

DISCUSSION OF SEVERAL PROBLEM AREAS DURING THE APOLLO 13 OPERATION

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Abstract

The successful recovery of the Apollo 13 flight is shown to have been the direct result of the performance of the flightcrew and the application of the talents of many different organizations focused on the mission support task through the Mission Control Center. This paper illustrates the treatment of the following phases: the time-critical activities in the hours after the oxygen tank rupture, the process of selecting a strategy for the return path to earth, the development of a technique for carbon dioxide removal, and the development and verification of the procedures used for entry.

Introduction

"Hey, we've got a problem here." With these words on April 13, 1970, the course of the Apollo 13 mission was changed, and the entire mission operations team was challenged by the most difficult and dangerous situation encountered in nearly 10 years of manned space-flight activity. The successful recovery of Apollo 13 was the direct result of (1) the performance of the vehicles, (2) the premission preparation and performance of both elements of the real-time team — the flightcrew and the flight control team in the Mission Control Center (MCC), and (3) the near-real-time application of the talents of many different organizations focused on the mission support task through the MCC. The purpose of this paper is to provide some insight into the varied types of problem-solving capabilities and resources that were used during the flight. This will be done by outlining the activities and processes in response to several of the problem areas encountered during the flight. A complete review of all of the mission support tasks is beyond the scope of this paper; but, for illustration, the following phases will be treated:

1. The real-time sequence of events and decisions in the first few hours after the oxygen tank rupture
2. The near-real-time process of selecting a mission strategy for the return to earth
3. The "off line" laboratory development of an improved technique for the removal of carbon dioxide (CO_2) from the cabin atmosphere
4. The off-line development and verification of the procedures used during the final hours of preparation for entry

Sequence of Events Following the Oxygen Tank Problem

Before discussing the sequence of events immediately following the oxygen tank rupture, it will be helpful to describe the makeup of the flight control team in the MCC. This team is composed of personnel responsible for conducting the real-time flight operation. The training of the flight control team is a lengthy process that includes participation in the vehicle design, test, and performance definition activity; participation in the mission planning cycle; participation in the establishment of crew and ground procedures for the conduct of the normal

and contingency missions; participation in a rigorous training plan which is culminated in the last 3 months by integrated simulation exercises with the astronauts in their various simulators; and the experience of actual flight operations gained throughout the three manned space-flight programs. This process results in a team of astronaut flightcrew and MCC ground controllers that is tightly knit. The team outlook is to plan and support the mission such that "the nominal mission" is the result and, if necessary, to be able to act in an emergency either with predetermined techniques or with improvisations as required.

Figure 1 shows how the flight control team is organized according to the different disciplines involved. The organization shown does not include the interface with the engineering and contractor support groups and is thus considered to be the real-time element of the mission team.

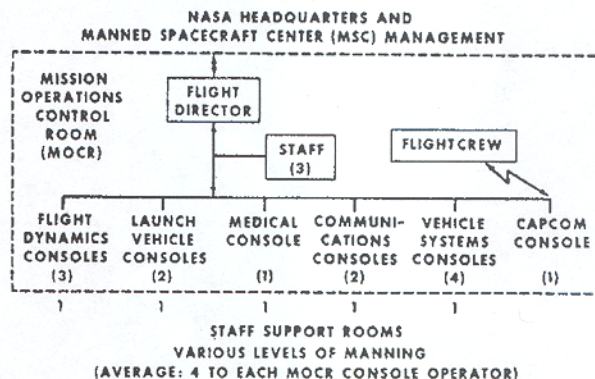


Figure 1. Organization of the Mission Control Center.

The several console operators follow definite procedures for the various phases of a nominal mission, and they identify and resolve any problems within their areas. Recommendations from the console operators are passed to the Flight Director and, on approval, are voiced to the flightcrew by the spacecraft communicator (CAPCOM). Any problem which does not lie completely within the province of one of the Mission Operations Control Room groups is discussed with the other members of the team before a disposition of the problem is made. The Apollo 13 mission situation at the time of the oxygen tank rupture is shown in figure 2.

The vehicle was on a trajectory that had been deliberately modified by the hybrid transfer mid-course maneuver to set up the desired timing and lighting for the lunar orbit and landing activities. This trajectory is called "non-free-return" because the resultant closest approach of the spacecraft to the earth with no subsequent maneuvers would be approximately 2500 nautical miles.

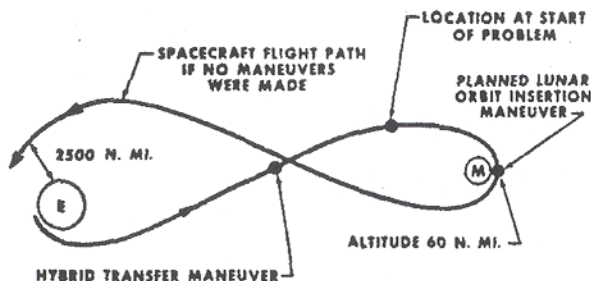


Figure 2. Apollo 13 trajectory profile.

"We've got a problem here."

At 55:55*, these words of Astronaut Jack Swigert identified the beginning of the Apollo 13 problem. Flightcrew and MCC reaction to the first report produced a growing realization over the next 30 to 60 minutes of the extent and severity of the problem. However, the initial efforts of the crew and the console operators were directed toward trying to establish that the instrumentation was valid to define the problem. Just prior to the incident, a minor problem had been encountered with the high-gain antenna (which was transmitting the telemetry), and now indications were that one-half of the electrical power distribution system had been lost. Because essentially all of the spacecraft instrumentation is provided electrically, the first step in evaluating the situation was to attempt to verify whether the telemetry indications were valid. Shortly thereafter, it was clear that main bus B was unpowered and that there was a problem with pressures in at least one fuel cell.

"... we are venting something."

This venting report confirmed a real, but still not completely defined problem; and the venting caused perturbations to the vehicle attitude rates. The dropout of one-half of the electrical distribution system also left some of the attitude-control thrusters unpowered; although at the time, it was not clear that there was not an additional problem in the reaction control system (RCS) itself. For the next three-quarters of an hour, efforts were directed along the following lines:

1. Understanding the extent of the problem
2. Establishing adequate attitude control
3. Acting only as justified to avoid making the problem worse by being hasty

(During the course of the night, and for the rest of the flight, this third admonition remained an important one.)

At the recommendation of the MCC, the following steps were taken by the astronauts in this general time period:

1. One of the three fuel cells was taken off line (56:08).
2. A powerdown to about 40 amperes was begun (56:15)**.
3. Further powerdown was begun (56:31) because of the pressure decay in the only remaining oxygen tank.

*All times are ground elapsed time (g.e.t.) from lift-off.

**This was done by using the onboard checklist.

4. Attitude-control switching was established to prevent losing the reference of the three-gimbal platform.

With the situation reasonably defined and the vehicle stable, the following steps were then taken in an attempt to save as much capability in the command and service module (CSM) as possible:

1. Fuel cell 3 was shut down to prevent the leakage of oxygen through a damaged cell (57:06).
2. Fuel cell 1 was shut down for the same reason (57:14).

"... and we're starting to think about the LM lifeboat."

With only one fuel cell (number 2) supplying power and with a continuing decay in the only remaining oxygen tank in the service module (SM), two astronauts were already on their way into the lunar module (LM) at the time the MCC suggested it. All team members knew that the mission had become a "lifeboat" operation. This capability for using the LM systems had been recognized at the beginning of the Apollo Program; and many discussions, plans, and procedures had been prepared to that end. The task, at this juncture, was to apply that knowledge to the precise situation at hand in order to use the LM for up to 90 more hours of flight.

Initial powerup of the LM was accomplished by the astronauts according to the activation checklist they would have used in lunar orbit; that is, the LM systems were activated in the following sequence: power system, life support system, communications system, control system, and guidance system.

"... I see a lot of particles out there."

This report convinced the team of the need to transfer the known inertial reference in the CSM to the LM because future alignments in the LM might be very difficult. Lunar module alignments are obtained by sighting known stars through an optical telescope. Before the flight, it was known that CSM reflections could make star constellation identification difficult; and now all the starlike particles venting from the SM completely precluded any alignment sightings — at least for a time. The mission situation required a propulsive burn to return to earth and, therefore, a good alignment. On the CSM side, the last fuel cell was maintaining bus voltage at an adequate level for the CSM guidance system. As the oxygen supply pressure decreased, the fuel cell performance and the bus voltage followed. At 58:04, the MCC recommended putting one of the three entry batteries on line to help maintain bus voltage. This was done as late as possible because the three entry batteries are relatively small in total power (120 ampere-hours), and it was not clear that they could later be recharged from LM power. By 58:40, the procedural manipulations for alignment transfer to the LM (involving the LM crew, the CSM crew, and the MCC) had been performed and the LM had a good alignment. The CSM was then completely powered down. The SM components and consumables were not used for the remainder of the mission, and the reentry capability of the command module was still adequate.

During the next hour, MCC attention was focused on developing a mission plan to match the available consumables on board the LM. Essentially, three immediate options were available:

1. Perform a midcourse maneuver to correct the path back to earth and then decide how to save consumables.
2. Power down immediately to conserve LM consumables and determine later how to align again for a burn.
3. Do a direct-return abort burn without going around the moon.

The first option was selected, primarily to seize the opportunity of trajectory correction while the guidance system was operating and to concentrate later on conservation of LM provisions — power, water, and oxygen. The third option could not have been performed with the LM engine because of the very large velocity change (ΔV , on the order of 6000 fps), and to obtain that ΔV with the service propulsion system (SPS) engine would have required jettisoning the LM.

This midcourse correction maneuver was performed at approximately 61:30 by using an onboard checklist, which was prepared and carried in case of an abort at the time of lunar orbit insertion. As the crew called it out, this checklist was modified to avoid any unnecessary power users. A period of securing the systems and of further detailing the plan for return to earth followed the midcourse correction. By approximately 63:20, a mission plan was established with consumables budgeted for a burn after rounding the moon and for two midcourse corrections on the return leg. This plan is shown in figure 3, and the rest of the flight activity came remarkably close to the predictions made at this point in the flight.

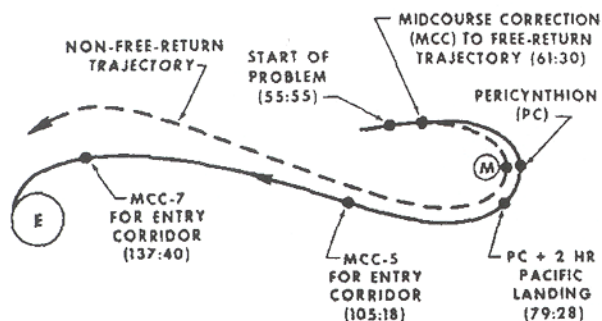


Figure 3. Apollo 13 midcourse correction maneuvers.

Additional primary decisions still had to be made, and many more secondary problems needed attention. Furthermore, careful attention had to be continually focused on conserving the LM consumables. However, this section of the paper outlines the major sequences which the operations team defined and dealt with during the first few hours after the problem. The identification of problems, the assessment of options, the recommended courses of actions — all were essentially handled within the flight control team described at the beginning of this section. The preparation, training, and use of premission planning permitted the team to derive a reasonable solution to the problem at hand.

Selection of Plan for Transearth Return Leg

For approximately the next 15 hours, starting at about 64 hours g.e.t., major activities consisted of the following:

1. Establishing a reasonable passive thermal control mode to assure a uniform thermal exposure
2. Conserving LM consumables as much as practical and reasonable
3. Establishing a sleep-work cycle with the flightcrew and tending to the systems management problems
4. Deciding the kind of maneuver required at 2 hours after pericynthion (PC + 2), or at 79:30 hours, to accelerate the return to earth

This part of the paper describes the activity associated with item 4 as representative of the near-real-time decisionmaking process and the additional resources and judgments that were sought, considered, and used. From the first manned program and as the programs became increasingly complex, the MCC configuration and organization has recognized the strong and valuable judgments which might only be available from the engineering organizations or which might be used in conjunction with the real-time team judgment for an optimum solution. Therefore, definite steps were taken to marshal these organizations. Figure 4 shows the role of the engineering team in support of the real-time team (fig. 1).

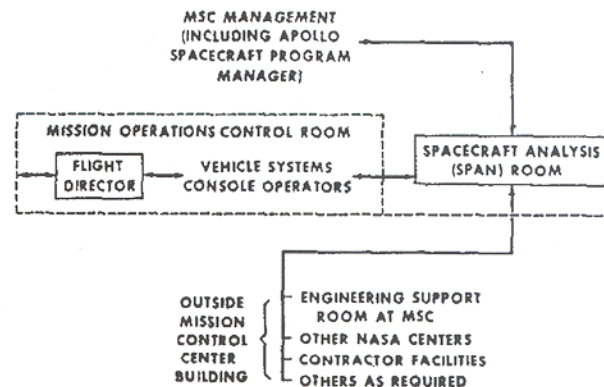


Figure 4. Engineering support to the Mission Control Center.

The Spacecraft Analysis (SPAN) room is manned by representatives of the flight control team, the NASA Manned Spacecraft Center (MSC), the Apollo Spacecraft Program Office, and the prime contractors. The SPAN group operates as a point of contact and control on a wide range of problems, such as the following:

1. Obtaining data, which may not appear in the documentation system, for operational use
2. Providing recommendations to the vehicle systems flight controllers on specific system problems
3. Providing recommendations and judgment to the Apollo Spacecraft Program Manager on any selected subject
4. Organizing any external test, analysis, or consultation activity at any of the Government or contractor facilities

The primary role of the SPAN group, then, is to deal with problems which have some leadtime and lend themselves to additional considerations or re-search. For example, this group could not be involved in a launch-abort decision that would be made in seconds or minutes; but it would have a valuable input to a situation in which a decision has to be made in a matter of hours. Consideration of the options associated with the type of propulsive burn to do after rounding the moon at 79:30 hours is an excellent example of the latter.

By approximately 64 hours g.e.t., the possible options were outlined and all elements of the mission team began to consider them in earnest. The options are shown in table 1.

TABLE 1. SUMMARY OF RETURN-TO-EARTH OPTIONS

ΔV magnitude burn at 79:30, fps	Engine	Vehicle configuration	Landing location	Ground elapsed, time of landing, hr
1. None	None	CSM/LM	Indian Ocean	155
2. ≈ 850	LM descent	CSM/LM	Mid-Pacific	143
3. ≈ 2000	LM descent	CSM/LM	South Atlantic	133
4. ≈ 1800	LM descent	Jettison SM	Mid-Pacific	118
5. ≈ 1800	SPS	CSM/LM	Mid-Pacific	118

Several of the options were eliminated relatively quickly. Option 1 was discarded because there were no known reasons for not performing a burn to accelerate the return, and the Indian Ocean recovery posture would be far from ideal. Option 5 was considered a "last ditch" measure because it entailed using the SPS engine of the CSM and, although all telemetry had looked normal on the tanks when the CSM was powered down, there was enough uncertainty about the structural status of the SM to eliminate it.

Consideration of options 2, 3, and 4, then, revolved around the overall prudence of each course of action weighed against the various landing times available. Option 2 was well within the mission capability and offered an excellent recovery posture. While saving about 9 hours of time over option 2, option 3 had two disadvantages:

1. A poorer recovery posture in the Atlantic would result.
2. The burn required would essentially exhaust the descent propellant supply, leaving no margin for midcourse corrections; and, with the uncertainty of being able to do a realignment on the platform, a subsequent midcourse correction was likely to be needed.

Option 4, which had the quickest return time and was to the primary recovery area, was attractive but also had two drawbacks:

1. By jettisoning the approximately 50 000 pounds of SM weight, the effective ΔV of the burn would be much greater. However, the heat shield and the RCS for entry would be exposed to the cold thermal environment for about 40 hours and would thereby introduce the question of entry integrity.

2. This option also would have required a near depletion of the descent propellants.

The options and ramifications were defined, studied, and considered by all the appropriate elements of the operational and engineering teams. (The heat-shield thermal environment problem was assessed primarily by the engineering team.) By 69:30 hours, a conference was called where the alternatives and a recommendation were presented to the NASA and contractor management personnel. This conference resulted in acceptance of the team recommendation to return to the mid-Pacific at 143 hours.

The resultant conclusion had the strength of the detailed considerations of not only the fairly obvious mission options, but also the nonstandard use of the descent engine with its ablative throat in this burn sequence, an assessment of the risks of exposing the heat shield by jettisoning the SM, the recovery posture at various locations, and other factors. The organization of the various team elements gave assurance that all of the pertinent considerations were available and that the best judgment on diverse subjects was available. This assurance permitted an early, confident choice of the burn for accelerating the return to earth.

Development of Improved Carbon Dioxide Removal Technique

Shortly after the oxygen tank rupture, when the LM consumables were being evaluated, it was clear that a method for cleansing the cabin air of CO_2 had to be selected. The capability of the two primary lithium hydroxide (LiOH) cartridges in the LM environmental control system (ECS) augmented by three secondary units from the backpack would be exhausted in approximately 53 hours, or at 110 hours g.e.t. Also, the LM and command module (CM) cartridges were not interchangeable (CM — square, LM — cylindrical) because of early design considerations in each vehicle. At this early time, planning for the end of mission varied from 133 hours to 155 hours. Because the resolution of this problem was not time critical, the engineering support organization (coordinated from the SPAN room discussed earlier) began to consider the various possibilities for the best CO_2 removal technique while the real-time team concentrated on the ongoing flight activities.

Three general approaches were considered:

1. Attach the LM and CM hoses together in such a fashion that the LM suit fans would force the oxygen through the hoses, through the cartridges installed in the CM, and back to the LM area.

2. Operate the CM suit fans through the ship-to-ship umbilical with LM power, and use the CM loop to remove CO_2 .

3. Use the CM cartridges in some fashion in the LM ECS loop.
- Figure 5 shows the physical layout.

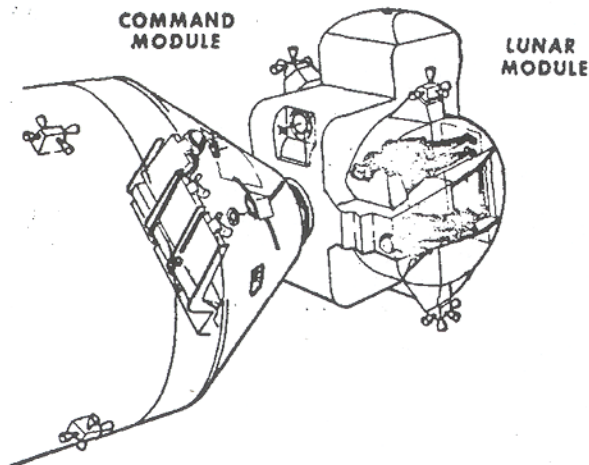


Figure 5. Tunnel geometry of the docked Apollo vehicles.

Early discussions quickly eliminated the first alternative because of the uncertainty over the size of the pressure drop which would occur with the long length of hose. Uncertainty as to the performance of the water separators in this loop, which are ram-driven by the oxygen flow, was also a factor. The second alternative, which had been discussed the most before the mission, remained a possibility if an improved method could not be found. However, the electrical configuration required to achieve it was an inefficient one, because a CM inverter would have to be powered to provide alternating current for the suit fan. The power cost for a CM suit fan is 1.5 times higher than for an LM fan. With LM power limited as it was, this alternative was not attractive.

The attention of the engineering team was concentrated on the third option. The team was composed of personnel from the MSC Crew Systems Division, which has an engineering responsibility in the entire life support area; from the Astronaut Office and the Flight Crew Support Division at MSC; from North American Rockwell (NR); and many contractor personnel from Taft Broadcasting and Brown and Root-Worthrop who conducted the testing and chamber facilities work.

In the first few hours (around 60 g.e.t.), consideration was given to taping a CM LiOH cartridge to the LM outlet hose, with a plenum chamber made of a transparent stowage bag to direct the flow from the hose into and through the cartridge. While this configuration development work was in progress, the 11-foot vacuum chamber at MSC was prepared for a test of the final configuration. Phone requests to the NR plant at Downey, California, and to the NASA John F. Kennedy Space Center (KSC) quickly resulted in the location of several CM LiOH cartridges, which were brought to Houston by plane within a matter of hours. Figure 6 shows the configuration that had been selected for test by approximately 65 hours into the flight.

It was decided that it would be preferable to attach the CM cartridge to the inlet ECS hose so that the air would be at a higher temperature and humidity, which improved the efficiency of the chemical in the absorber cartridge. This configuration also avoided a constriction on the outlet side of the loop; thus, flow distribution would be improved.

With the absorber on the inlet side of the loop, the stowage bag that was taped around the hose and the cartridge tended to collapse because of the suction. Figure 6 shows an extravehicular activity cue card cut to shape as an arch and placed over the inlet side of the canister to prevent this collapse. While the configuration was being established, detailed instructions for using onboard equipment were written for eventual astronaut use. One member of the Astronaut Office observed the fabrication of the second test absorber and inspected the installation in the chamber. By approximately 79 hours g.e.t., the chamber test to demonstrate the CO₂ cleansing capability was begun. Final procedures were then prepared and read to the flightcrew.

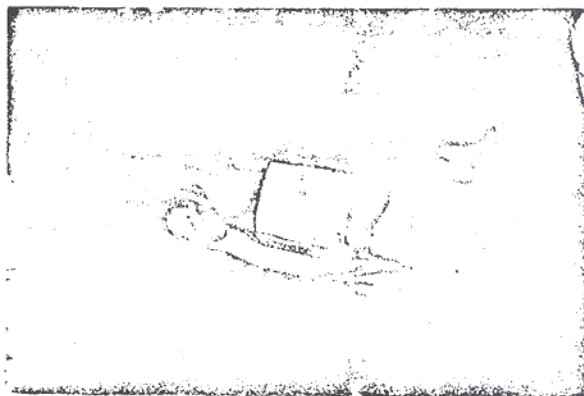


Figure 6. Ground-test configuration of lithium hydroxide canister.

Figure 7 is a photograph of the flight configuration, which was essentially identical to the ground-test article. Further analysis showed that two additional canisters would be required for the mission duration. A review of the chamber test data indicated that another cartridge could simply be taped to the first one, in series. A further chamber test verified this configuration, and this technique was used with a final reading of below 1 mm Hg at CM ingress near the end of the mission.

This episode is a good example of the type of resource and capability for problem solving which is available and can be utilized. The situation was such that a definite improvement in the proposed procedures could be derived, considered, and verified by test before commitment to flight use.

Development of Entry Procedures

From the start of the difficulties with the CSM at approximately 56 hours, the need for a considerable change to the time-line activities for the entry preparations was apparent. This section will briefly outline the sequence of development and verification of the flightcrew procedures required to perform this all-important phase. In considering this portion of the flight, it is well to remember that once the trajectory was established by the maneuver at 79:30, the time of entry into the atmosphere was fixed. All entry preparation operations had to be performed between that inflexible deadline, yet had to be started as late as practical

because of the very limited energy (about 120 ampere-hours) available in the three entry batteries in the CM.

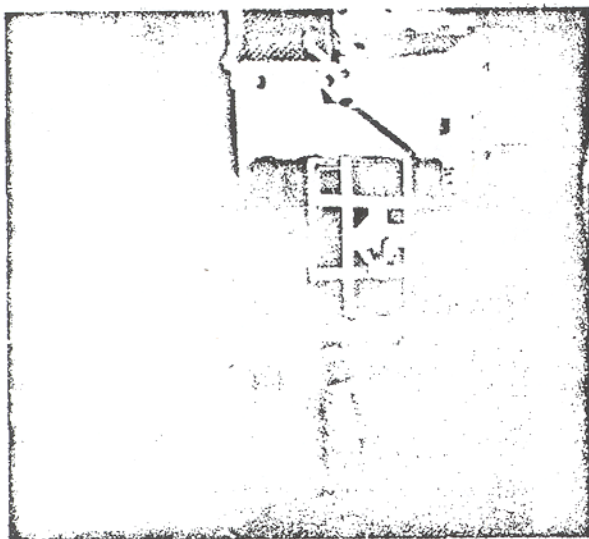


Figure 7. Apollo 13 flight configuration: command module lithium hydroxide canister installed in the lunar module.

It is helpful to consider the normal entry time line (times measured from entry interface (EI) at 400 000 feet) which follows:

EI - 3 hours	Final midcourse correction (MCC-7)
EI - 15 minutes	CM/SM separation
EI + 14 minutes	Splashdown
Nominal margin in batteries	90 ampere-hours at landing

In the Apollo 13 case, the primary differences were as follows:

1. The final midcourse correction (MCC-7) was to be performed by using the LM systems.
2. Lunar module closeout and jettison had to be scheduled.
3. The CM had to be powered up from a completely unpowered condition.
4. The CM guidance system has to be aligned.
5. The only power source in the CM was the entry batteries (no fuel cells).

Premission planning had established a gross timeline sequence for MCC-7 and for LM and SM jettison, primarily from a "trajectory recontact" point of view. This planning was used as a point of departure for the optimization of the Apollo 13 considerations, primarily to minimize CM power requirements. After the maneuver at 79:30, a team of personnel was established to finalize these procedures, with emphasis on using premission planning and existing onboard checklists where possible. The same people who were normally involved in this planning area prior to the flight were used — that is, personnel from the Mission Planning and Analysis Division, from the Flight Crew Support Division (which publishes and controls the checklists), from the Astronaut Office, and members of the flight control team. This planning was started with an "all switches off" configuration, which had been voiced to the astronauts and verified by one of the pilots in the CM.

The first order of business was to establish a nominal time line and the CM switch sequence required to prepare the vehicle for entry. This activity began in conference approximately 48 hours prior to entry; and, by approximately 35 hours prior to entry, a run had been conducted in the CSM simulator at MSC to verify the switch settings and functions scheduled. It should be noted that, wherever possible throughout the mission, any changes made to procedures were verified on ground simulators. The facilities used for verification were the simulators at MSC, the simulators at KSC, and various part-task simulators at a number of the contractor plants. Even though every item could not be checked out in a completely realistic manner, these simulator runs added a great deal of assurance that the modified procedures were correct and workable.

After this first verification run through the CSM simulator, another working session further improved the checklists with emphasis on giving the crew more time in the CM preparations. The product of this working session was also cycled through the simulator verification route by the astronaut team. Again, these runs (primarily in the CSM simulator) gave assurance that the proposed sequences were correct and adequate. The sequence, as modified from the earlier described normal CSM solo entry, was as follows:

EI - 7 hours	LM power up for MCC-7
EI - 5 hours	MCC-7
EI - 4:30 hours	SM jettison
EI - 2:30 hours	CM power up
EI - 1 hour	LM jettison

The detailed checklist, including each individual switch position and procedure, was voiced to the crew at approximately 15 hours prior to entry in order to give the astronauts time to review, to digest, and to consider any modifications that might occur to them. The continuity of preflight planning personnel and the participation of the Apollo 13 backup crew and other astronaut teams were vital factors in assuring that the flightcrew would find these to be workable and correct procedures.

On the morning of entry, several changes were made to the procedures. These were primarily welcome changes, afforded by the fact that the LM power margin now permitted greater use of power by the CM through the umbilical from the LM. This allowed a further spreading out of some of the early CM activities (e.g., guidance system powerup). At landing, the entry battery margin was about 25 ampere-hours. Figure 8 describes the actual entry sequence.

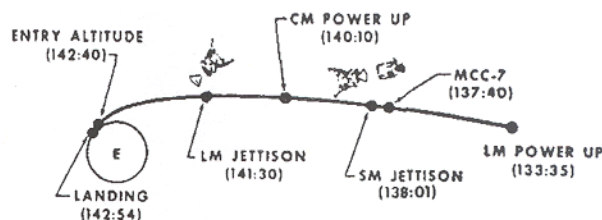


Figure 8. Apollo 13 entry sequence of events.

Summary

This paper has outlined the processing and the solving of four different problem areas during the Apollo 13 flight. This approach has been oriented to attempt to give some insight into the various types of capabilities and resources which can be called upon during manned space flights. These

capabilities range from time-critical sequences by a fairly small team of flight controllers, and from analyses of options and consultation with program office and engineering organizations, to completely "off line" activities, such as laboratory verification of a new CO₂ removal configuration or development and verification of new flight procedures.

