NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

mission report

APOLLO 13

A SUCCESSFUL FAILURE

As Captain James Lovell, commander of the ill-starred Apollo 13 mission described it: "Fred (Haise, the lunar module -- LM -- pilot) was still in the lunar module. Jack (Swigert, pilot of the command module -- CM) was back in the command module in the left-hand seat, and I was half-way in between, in the lower equipment bay, wrestling with TV wires and a camera -- watching Fred come on down -- when all three of us heard a rather large bang -- just one bang. Now, before that ... Fred had actuated a valve which normally gives us that same sound. Since he didn't tell us about it, we all rather jumped up and were sort of worried about it; but it was his joke and we all thought it was a lot of fun at the time. So when this bang came, we really didn't get concerned right away ... but then I looked up at Fred ... and Fred had that expression like it wasn't his fault. We suddenly realized that something else had occurred ... but exactly what we didn't know."

Haise said he felt a vibration. Up in the CM Swigert reported, "... about two seconds elapsed when I had a master alarm and a main Bus 'B' undervolt (i.e., a loss of power) ... I transmitted to Houston that we had a problem."

Lovell continued: "I guess it's kind of interesting to know what the feelings of the crew are when something like this happens. When you first hear this explosion or bang ... you don't know what it is. We've had similar sounds in the spacecraft before that were for nothing. ... and then I looked out the window and saw this venting ... my concern was increasing all the time. It went from 'I wonder what this is going to do to the landing' to 'I wonder if we can get back home again' ... and when I looked up and saw both oxygen pressures ... one actually at zero and the other one going down ... it dawned on me that we were in serious trouble."

Lovell's assessment was accurate -- and, if anything, conservative. The bang he heard was the explosion of liquid oxygen tank (LOX) #2 in the service module. This tank provided the vital oxygen on which fuel cells #1 and #2 relied to generate the electric power to operate the systems in the command and service modules (CSM). The fuel cells were Apollo's primary power source. There was a backup battery-powered electric supply in the CSM with a lifetime of as much as ten hours -- and under ideal circumstances, Apollo 13, at the time of the explosion, was 87 hours from home.

MAY 20, 1970

Emergency in Space

The nature and dimensions of the emergency were starkly evident to the crew, and to Mission Control. Lovell and his crew mates were more than 200,000 nautical miles (nm) out in space with a dead SM, including its main propulsion engine. The explosion had wiped out the CSM's main supply of life-sustaining oxygen and power. The CM's 10 hours of operating life had to be reserved for the approach to the earth's atmosphere because, of the three components, the CM alone had the heat shield which would allow the crew to re-enter the atmosphere and splashdown safely.

The crew's salvation rested with the LM, the oddly-shaped spacecraft designed to drop out of lunar orbit after separating from the CSM, land two astronauts gently on the moon, sustain them while there and then carry them back to a rendezvous with the mother ship in lunar orbit. But now that the mother ship was a partial wreck, drifting in space, the LM became the lifeboat.

Mission Control aborted the mission and ordered the crew into the LM.

What followed was an epic struggle that pitted men -- the skilled and highly-trained professionals in the spacecraft working in close coordination with the ground-based team at Mission Control -- against the hostile environment of space. For 86 hours and 57 minutes -- more than three tension-packed days -- the struggle continued with final victory coming only when Odyssey's trio of orange-striped parachutes dropped the spacecraft into the gently rolling Pacific Ocean, 3-1/2 nm from the prime recovery ship -- the carrier Iwo Jima.

World Wide Concern

The drama of the crisis attracted the sympathetic attention of people around the world. Prayers were offered in churches of all denominations and at the Wailing Wall in Jerusalem. Crowds gathered in front of television screens in many nations to follow the flight. Twelve nations, including the Soviet Union, volunteered assistance in recovery.

Minor Problems

In retrospect, those given to looking for omens that presage disaster could have found a few in the early stages of the Apollo 13 flight. Before launch, a helium tank showed a higher pressure than expected, and was watched with some concern. A member of the prime crew, Lt. Commander Thomas K. Mattingly, had been exposed to German measles a few days before launch, and medical tests revealed that he lacked the anti-bodies that would make him immune. Swigert, of the backup crew, replaced him at the 11th hour. A liquid oxygen vent valve refused to close on the first command, and had to be re-cycled several times before it would shut.

In flight, the center engine of the S-II stage cut off more than two minutes early and, to compensate, the remaining four engines were burned 34 seconds longer than planned. As a further remedy, the engine of the Saturn V's third stage was fired for an extra 9 seconds in its orbital insertion burn. The end-product was a trivial discrepancy, a velocity 1.2 feet per second greater than predicted.

In actuality, as auguries, these were insignificant. They were typical of the minor anomalies that launch and flight crews expect to encounter, and for which they have ready remedies.

The early events of the flight proceeded with gratifying smoothness. After Apollo 13 entered the lunar corridor, the CSM separated from the third stage and maneuvered to extract the LM from its housing atop the stage.

The Third Stage Hits the Moon

This accomplished, the crew performed the mission's first scientific experiment: driving the third stage on a collision course with the moon so that its crash-landing would be recorded by the geophysical station placed on the Ocean of Storms by the crew of Apollo 12. The stage's course was true and at 08:09 p.m. (EST) April 14th, it slammed into the moon's surface, 74 nm from the seismometer erected by Conrad and Bean.

On the preceding Apollo 12 flight, before setting their course for a return to earth, the crew of Apollo 12 had performed a similar experiment with the LM, driving it from lunar orbit into the moon's surface. For reasons of orbital mechanics, that LM had struck at a shallow angle which minimized the shock of its impact. However, on Apollo 13, the path of the 30,700-lb. (earth weight) stage brought it in at an angle of 80°, nearly perpendicular to the lunar surface, and at a speed of 8,465 feet per second -- slightly less than 6,000 miles an hour. The force of the impact was equal to 11.5 tons of TNT.

The seismic signal produced was 20 to 30 times larger than the LM impact and lasted for four hours. So large was the signal that the sensitivity of the seismograph was cut back by ground command to keep the readings on the scale. Geophysicists believe the impact signal penetrated the lunar surface to a depth of between 20 and 40 kilometers, which suggests that the outer shell of the moon -- at least to 40 km -- may be composed of the same kind of crystalline rock that has been found on the surface.

The rapid build-up of the signal to its maximum has scientists puzzled. Seven minutes from its beginning, it was at its greatest intensity; it then declined very slowly. This casts doubt on the validity of one hypothesis that evolved from the LM impact on the Apollo 12 flight; i.e., that the energy waves were scattered by a rubble material. Several alternate theories are being examined, but no conclusion has been reached.

The instrument on the moon's surface that detects ions also reacted to the impact of the stage. A few ions were recorded 22 seconds after the impact, then 250, then a jump to 2,500 and then a quick drop back to zero -- all within 70 seconds. Ions could have been produced by the very high temperatures created by the impact, or particles blasted to a height of 60 km above the lunar surface could have been energized by sunlight.

Change In Trajectory

The initial trajectory of Apollo 13 was what is called a "free return" course. Such a trajectory, if undisturbed would carry the spacecraft behind the moon, out again, and on a correct course for earth -- a safety factor in the event of a propulsion malfunction. The location of the Fra Mauro area where the Apollo 13 crew was to land required changing this trajectory to a "hybrid" course which did not have the "free return" feature. This transfer was routinely accomplished in the evening of the mission's second day. The maneuver complicated the problems that attached to getting the crew back safely after the explosion -- because it would have to be reversed.

Mobilizing For The Emergency

While the astronauts powered up the LM lifeboat, Mission Control set about mobilizing the substantial and varied talents available to it to help in dealing with the crisis. In addition to the contractor's representatives normally posted to Houston to assist with the flight, Mission Control phoned the manufacturers of the major systems and sub-systems in the LM and the CSM and instructed them to have their top specialists immediately available to help provide hard answers to even harder questions. Thus the engineers and their simulators and computers at North American Rockwell were brought on line. Experts at Grumman Aerospace Corporation, makers of the LM, were alerted as were rocketeers at TRW Systems who built the descent propulsion engine that would have to supply the thrust to put the spacecraft on the correct return course. There were others. In sum, a coast-to-coast network of simulators, computers and experts was quickly hooked up. Their operation provided a tour de force of the breadth and depth of American technological competence.

The problem had two major aspects. One was getting Odyssey and Aquarius, call signs for the CM and the LM respectively, on the true and quickest course for home. The decisive factors here were propulsion and guidance. The second centered on the consumables -- power, oxygen and water. Here the key was conservation. To make matters more difficult, there was often an incompatible interlock in the moves that had to be made. It was essential to align the guidance platform. As Lovell later explained it, this was the "first milestone, because without knowing exactly which attitude the spacecraft is in, there's no way to tell how to burn or how to use the engines of the spacecraft to get the proper trajectory to come home." But activating the guidance platform drew heavily on a supply of electric power that was critically short.

Conserving The Consumables

Husbanding of consumables was the first order of business. The CM was shut down completely after Lovell and Haise had powered up the LM and made sure that its systems were functioning properly. Except for the final phase of the flight, the CM was used only as a bedroom. Later, during the flight home, all the LM's systems except those relating to life support, communications, and environmental control were turned off, and Aquarius' power consumption reduced to 11 amps an hour. Economies of this kind stretched the LM's design capability of supporting two men for 49.5 hours to providing life support for 3 men for 84 hours.

After the LM's guidance platform was aligned, the next order of business was an engine burn that would restore the free-return factor to the spacecraft's trajectory. After running this maneuver through the computers and simulators, as was done with all problems, Mission Control ordered a burn that would add 38 feet per second to the spacecraft's velocity.

Normally, a course correction of this kind presents no difficulty. For Apollo 13, there were complicating factors. The LM's descent engine, not the SPS, was doing the pushing this time, and it was pushing a spacecraft that had a different mass and center of gravity. The question of the LM engine's ability to execute the maneuver had been answered by a test conducted during the flight of Apollo 9 when Astronaut McDivitt operated the LM in a "tugboat" mode for more than six minutes. The maneuver was performed successfully.

A Shorter Course For Home

The second "milestone" as Lovell put it, was cutting the elapsed time of the return leg. As Lovell described the situation at this point: "The nominal flight time . . . was 153 hours (from launch) if we had done nothing else. Because consumables were critical, Fred was doing the back-of-the-envelope type of calculation and he figured, if we were lucky, we had about one hour of consumables to spare."

To improve this too-close-for-comfort margin, it would be necessary to step up the spacecraft's velocity substantially. Several velocity changes were possible. One, which would have saved the most time, would have brought the crew down in the Indian Ocean: a possibility, but recovery would be awkward, at the very least. A second, which would reduce return time from 153 hours to 143 hours and would bring the spacecraft in to a splashdown in the Pacific as planned, required a velocity increase of 860 fps. The question was whether the LM's descent engine could do it. Mission Control called the rocket specialists at TRW Systems for the answer.

The descent engine can operate for some 17 minutes, can be throttled, and can be re-started 20 times. Engineers at TRW Systems had test-fired Aquarius' engine and were confident it was good. The tests had also given them a useful reading on its performance. Nevertheless, they went to the simulators and computers to make sure, and the findings confirmed that the engine could do the job with plenty to spare. Thus reassured, Mission Control worked out detailed procedures and relayed them to the crew. The engine was fired and the maneuver successfully executed. Everyone breathed easier.

More Problems

The accident and the economies it forced on flight operations created a sequence of problems that kept Mission Control, its teams of experts, the simulators and computers busy for most of the return leg. The three-module configuration made it necessary to re-calculate course corrections and work out new detailed time lines. Maneuvers had to be refigured so that they could be executed with a minimum use of power and water (for cooling equipment). How would the linked LM and CM behave after the SM had been jettisoned? What would be the effect of discarding the LM one hour's flight from re-entry?

Questions of this kind, and there were many of them, were put through the various simulator-computer complexes until the ground team was certain that all possibilities had been checked out, and the best answers were in hand. Astronauts Alan Shepard and Ed Mitchell were operating one of the LM simulators at the Manned Spacecraft Center in Houston and Gene Cernan and David Scott were working in the other. At Cape Kennedy, Astronaut

Dick Gordon was simulating emergency procedures in a third LM. It is estimated that these simulators were used about 40 hours each during the flight. One team of simulator specialists worked round the clock without a break. No procedure, no maneuver instruction, no check-list was relayed to the crew that hadn't been thoroughly proved out.

A Cold Ride Home

For the astronauts, the ride home was a cold one. With the systems in the CM shut down, there was no internal heat source to keep the cabin temperatures at a comfortable level. The inert CM settled to a level of 38° F, so uncomfortable that the crew no longer used the couches for their sleep periods. They made makeshift in the LM, which was warmer than the CM but still uncomfortable. Worse than the discomfort, the cold prevented the astronauts from resting well, and Mission Control was concerned lest fatigue impair their ability to function.

Ingenuity At Work

Some difficulties that arose on the return leg were dealt with by means of jury rigs that were marvels of ingenuity. The atmosphere in the spacecraft cabins is "washed" of carbon dioxide (produced by the crew's exhalations) by canisters of lithium hydroxide. The overload on the LM's canister system saturated it and the carbon dioxide in the cabin atmosphere began a potentially dangerous rise.

After studying the problem, Mission Control read up instructions to Lovell on how he could make an adapter by hand that would allow the attachment of a hose to the lithium hydroxide canisters in the CM so that they could be used to purify the air. Lovell went the "ground" one better by splicing together two hoses so that the rig would reach through the docking tunnel into the CM. Within an hour carbon dioxide levels dropped sharply.

The amended re-entry procedure called for two course corrections, the first to get the spacecraft more toward the center of the re-entry corridor and the second to refine the angle of entry which must be between 5.5° and 7.5°. Without the guidance platform powered up, the normal method of determining the attitude of the spacecraft would be by taking star sights. However, ever since the explosion in the SM, the spacecraft had been shrouded in a cloud of debris that glittered in the sun and made sighting on a star impossible. The Apollo 8 had worked out a technique of using the earth's terminator and the sun. Lovell recounted his reaction at a post-flight press conference:

"When the ground read out the procedure to us, I just couldn't believe it. I thought I'd never have to use something as way-out as this. And here I was on Apollo 13, using this very same procedure. . . . Because it was a manual burn, we had a three-man operation. Jack would take care of the time. He'd tell us when to light off the engine and when to stop it. Fred handled the pitch maneuver and I handled the roll maneuver and pushed the buttons to start and stop the engine." The burn made the desired refinement in the re-entry angle of 6.49°

Readying the CM

Six and a half hours before re-entry, ground-based studies established that the three CM batteries, two of which had been re-charged from the LM, did not have enough power to maintain all the CM systems for that length of time. After intensive simulation on the ground, Mission Control passed up to the crew a phased power-up sequence wherein all needed systems were up only 2.5 hours prior to re-entry -- well within the capacity of the storage batteries.

On the final phase of the return leg, as Lovell later put it, ". . . things were getting better all the time." But the crew's troubles were not at an end. Lovell summed up their situation for the benefit of reporters after the flight. "We were in a different situation now, because, normally when you come home you have only the CSM . . now, though, we had a dead service module ... a command module that had no power . . . a lunar module . . . a wonderful vehicle . . . but that didn't have a heat shield and shortly we'd have to abandon it.

Discarding The SM

"Our procedure . . . was to make sure we had a good angle of entry and then at about 4-1/2 hours (before re-entry) to maneuver to a position to get rid of the service module."

Swigert told the newsmen of the jettisoning: " . . . the ground had read up a very nice time line. The only nervous moment we had . . . normal procedures require arming the logic busses (the pyrotechnic system that explodes the SM away) and letting Houston look at all the relays. At this time, we didn't have any telemetry with Houston and Fred came up and I said . . . 'Fred, I'm all ready to jettison the service module . . . just getting ready to arm the pyros.' "

"Fred said, 'I'll get a go from Houston.' I said, 'Fred, we don't have any telemetry with Houston so you're just going to have to put your fingers in your ears and stand by."

" . . . so I armed the 'A' system and I could hear the relays . . . and nothing happened (an encouraging sign) . . . and I armed the 'B' systems and nothing happened . . . so I kind of felt we were home free."

"The procedure went well -- we used a push-pull method . . . Jim and Fred were in the LM and using the translation controller to give us some velocity . . . when Jim yelled 'Fire!', I jettisoned the service module and it went off in the midst of a lot of debris, which is usual."

The crew's inspection of the SM, from a safe distance, disclosed that a whole panel of the SM housing, 12 feet high and 5-1/2 feet wide, near the high-gain antenna, had been blown off by the explosion and that material was hanging out. They could not get a good enough look at the area to see what had been damaged, but photographed the SM for later scrutiny.

"Farewell Aquarius"

An hour and a half before re-entry, the LM "lifeboat" that had been their salvation was discarded. Mission Control radioed, "Farewell Aquarius and we thank you." Lovell's benediction was: "She was a good ship." Clear of the LM, in Swigert's words, Odyssey "came on in" to the most accurate landing in the history of manned space flight.

A Successful Failure

By a matchless display of tenacity, resourcefulness, ingenuity and courage, a determined body of men at Mission Control working in close coordination with a coolly expert crew had averted catastrophe and brought the astronauts through a brush with death.

As an aborted mission, Apollo 13 must officially be classed as a failure, the first in 22 manned flights. But, in another sense, as a brilliant demonstration of the human capability under almost unbearable stress, it has to be the most successful failure in the annals of space flight.

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