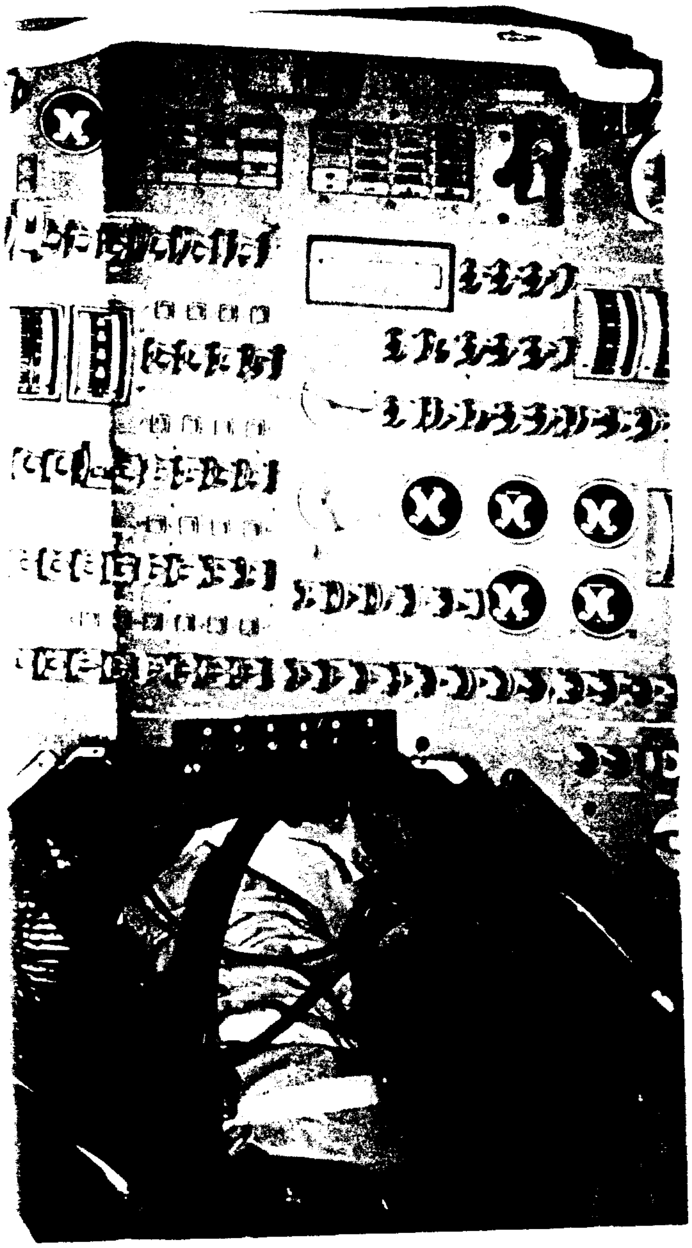
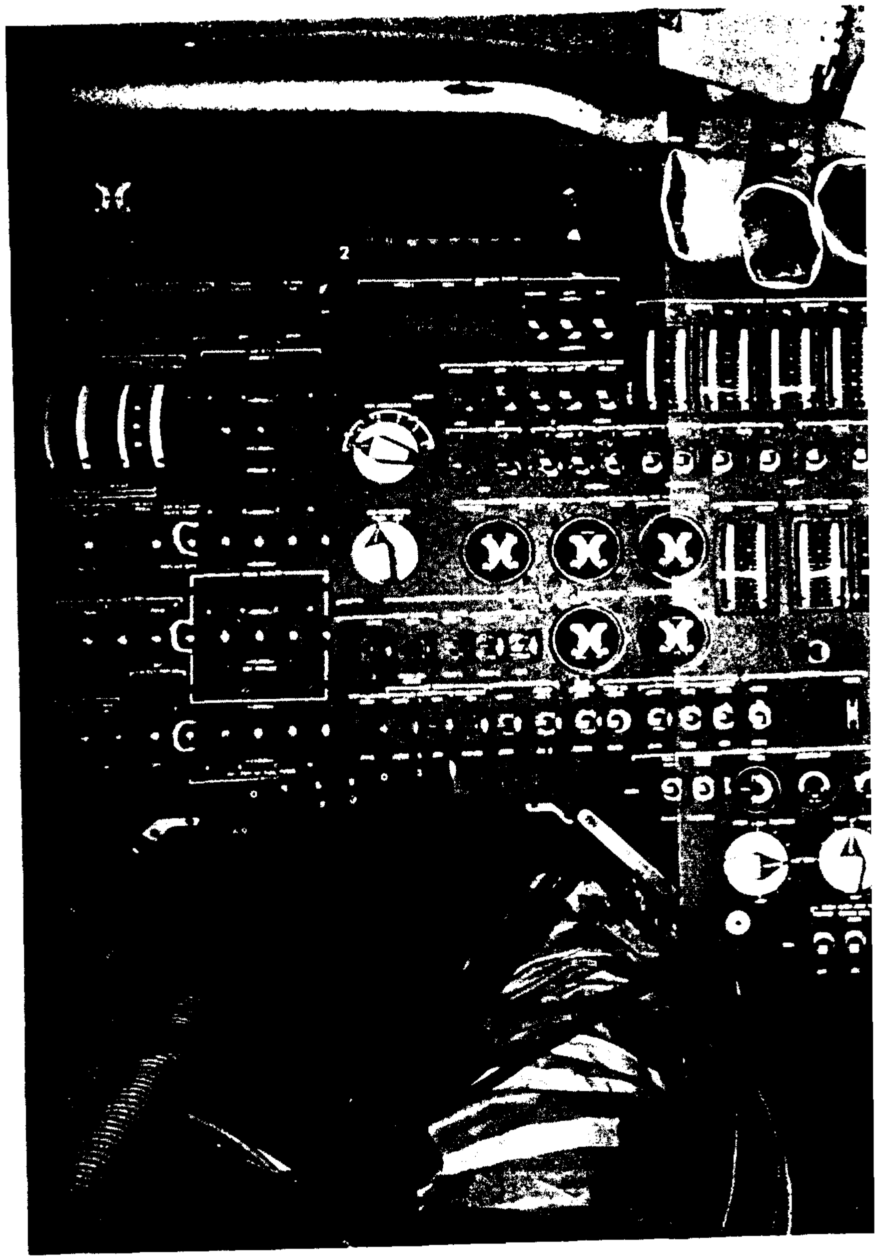
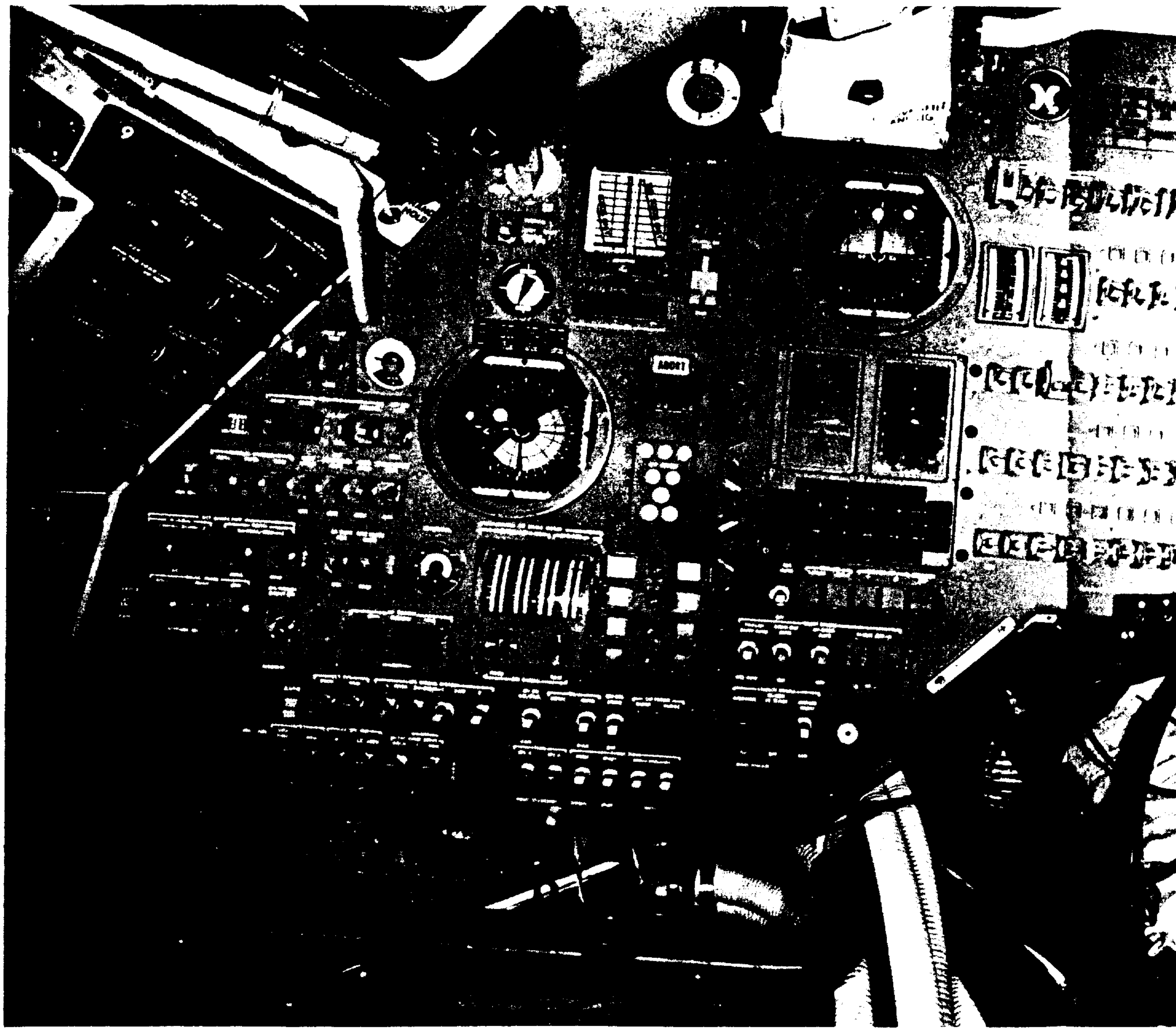


Figure 4-15.- Main display panel.






ABORT

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

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

The minimum practical return time was 133 hours g.e.t. to the Atlantic Ocean, and the maximum was 152 hours g.e.t. to the Indian Ocean. Recovery forces were deployed in the Pacific. The return path selected was for splashdown in the Pacific Ocean at 142:40 g.e.t. This required a minimum of two burns of the LM descent engine. A third burn was subsequently made to correct the normal maneuver execution variations in the first two burns. One small velocity adjustment was also made with reaction control system thrusters. All burns were satisfactory. Figures 4-14 and 4-15 depict the flight plan followed from the time of the accident to splashdown.

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 cannisters used to remove carbon dioxide from the spacecraft cabin atmosphere. These consumables, and in particular the water and LiOH cannisters, 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 at MSC developed a method which allowed the crew to use materials on board to fashion a device allowing use of the CM LiOH cannisters in the LM cabin atmosphere cleaning system (see fig. 4-16). At splashdown, many hours of each consumable remained available (see figs. 4-17 through 4-19 and table 4-III).

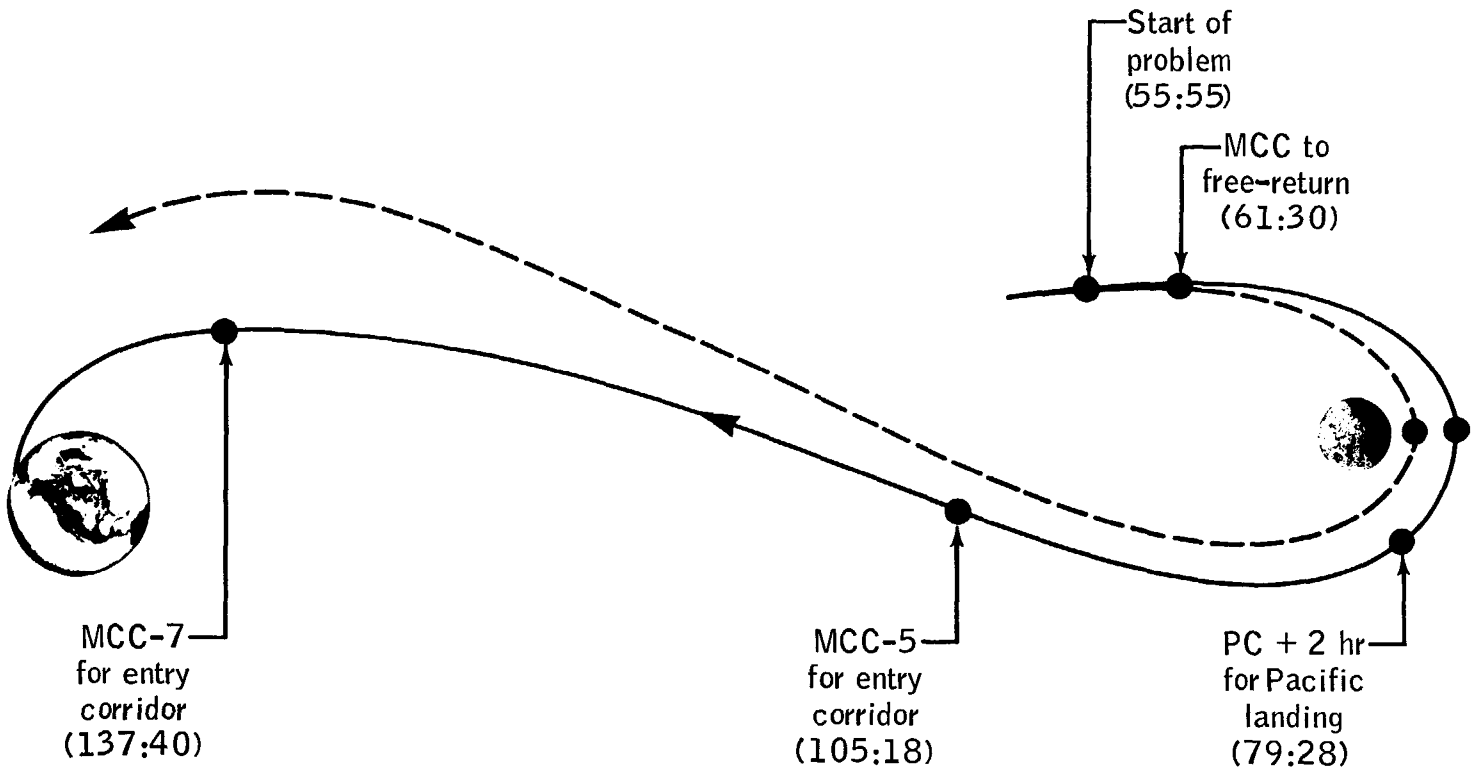


Figure 4-14.- Translunar trajectory phase.

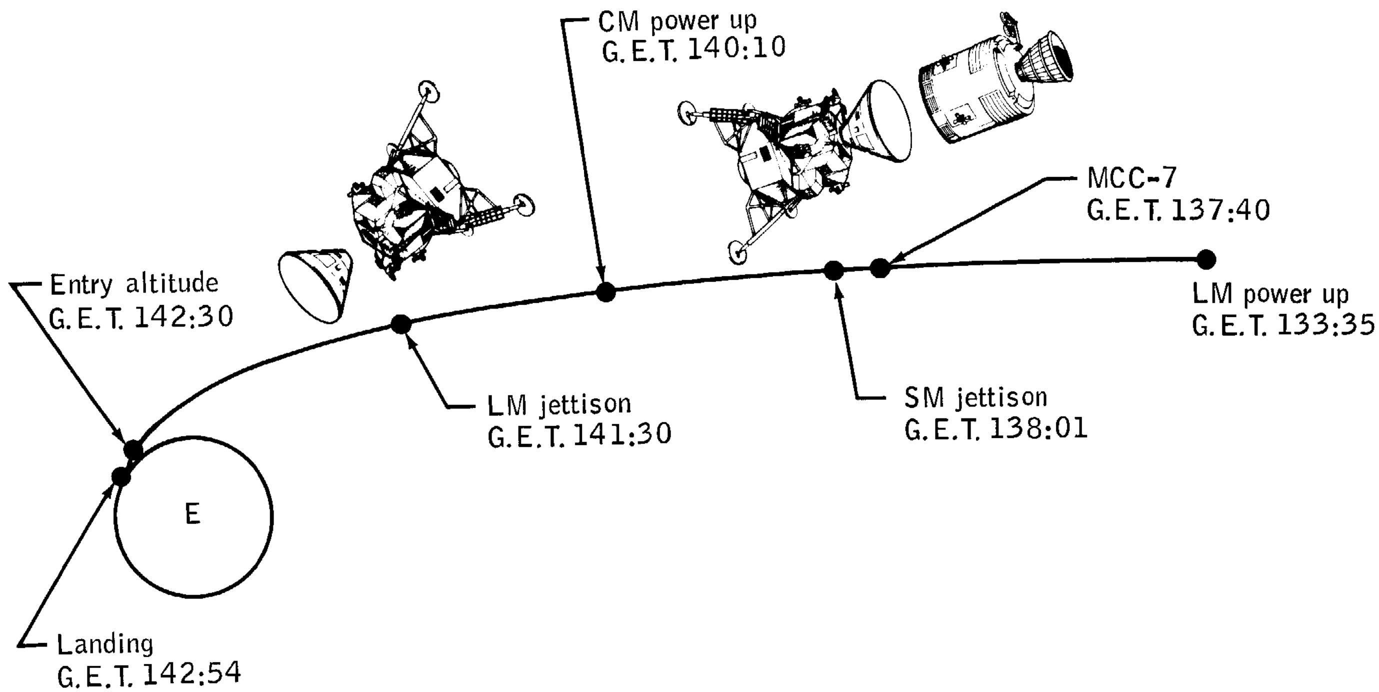


Figure 4-15.- Final trajectory phase.

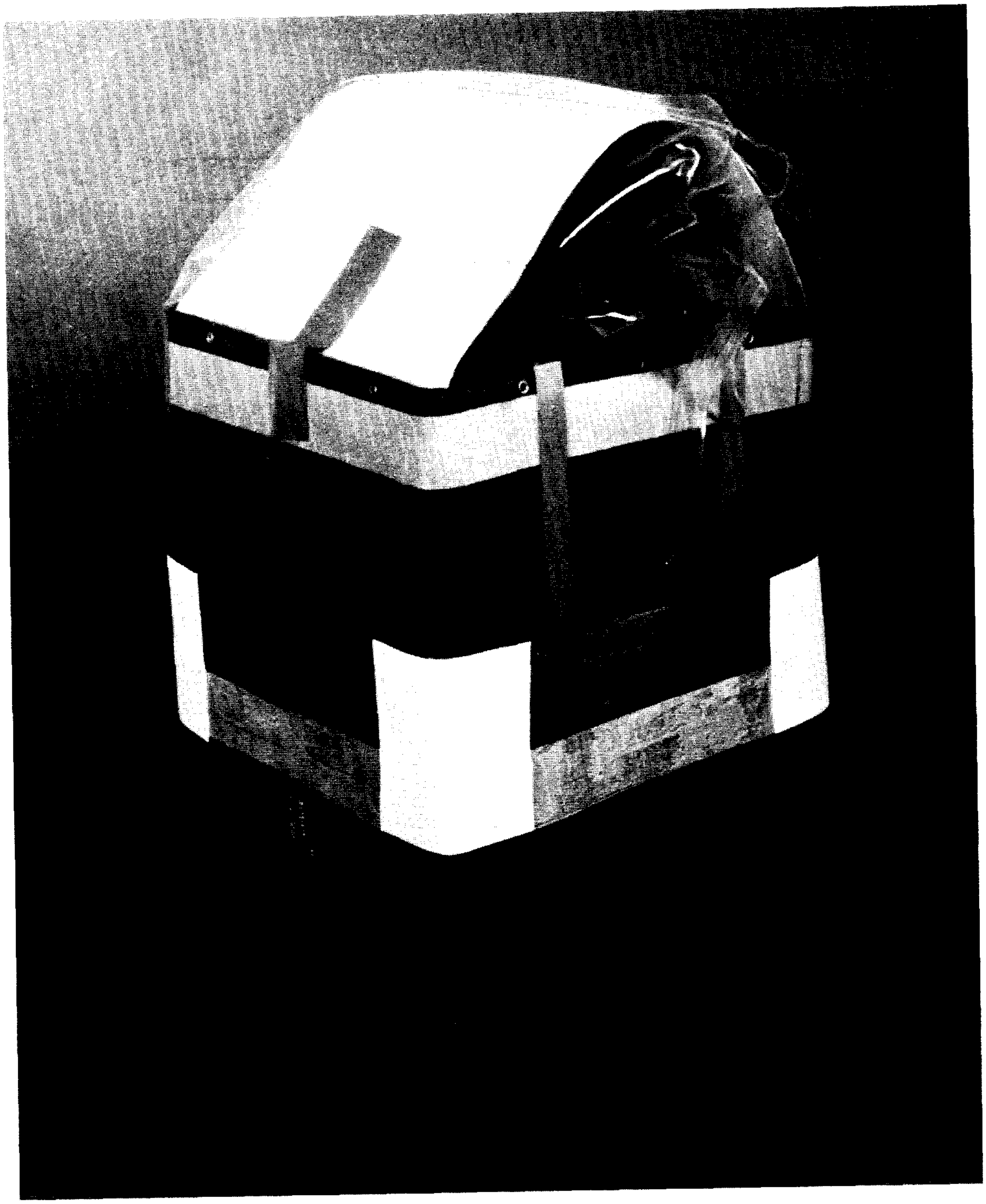


Figure 4-16.- Lithium hydroxide canister modification.

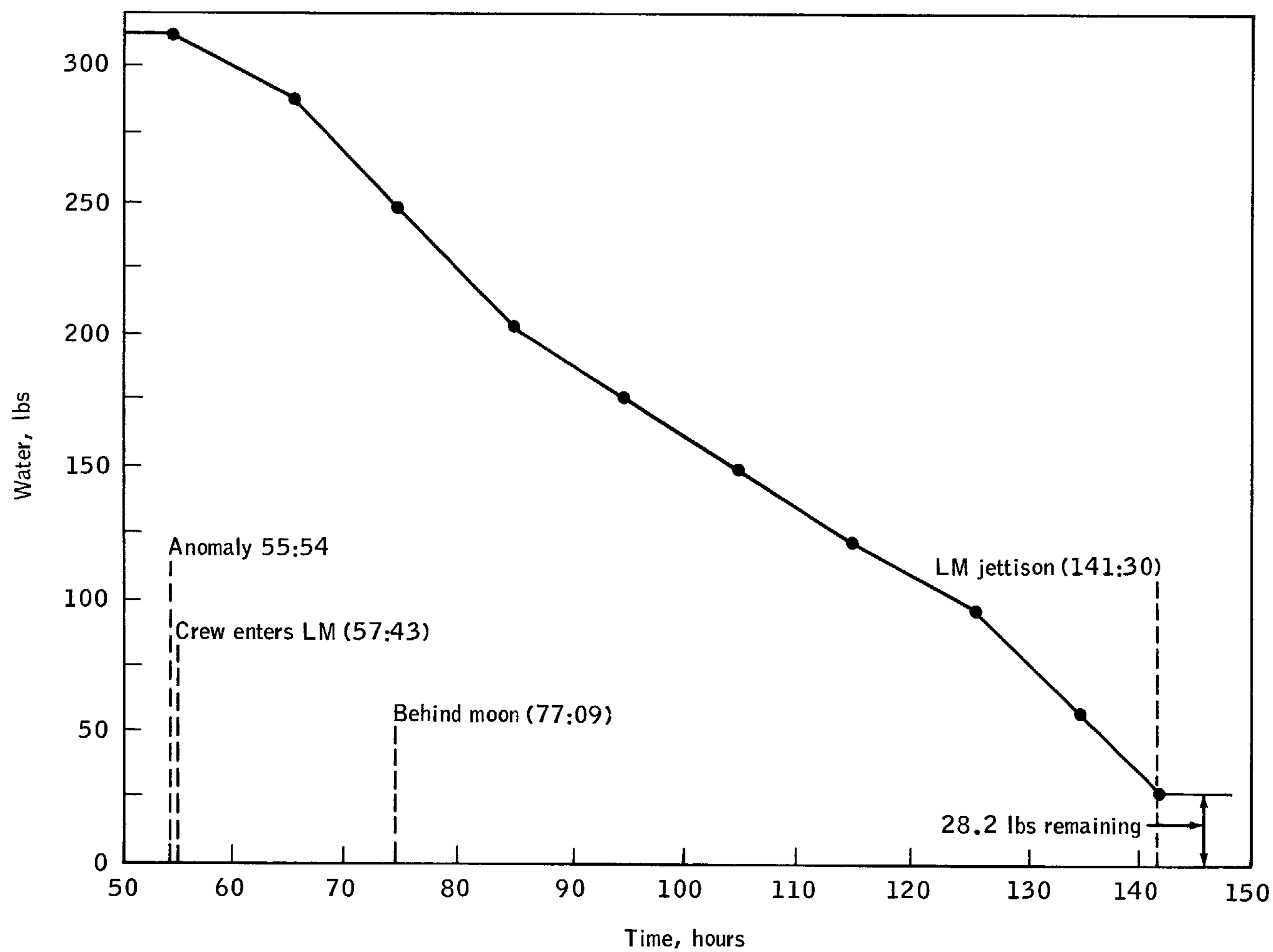


Figure 4-17.- Usable remaining water.

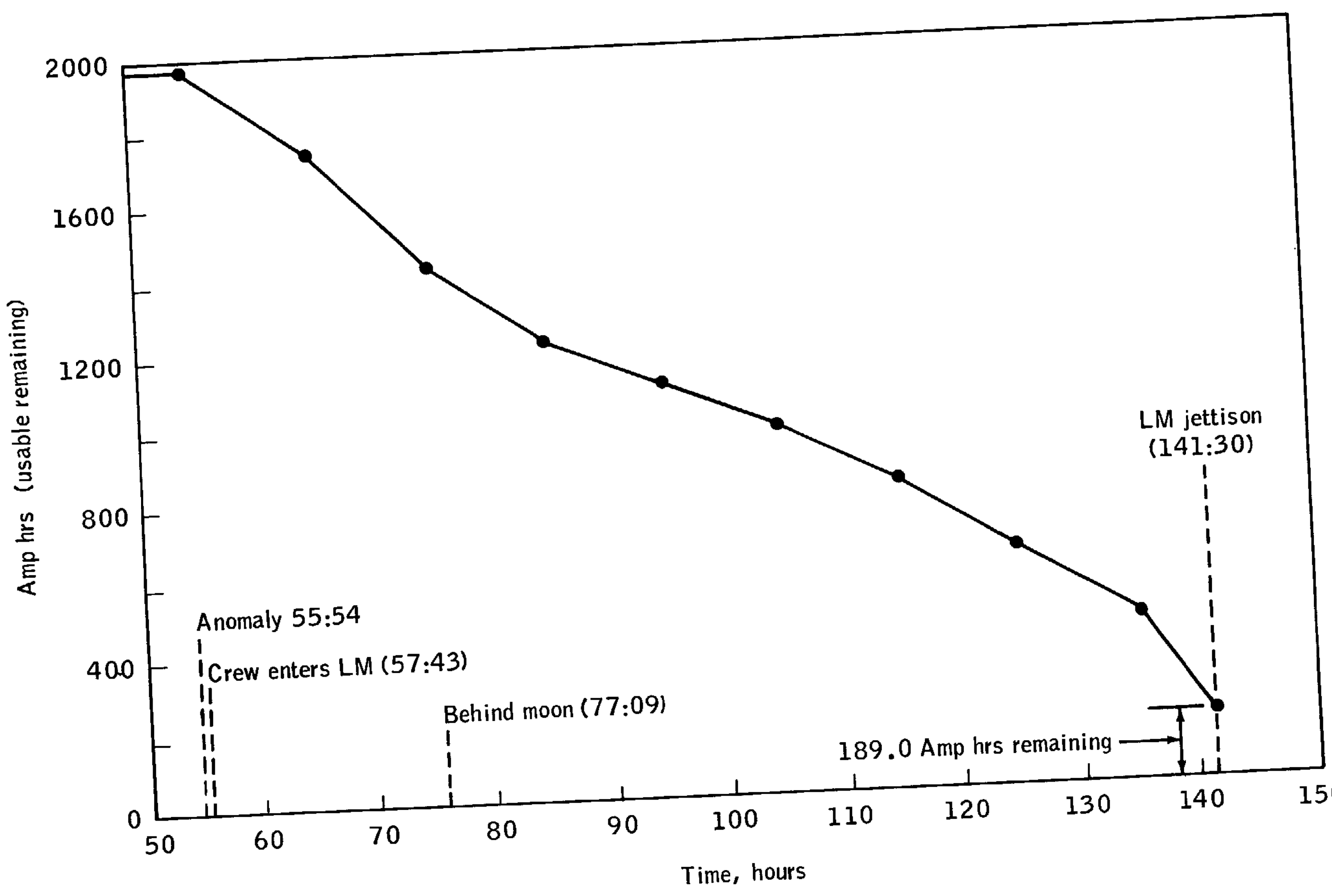


Figure 4-18.- Electrical power system consumables status.

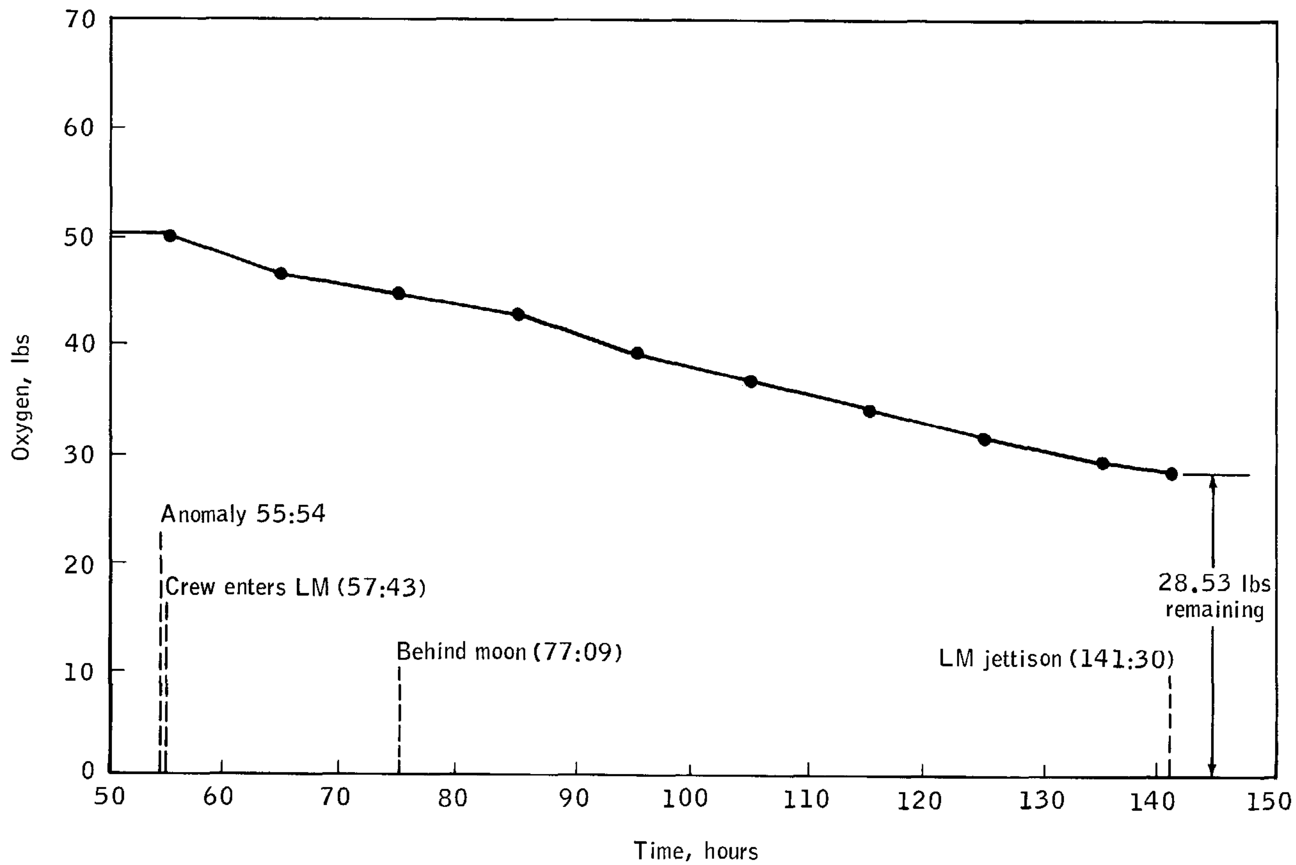


Figure 4-19.- Usable remaining oxygen.

TABLE 4-III.- CABIN ATMOSPHERE CARBON DIOXIDE REMOVAL BY LITHIUM HYDROXIDE

Required	85 hours
Available in LM	53 hours
Available in CM	182 hours

A more detailed recounting of the events during the Apollo 13 launch countdown and mission will be found in Appendix B to this report.

This page left blank intentionally.

NASA — MSC — Coml., Houston, Texas