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Chapter 10

Engineering Development of the Apollo Lunar Module*

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Introduction

The purpose of this paper is to discuss some of the practical problems encountered and solved in the design, development, and mission support of the Lunar Module. The Lunar Module performed as designed on all missions and was the "lifeboat" for the Apollo 13 aborted mission. This record of success was largely the result of extraordinary efforts of a truly dedicated team of Grumman and NASA individuals. Figure 1 shows the Apollo 15 (LM-10) on the lunar surface; this was the first mission to carry the Lunar Rover. Figure 2 shows the ascent stage approaching docking with the Command Module.

It is difficult to recall the state-of-the-art in the early and mid-1960s. Electronic chips were in their infancy and, until Surveyor landed on the Moon, we had no direct knowledge of its surface. It was in 1965 that a prominent astrophysicist assured me that the lunar surface was covered by 10 meters of impalpable dust; fortunately, he was wrong!

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† Huntington, New York.

One of the first problems encountered was that there was no practical way to flight test each Lunar Module in the manner that aircraft are tested. This led to the development of an exhaustive ground test program at component, subsystem, and vehicle levels. In all, there were 29 major test articles. Typical components underwent Design Feasibility Testing and Design Verification Testing. The final configuration underwent Certification Testing. All flight components underwent Acceptance Testing—some 6,889 vibration tests and 3,294 thermal tests—and Preinstallation Testing. The assembled Lunar Module was tested at Bethpage before shipment, and again at the Kennedy Space Center. The state-of-the-art in 1963-1965, predicted entirely unacceptable frequencies of failure in most electrical or electro-mechanical devices. This led to conservative assumptions concerning the environment, derating of components, and careful attention to thermal design. In time, we recognized the concept that "there is no such thing as a random failure" or, conversely, "all failures have a cause that can be found and fixed." In 10 years, we tabulated 14,247 test failures or anomalies, of which only 22 defied satisfactory understanding.

We also began to understand, early in the program, that there is little freedom to trade performance vs. schedule vs. cost. Acceptable performance had absolute priority. Great effort was directed toward meeting the schedule, inasmuch as the Lunar Module was the late starter in the larger Apollo project. While continual adjustment of the program, especially test programs, was aimed at efficiency, the cost came out what it would be. There were some 3,600 contract changes, and approximately 55% of the Lunar Module contract value was subcontracted. The following are some of the challenges encountered in developing the Lunar Module.

Landing Gear

We designed the landing gear to a maximum vertical sinking speed of 10 feet per second (fps) and a combination of 7 fps vertically and 4 fps sideways. We assumed vehicle attitudes of ±6° and attitude rates of ±2° per second—all in combination with a ±6° surface slope. We assumed a range of surface friction from 0 to ∞—i.e., the landing gear in mini-craters. A quarter-scale dynamic model was used to validate the computer modeling program. About 500 computer runs were made, producing a reasonable level of confidence that the Lunar Module would not topple over. For the conditions examined, and the geometry of the vehicle, it was stable up to 45° tilt (Figure 3). The ascent stage was designed to take off from an inclination of 30°—the maximum experienced proved to be 8.6°.

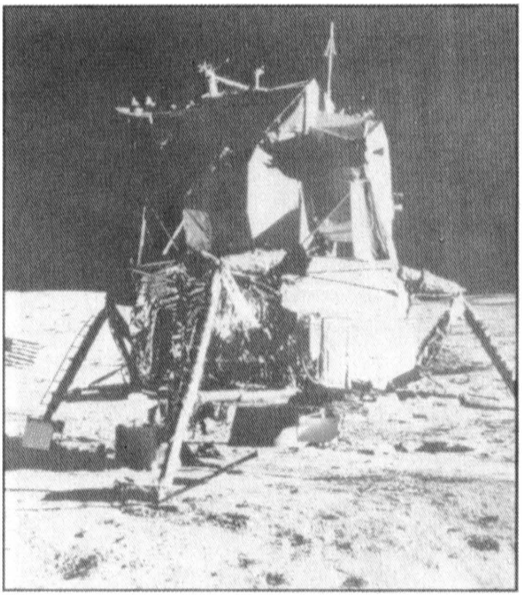

Figure 1 Apollo 15 (LM-10) on the lunar surface.

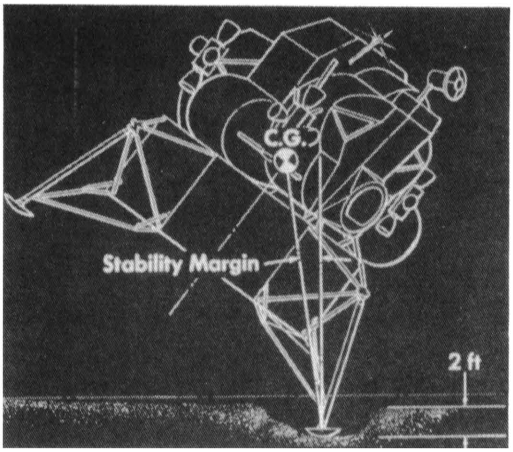

Figure 3 Vehicle stability examined; infinite surface friction.

Figure 4 Inserting the honeycomb shock absorber into the landing gear.

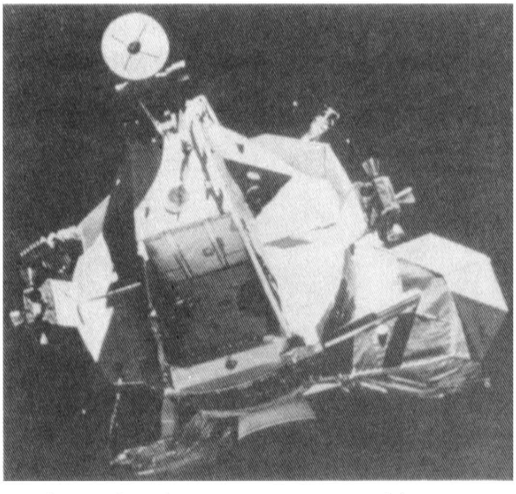

Figure 2 Ascent stage approaching docking with the command module.

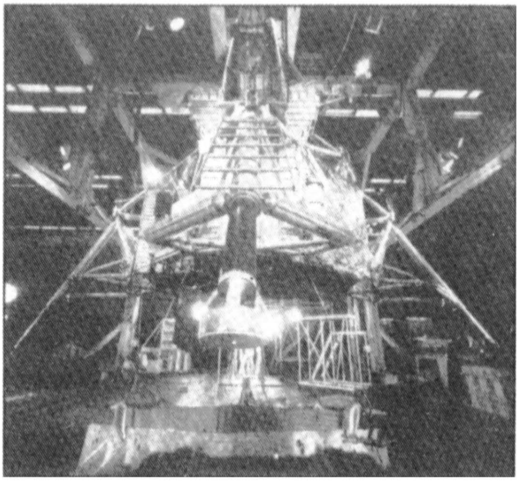

Figure 5 Drop test fixture.

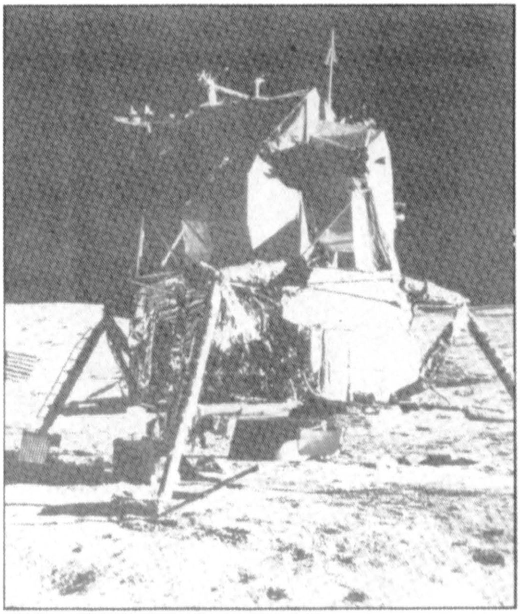

Figure 6 Landing showing lack of lunar dust and descent engine clearance.

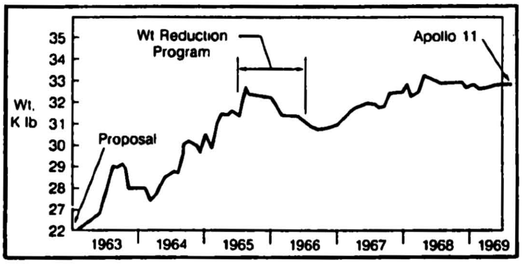

Figure 7 Lunar Module weight history.

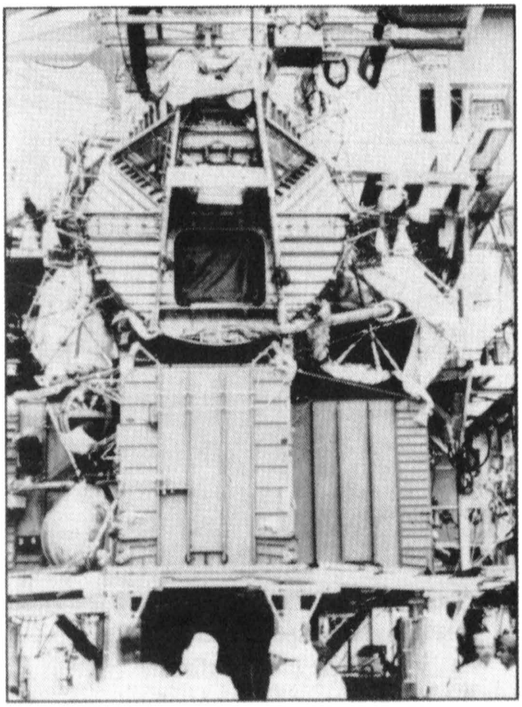

Figure 8 Ascent and descent stages showing panel/stiffener design.

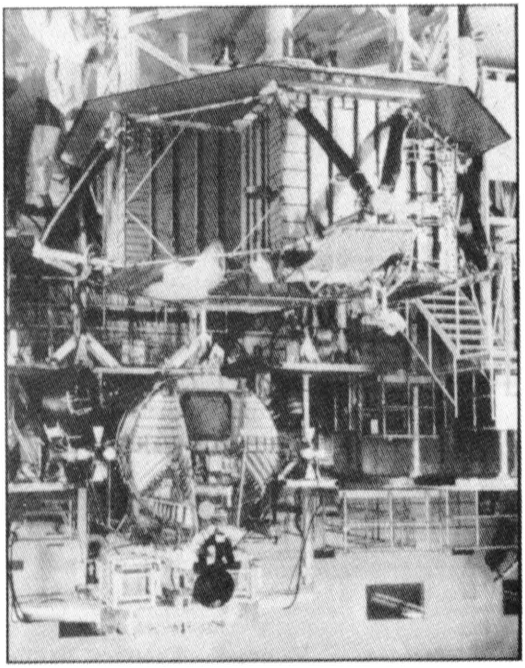

Figure 9 Another view of ascent and descent stage structural arrangement.

The landing gear was designed with a 32 in. stroke, using aluminum alloy honeycomb as the shock-absorbing medium (Figure 4). Actual experience showed a maximum deflection of 3 in., corresponding to a vertical sinking speed of about 2 fps.

Two drop tests of the vehicle were performed; the first for basic structural demonstration (Figure 5) and later the second, with electrical systems "hot." This second test was considered necessary because the Lunar Module, designed for lunar gravity, proved to be a very limp, flexible structure.

In hindsight, the landing gear was significantly overdesigned. I mentioned dust earlier. Only two of the six landings produced enough blown dust to obscure the surface (Figure 6). Another concern was the proximity of the descent engine skirt to the surface; this turned out not to be a problem. When the skirt was lengthened to provide greater performance for the last three missions, we were able to demonstrate, using a hot-gas ground test, that the columbium skirt would fold back on itself and not touch the surface.

Structure and Weight

The need to resist the tendency for growth in the weight of the Lunar Module never ceased (Figure 7). The history of vehicle weight shows the effect of a major, expensive weight-reduction effort. Early in the program, weight savings were realized when we eliminated the seats for the crew and relocated the windows closer to the crew eye position—quite different from most helicopters. Chemical milling of aluminum alloy shear webs was used extensively (Figure 8) to reduce the thickness of the cabin walls to 0.012 in., in other places to 0.010 in. (Figure 9). We examined the possible use of 0.008 in. thickness, but we ruled against it after counting the number of grains in a cross-section. Fuel lines were chem-milled between connectors.

We used 26-gauge electrical wiring in many places, and paid we a penalty in handling damage rework, but we did achieve a weight saving (Figure 10). The fuel tanks represented a bold approach to minimizing weight. The titanium alloy tanks were designed on the basis of fracture mechanics considerations for a life not to exceed 100 pressure cycles.

After the tragic fire in the Command Module at Kennedy Space Center, the Lunar Module had to absorb the weight consequences of a rigorous fireproofing campaign. In many cases, the thickness of material being bolted was much less than aircraft experience, leading to overstressing and stress corrosion. On one Module, we replaced a number of fittings at Kennedy Space Center.

Late in the Lunar Module design, we faced the real problem of minimizing the weight/unit area of the thermal and micrometeoroid shielding (Figure 11).

We required a basically passive thermal system, and the total area was so large that much analysis and vacuum chamber testing were required (Figure 12).

Batteries

Although fuel cells had been postulated as the source of electrical power, an early change was made to batteries—considered to be a more conservative and less expensive choice. The batteries were based on orbital experience—2.5 ampere-hours per pound, 28 Volts, direct current, silver, zinc with potassium hydroxide electrolite. Weight was minimized by using a magnesium casing and designing for one deep discharge. The batteries were qualified for flight by a sampling procedure.

At first, the performance showed an entirely unacceptable scatter. The production process was analyzed, and handling of the materials was changed. The scatter was eliminated.

We discovered that the individual plastic cells were being abraided by the magnesium case—all brought on by the dimensional changes in the electrodes during discharge. Instead of seating the cells in potting compound, we used a lubricant.

During the early missions, a question came up concerning venting in zero-g. Every mission had a slightly different configuration. All the different configurations worked.

Figures 13 shows the batteries mounted on the cold rails in the aft equipment bay. Figure 13 also shows some of the extensive paperwork we found necessary to prove to our satisfaction that the Lunar Module was built as intended and was flight-ready. Figure 14 shows another view of the aft equipment bay.

Propulsion Systems

There were three systems, all using pressure-fed, storable propellants: the descent stage system with its gimbaled, throttleable rocket engine (a first!) (Figure 15), the ascent stage system, with its fixed, non-throttleable rocket engine (Figure 16), and the reaction control system, with its 16 pulsing minirocket engines (Figure 17). The reaction control system had maximum redundancy and a bladder-supplied pressure-fed fuel system. It was used to "settle" the fuel for descent or ascent engine burns. Figure 18 shows the heat shield that protected the descent stage.

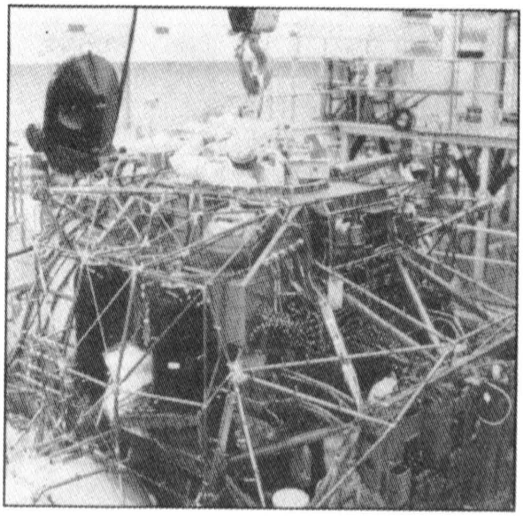

Figure 10 Ascent stage—electrical wiring bundles routed outside the pressure cabin.

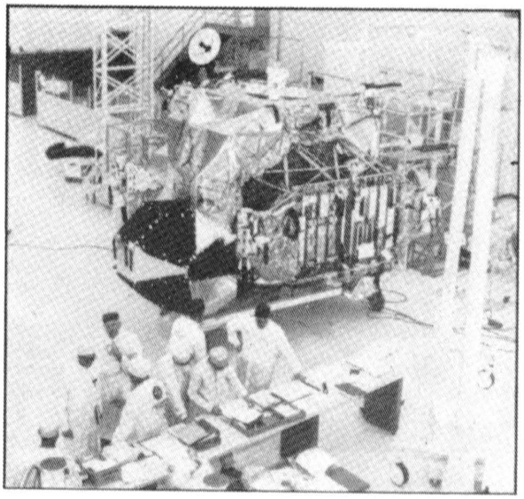

Figure 13 Batteries mounted on the cold rails in the aft equipment bay—ascent stage.

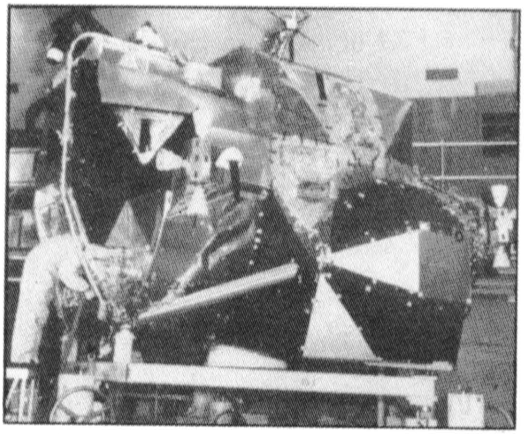

Figure 11 Thermal and micrometeoroid shielding—ascent stage.

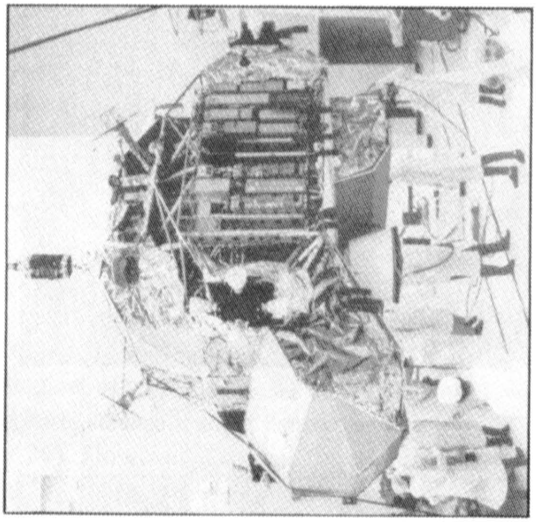

Figure 14 An elevated view of batteries mounted on the cold rails in the aft equipment bay.

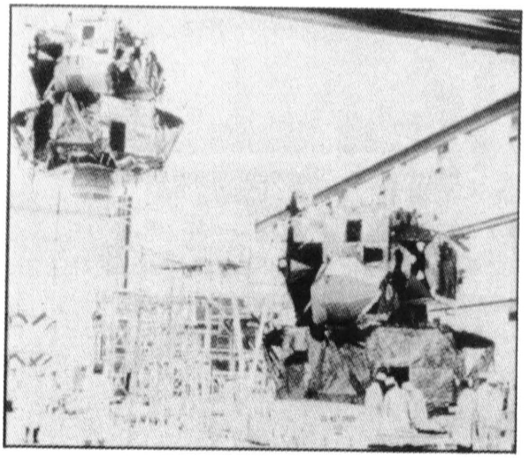

Figure 12 Additional views of ascent and descent stage thermal and micrometeoroid shielding.

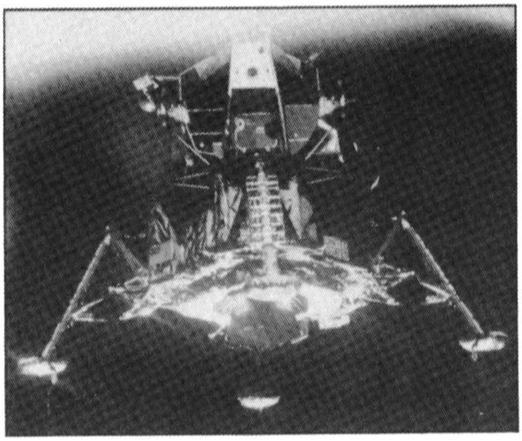

Figure 15 The descent stage rocket engine and heat shield.

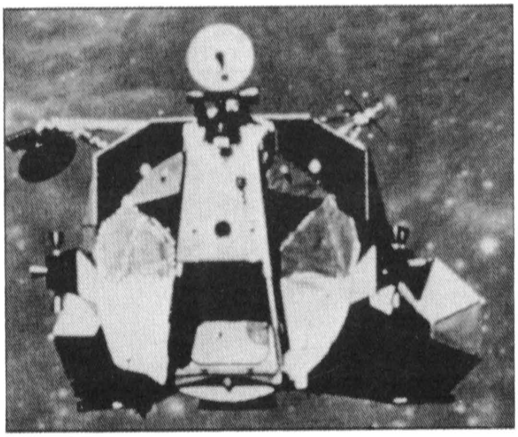

Figure 16 The ascent stage rocket engine, burned in the ascent stage.

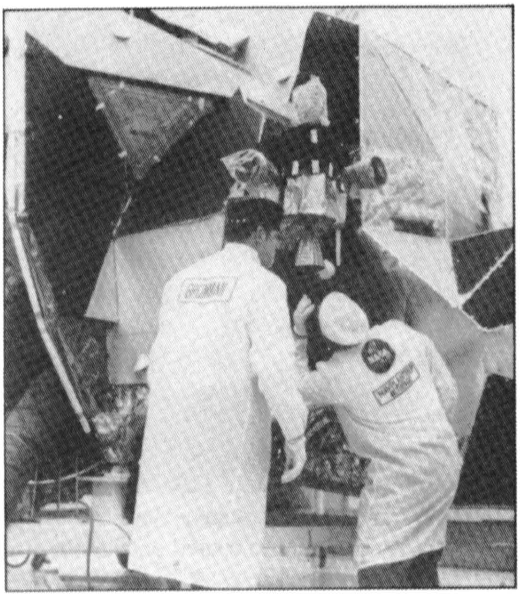

Figure 17 Reaction control system—one of four rocket clusters.

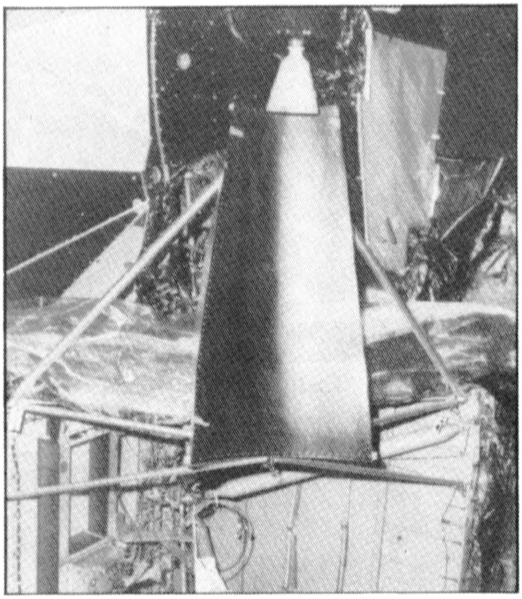

Figure 18 Descent stage protected by heat shield.

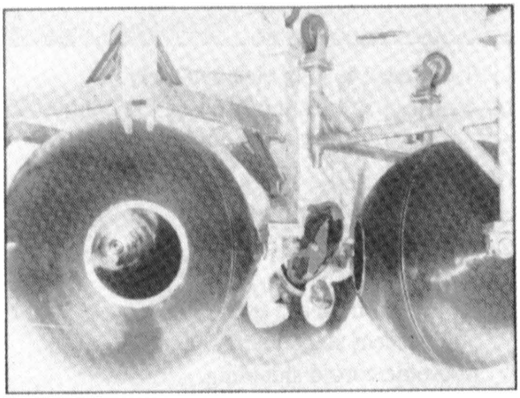

Figure 19 Titanium alloy ascent stage fuel tanks.

All rocket engines were critically examined for combustion stability. In fact, this effort to demonstrate "man-rating" just about doubled the time required to develop the engines. Late in the development program, the ascent engine was changed to use a backup injector that showed a greater stability margin.

The titanium alloy fuel tanks were mentioned earlier; Figure 19 shows the ascent tanks. Figure 20 shows how the swirl baffles were modified after extensive testing with referee propellants. Figure 21 shows a descent stage tank being mounted in its structural support. These tanks were so thin that filling the first of the flight-weight tanks produced consternation—the weight of the fuel stretched the tank enough to accept additional fuel, about 20 seconds worth, as I recall. This was very acceptable, when landing hover times were being planned at 140-150- seconds.

Figure 22 shows the ascent stage, the reaction control fuel tanks, and one of the ascent engine fuel tanks. It also shows the fuel lines leading to the reaction control quad. We found that the only way we could clean fuel lines adequately to avoid solenoid valve contamination was to flush while vibrating the lines.

Figure 23 shows a view of the outlet from a descent-stage fuel tank. The point to be made here is that we found—later than convenient—that our weight-skimping designs led to leaks. The flanges were not rigid enough between the securing bolts to hold the O-rings. In some cases, we changed to double seals and/or we reinforced the flanges. The leakage problem was particularly critical because the fuel and oxidizer were hypergolic, and the oxidizer, N_2O_4, was highly corrosive. When leakage became evident during testing in the NASA facility at White Sands, New Mexico, the significance was not immediately realized until the situation became desperate.

One aspect of the propulsion system operation that was not 100% validated until the last mission was the staging at lunar takeoff. At White Sands, brief ascent engine bursts were run in proximity to the descent stage, and the top of the descent stage was shielded (Figure 24). However, the real-time situation was not known until the TV camera on the Lunar Rover recorded the takeoff of Apollo 17 (Figure 25).

Glycol Coolant Crystals

The glycol cooling system test rig had been run very successfully for 5-6 years, to demonstrate heat transfer from the cabin environmental system, and the cold rails holding the electronic boxes and batteries. The system had redundant pumps, filters, and filter bypass valves. Provision was also made to sample the condition of the coolant in an assembled Lunar Module.

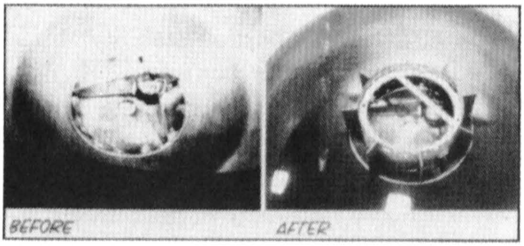

Figure 20 Swirl baffles modified after extensive testing with referee propellants.

Figure 21 Descent stage tank being mounted in its structural support.

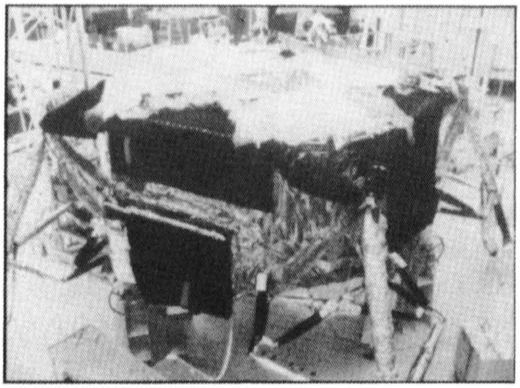

Figure 24 Top of descent stage with shielding.

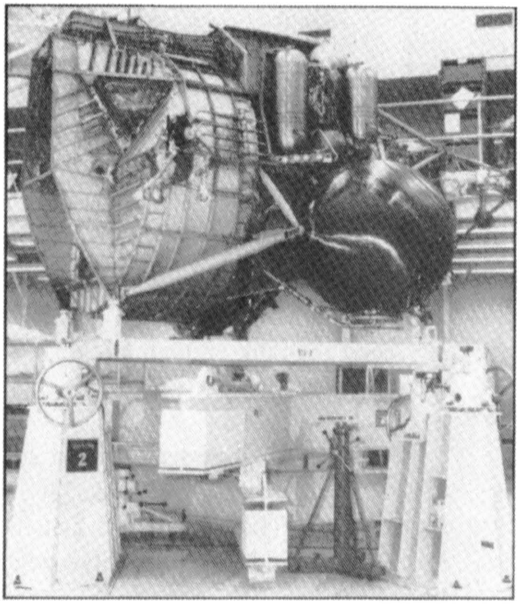

Figure 22 Ascent stage showing reaction control fuel tanks and one ascent engine fuel tank.

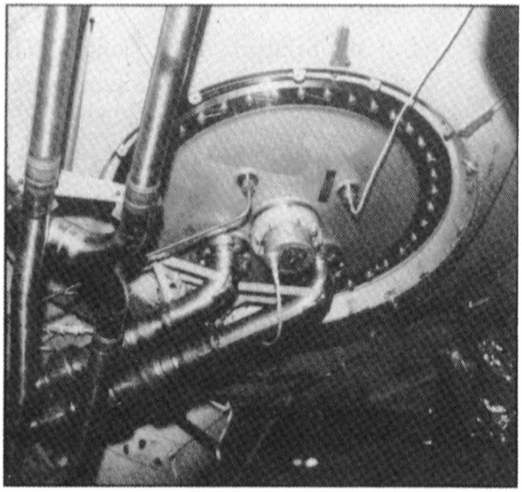

Figure 23 View of the outlet from a descent stage fuel tank.

When Lunar Module No. 5, for Apollo 11, was in the stack at Kennedy Space Center less than 90 days prior to launch date, a routine sampling revealed the presence of unknown, amorphous, needle-shaped crystals about 40 microns long in the glycol fluid. More sampling yielded more crystals. Extensive filtering and sampling outside the Lunar Module failed to produce a clear fluid—in fact, more filtering seemed to produce more crystals.

The next step was to transfuse a new charge of coolant into the vehicle. In short order, the new coolant developed its own crop of crystals!

Time was getting short, none of the bench analyses produced answers, so we ran a double mission profile with the worst crystal mix we had—it looked like orange juice. Everything worked quite satisfactorily, and I carried with me to Kennedy Space Center a set of vials (Figure 26) to show at the launch readiness review. The comparison of clear coolant and the "worst" is shown in Figure 27. History shows that the coolant system worked as it should have during the first lunar landing.

But we did solve the mystery. At some point, the inexpensive anticorrosion chemical coolant additive was changed to a much purer batch of the same chemical—ten times as expensive. In the change, we lost a vital impurity! The moral is clear: don't change something that works. For Apollo 12 and subsequent projects, we reverted to the earlier mix.

Conclusion

There are probably hundreds of similar recollections from the great undertaking that was Apollo. In hindsight, it was an extraordinary success, and it involved bold approaches to risks that were apparent to a relative few. In closing, Figure 28 shows members of the Apollo 17 Lunar Module preflight checkout crew at Kennedy Space Center—"It May Be Our Last, But it Will Be Our Best;" it was.

References

[1] Thomas J. Kelly, "Design Features of the Project Apollo Lunar Module," Grumman Aerospace Corp., Bethpage, NY, AIAA-81-0910, 1981.

[2] Donald F. Schlegel, "The Apollo Lunar Module," a collection of miscellaneous information, Grumman Aerospace Corp., Bethpage, NY, 1975.

[3] Ross Fleisig, "The First Manned Lunar Landing Spacecraft—Its Design, Manufacture, Ground Test, and Mission," Therus Dynamics, Inc., Garden City, NY, 1989.

Figure 25 Takeoff of Apollo 17.

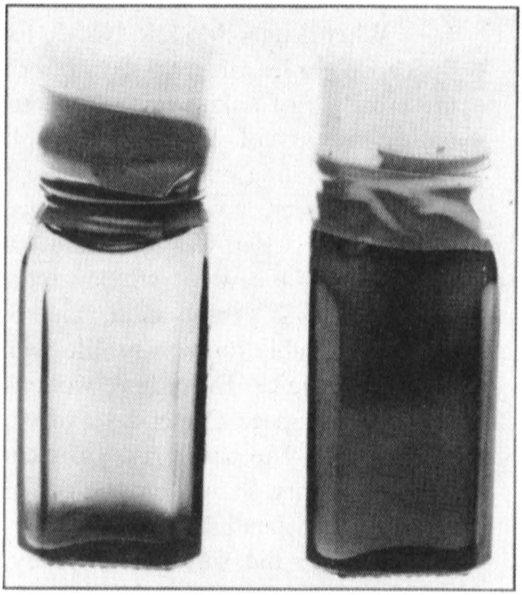

Figure 27 Comparison of coolants—
no crystals vs. maximum crystals.

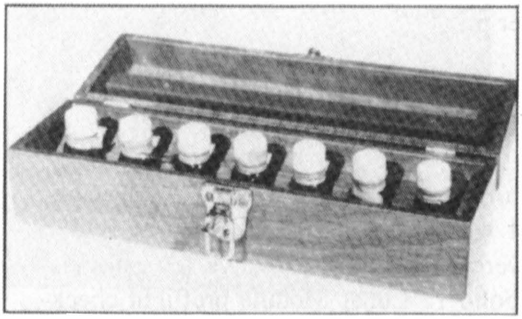

Figure 26 Set of vials shown at launch readiness review for Apollo 11.

Figure 28 Members of the Apollo 17 Lunar Module preflight checkout crew.