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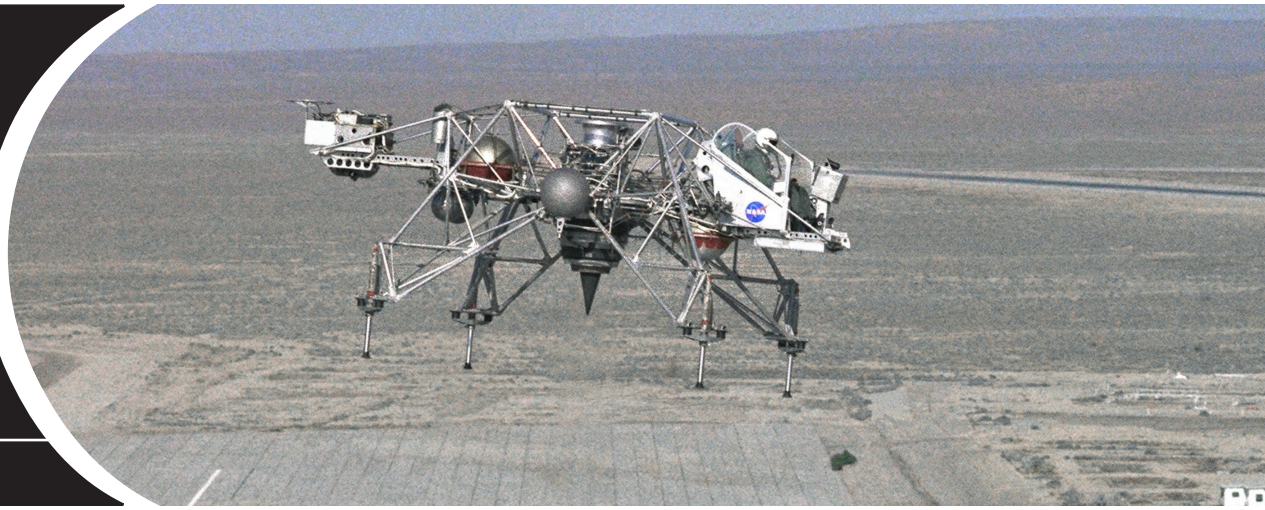

NASA SAFETY CENTER

SYSTEM FAILURE CASE STUDY

June 2015 *Volume 8 Issue 6*

Six Degrees of Freedom

The Valuable Failures of the Lunar Landing Research and Training Vehicles

FAILURES

- May 6, 1968 LLRV A1 Crash
- December 8, 1968 LLTV B1 Crash
- January 29, 1971 LLTV B2 Crash

UNDERLYING ISSUES

- Unknown aerodynamic limits of the LLRV/LLTV design
- Management of change issues related to unidentified failure modes

AFTERMATH

- Success of LLTV training facilitated the success of the Apollo lunar landings without one instance of lost lives

May 21, 1961: President John F. Kennedy challenged the United States to send humans to the moon. With unprecedented funding and the support of the nation, NASA's Apollo team committed to unraveling the program's numerous design challenges. Many of their solutions left them asking more questions. In 1962, NASA selected Grumman Aircraft Corporation to design and build a vehicle that could land in the airless lunar environment with a gravitational pull one-sixth that of the Earth. Grumman's bug-like, four-legged Apollo Lunar Modules (LMs) utilized a complex rocket propulsion system that controlled pitch, yaw, roll, descent, and ascent. Apollo astronauts realized they needed new piloting skills that no electronic simulator could fully develop. Beyond that, the limited fuel supply of Grumman's LM precluded multiple landing attempts that would allow the astronauts to master their skills during the mission. And although an autopilot would be available as a backup, true lunar surface conditions were almost unknown and could not be left to automation. So, in 1963, Bell Aerosystems was chosen to create one of the most bizarre flying machines ever built: the Lunar Landing Research Vehicle.

Background

The Lunar Landing Research Vehicles

To solve the LM training challenge, NASA employed a three-phased approach. First, astronauts mastered an electronic simulator at the Manned Spacecraft Center (MSC) in Houston, Texas, predecessor of NASA's Johnson Space Center. Next, flight on a tethered test unit increased experience with minimal risk. Finally, graduation from the training would require taming one of two free-flight Lunar Landing Research Vehicles (LLRVs) conceptualized by NASA's Flight Research Center (FRC) (a predecessor of NASA's Armstrong Flight Research Center).

The LLRVs were initially designed to give pilots a platform to study and analyze piloting techniques needed to fly and land the Apollo LM in the lunar environment. In only 14 months, Bell Aerosystems, extensively experienced with propulsive lift vehicles, built and tested two LLRVs that could take off and land on their own power, reach an altitude of 4,000 feet, hover, move horizontally, and remain inflight for 14 seconds. The first, LLRV No. 1, was delivered to FRC in April 1964, with LLRV No. 2 delivered later that year. The first LLRV free flight of LLRV No. 1 occurred October 30, 1964.

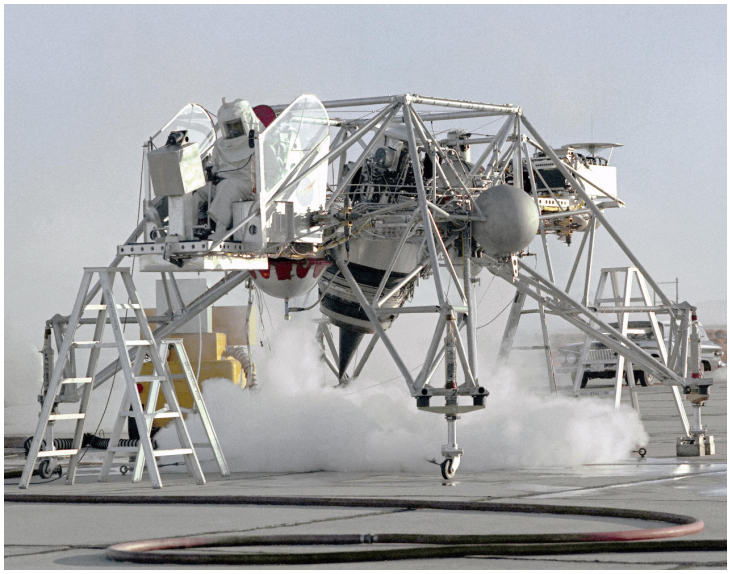

Figure 1. Bell Aerosystems testing the LLRV design. Note the open pilot platform. Source: NASA

The LLRV's open, four-legged, aluminum alloy truss frame was piloted from an open platform between the two front legs. An electronics platform extended between the two rear legs. In order to simulate a lunar landing profile, the LLRV utilized a 4,200-pound thrust General Electric CF-700-2V turbofan jet engine that was mounted vertically in a gimbal ring at the center of the LLRV skeleton. During ascent, the turbofan engine was locked in a vertical-to-vehicle thrust position and supported the full weight of the vehicle. Once at altitude, the pilot transitioned the LLRV to Lunar Sim Mode to throttle the engine back to support five-sixths of the vehicle's weight. The pilot would also unlock the gimbal so that onboard gyroscopes could keep the engine vertical-to-the-ground, regardless of vehicle attitude. This arrangement simulated how the vehicle would descend in the reduced lunar gravity.

The pilot could vary the thrust of two hydrogen peroxide lift rockets from 100 to 500 pounds of thrust to handle the LLRV's descent rate and lateral movement. The engines operated in as a pair to eliminate uneven thrust. A system of 16 smaller hydrogen peroxide thrusters, mounted in pairs, were linked to the pilot station through an electronic flight control system to give the pilot control in pitch, yaw, and roll. High-pressure helium tanks mounted on the vehicle frame pressurized the hydrogen peroxide propellant systems for the lift rockets and the attitude control system. The LLRV's programmed electronic fly-by-wire control system simulated the motions and system response Apollo astronauts would later face while nearing the lunar surface in the LMs.

If the main engine failed, six 500-pound rockets could take over the lift function and stabilize the craft for several seconds. Each vehicle was also equipped with a newly perfected "zero-zero" ejection seat, meaning that the pilot could safely eject and deploy a parachute at zero airspeed down to zero altitude.

A simple instrument cluster displayed vehicle attitude, Doppler radar return of ground movement below, fuel pressure, and little else. Telemetry was transmitted to a ground station and was collected for post-flight study.

Transition to Lunar Landing Training Vehicles

By 1966, NASA had accumulated enough test data from the LLRV flight program to demonstrate that a free-flight vehicle could safely simulate lunar descent conditions and could be used as a training vehicle. NASA engaged Bell to deliver three improved Lunar Landing Training Vehicles (LLTVs) for use as dedicated training platforms that more closely matched the LM configuration. The LLTVs were designated LLTV B1, B2, and B3.

In December 1966, LLRV No. 1 was shipped to MSC. LLRV No. 2 followed in January 1967. At the time or their respective arrivals, No. 1, the program's workhorse, had a total of 198 test flights, and No. 2 had a total of 7 test flights. Although conceptualized as research tools, the LLRVs soon became full-fledged training vehicles. Modifications were made to the LLRVs to give the pilot a three-axis side arm control stick, an enclosed cockpit with a more restrictive view, and a control panel relocation to the right side of the cockpit—all features representative of the real Apollo Lunar Module. Once modified, the LLRVs were redesignated LLRV A1 and A2 and LLRV research pilots began using them to learn how to become LLTV instructor pilots. In December 1967, the first of the LLTVs joined the modified LLRVs to make up the five-vehicle training and simulator fleet.

What Happened

May 6, 1968 LLRV A1 Crash

On May 6, 1968, LLRV A1 sustained a flight accident during an astronaut training flight. Pilot Neil Armstrong successfully ejected from the LLRV, but the vehicle was a total loss in the ensuing crash. An LLRV Accident Review Board was established on May 16, 1968 to determine the cause of the accident and find corrective actions, including implications of the accident on the follow-on training vehicle, the LLTV, and on the Apollo LM design and operations. The review board worked extensively with the MSC Accident Investigation Board, which had been previously established by the MSC director.

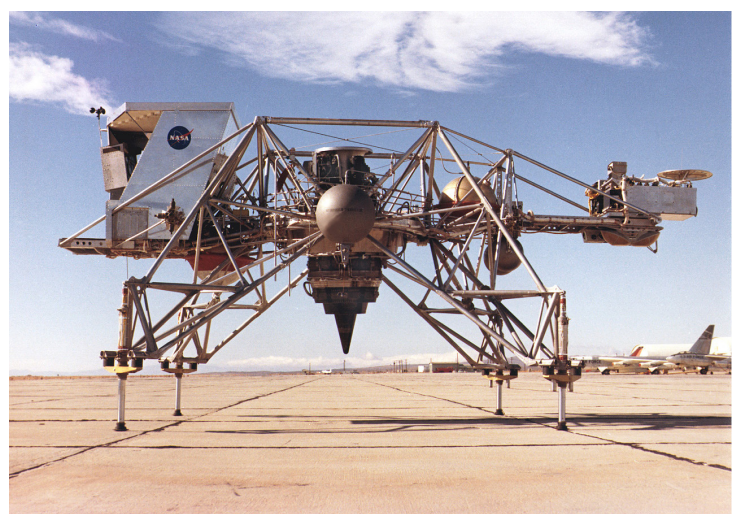

Figure 2. Bell Aerosystems' LLTV with enclosed cockpit was truer to Grumman's LM design. Pilots coped with reduced visibility in the same manner as they would during lunar descent. Source: NASA

The boards concluded that the proximate cause of the accident was a loss of attitude control stemming from a loss of helium pressure to the propellant system. The helium had vented through the hydrogen peroxide propellant tanks and out the lift rockets and small thrusters. It was determined that although the LLRV could be flown and landed by only using the gimbal-mounted jet engine and attitude control thrusters, it would have required exact and immediate response from Armstrong at the first moment of the warning. The MSC Accident Investigation Board described the action as a "critical pilot task during the heavy workload period which developed on [that] flight," and pointed out that the helium pressurization was not protected from loss where it had vented through the lift rocket system.

The boards concluded that contributing factors included a failure in one of the propellant tank sensing systems to give the operating crew in the ground control van adequate warning of the abnormally low propellant supply. The crew's failure to diagnose the loss of pressure in the tanks and the cockpit system's failure to warn the pilot in adequate time coupled with flight in gustier-than-normal wind conditions denied the pilot adequate time to respond to the situation.

The corrective actions indicated by the review therefore deal with certain design improvements in the vehicle; improved monitoring equipment to both ground and flight personnel; improved communications among operating personnel; and, in particular, more rigorous operating criteria, training procedures, and project discipline. The board cited an inadequate response by the operating engineers and flight control personnel on the ground

Figure 3. Pilot Neil Armstrong was the first to utilize the newly perfected zero-zero ejection seat after losing pressure to the LLRV A1's propulsion system. Source: NASA

Figure 4. Pilot Neil Armstrong parachutes back to the ground as the wreckage of LLRV A1 burns on the Ellington Airforce Base airfield at MSC. Armstrong's composure during the crash has been credited to his experience as a naval aviator during the Korean War and his post-war career as a test pilot at the National Advisory Committee for Aeronautics' High-Speed Flight Station. Source: NASA

to the developing emergency based on a lack of contingency training. For this, they recommended an addition of fire and rescue equipment on the ground and added manpower for the control team.

Due to the degree of similarity between the LLRV and the LLTV, the corrective actions developed for the LLRV were applied with equal force to the LLTV. The mishap also triggered a comprehensive study of the LM, but no significant problems or special actions resulted in LM corrections because of system design differences between the LLRV and LM and the high degree of training and operational discipline found present in this element of the Apollo program.

December 8, 1968 LLTV B1 Crash

Seven months later, on December 8, 1968, LLTV B1 was lost in a crash during a training flight. Pilot Joseph Algranti had climbed to 680 feet and had begun a simulated lunar landing run. Shortly after the turbofan engine was released from its fixed normal vertical-to-vehicle thrust position, the LLTV began to oscillate about all three axes. Algranti attempted to correct the vehicle by relocking the turbofan engine in its vertical-to-vehicle position; however, the LLTV continued to oscillate to angles of 102 degrees bank to the point where the turbofan and lift rockets could not counteract gravity. Algranti safely ejected before the vehicle crashed.

An LLTV B1 Accident Investigation Board was immediately appointed to investigate the crash. They determined that the primary cause of the accident was that the LLTV entered a region of flight where "aerodynamic movements overpowered the control system in such a way that attitude control was lost." The source of the issue was not identified by either Algranti or the

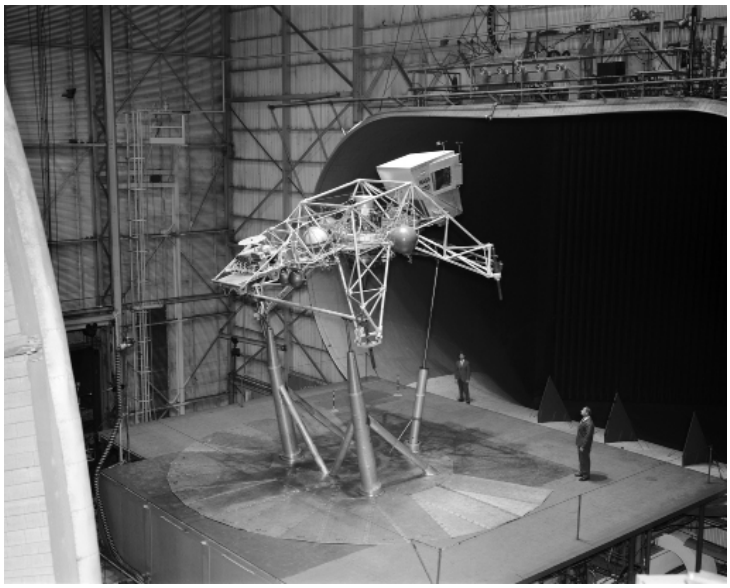

Figure 5. LLTV B3 at MSC underwent wind tunnel testing after the 1968 LLTV B1 crash that partly stemmed from the LLTV's unknown aerodynamic limits. Source: NASA

flight control van in time during the flight to add a second control system that could have restored control capability.

The board also noted that the vehicle entered the adverse region of flight because nobody fully understood the aerodynamic limitations of the LLTV, the existing wind conditions were insufficiently accounted for in preflight and real-time flight planning, and the configuration of displays in both the LLTV and the ground support van inadequately defined the existing flight conditions.

The board recommended that MSC conduct wind tunnel tests to measure LLTV aerodynamic characteristics in order to set operating limits and to detail those limits and flight profiles in the LLTV Operations Manual. They also made numerous recommendations involving improvements to automate portions of the attitude control system when the LLTV hit a hard stop, and to provide improved cockpit field of view, references, and displays.

January 29, 1971 LLTV B2 Crash

Almost 9 months after the launch of Apollo 13, LLTV B2 was destroyed on January 29, 1971 during a routine check flight. Pilot Stuart "Stu" M. Present ejected safely before the LLTV crashed on a runway and burned. The NASA Investigation Board formed to investigate the cause of the incident concluded that an electrical system malfunction was the principal cause of the failure. The Electrical Flight Control System lost its primary power source, and the emergency generator and switching malfunctions prevented the battery from supplying emergency power. The LLTV, without its stabilizing control system, went out of control and crashed.

General Electric had replaced the original generator with an upgraded model with a battery-powered emergency bus intended to improve reliability; however, the upgrade prevented the switchover circuitry from engaging the emergency bus. Post-mishap analysis showed that the exhaust from the ejection-seat rocket had caused the turbofan engine to flame out, causing the DC generator to spin down, removing the magnetic field, and enabling the emergency bus to activate with battery power. The attitude rockets began firing as the LLTV crashed. The obscure failure mode had not been identified in Bell's formal Failure Mode and Effects Analysis.

The board recommended that the electrical system be modified to ensure that the backup power was available to the flight control systems before flight operations were resumed. None of the recommendations resulting from the LLTV No. 2 crash affected LM design or operations.

Aftermath

Only two vehicles out of the five remained intact by the program's end. The experience gained by the instructors and astronauts from hundreds of successful flights and three failures led them to respect the ungainly vehicles' command of an unforgiving flight regime. Although, astronaut lunar landing training included 3 weeks of helicopter flight school, training on the tethered lunar landing simulator, and practice on the electronic ground simulator, the Apollo astronauts repeatedly praised and credited the experience and confidence gained from their LLTV training.

Astronaut Neil Armstrong said the Apollo 11 mission would not have been successful without the LLRV and LLTV training; that they did "…an excellent job of actually capturing the handling characteristics of the lunar module in the landing maneuver." Armstrong later said his practice flights in the LLTVs gave him the confidence to override the automatic flight control system and control Eagle manually during the Apollo 11 mission.

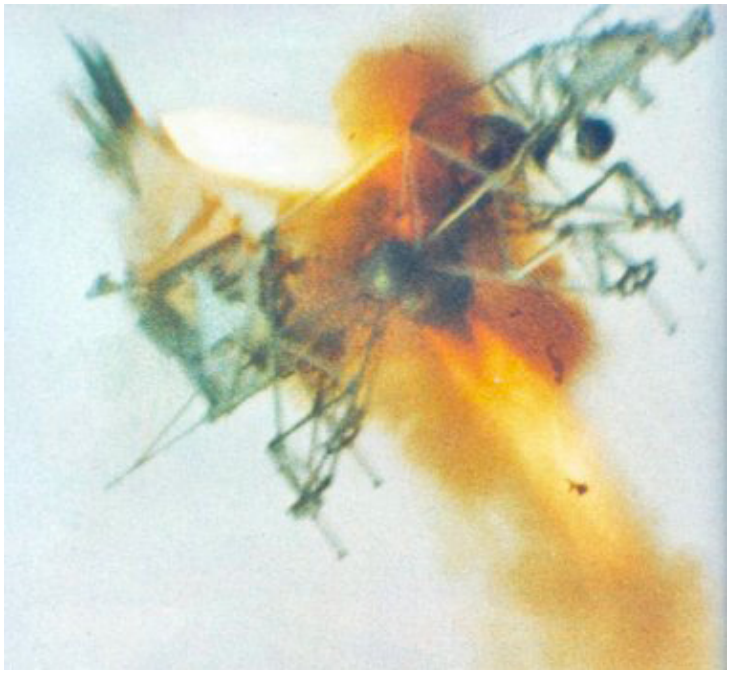

Figure 6. Pilot Stuart "Stu" Present ejected safely from LLTV B2 before it crashed. Source: NASA

Although engineers equipped the Apollo LM with a fully functional automatic landing system, all Apollo mission commanders opted to land the LM manually. As Apollo 1 astronauts Armstrong and Edwin "Buzz" Aldrin descended towards the lunar surface in the LM *Eagle*, Armstrong saw they were nearing a rocky area. He set a precedent for the program and disregarded the LM's automatic landing system and switched to manual control during the last moments of descent, landing the LM on a safer, more suitable spot. While it is impossible to speculate as to whether the automatic landing system would have operated successfully had it been utilized, it is clear that the LLRV testing at FRC and the LLTV training the astronauts received contributed to successfully placing humans on the moon.

Donald "Deke" Slayton, then NASA's astronaut chief, said there was "no other way to simulate moon landings except by flying the LLRV."

Apollo 12 Commander Pete Conrad on NASA Administrator Dr. Robert Gilruth's concerns over LLTV testing:

> "…bless his soul, just worried to death that somebody was going to get bagged in an LLTV. And so, he asked everybody when they came back [from the Moon] 'Do you think it's necessary to fly the LLTV?' And, the feeling that I think Neil had and myself—and I'm quite sure the rest of the guys—was, 'Yes, you really should go ahead and fly the LLTV.' But, having had the three accidents and having that one vehicle left, Dr. Gilruth asked the guys to figure out how many flights we got on a vehicle before we crumped one. And it turned out to be like 260 flights or something like that. To finish the training after the third accident, they had to fly 240 more flights; and, so, when Gene [Cernan, the Apollo 17 Commander] flew the last flight in his training, the thing went to the Smithsonian or whatever because nobody was ever going to fly that thing again as far as Gilruth was concerned. And he almost didn't authorize the training, see. And so, at least the early guys pushed very hard for everybody to continue flying it."

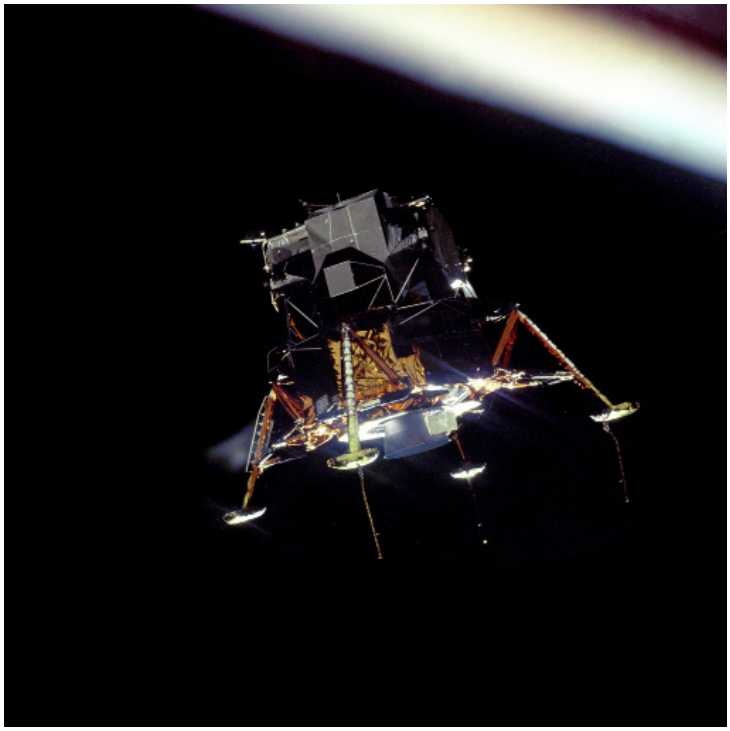

Figure 7. The Apollo 11 LM *Eagle* piloted by astronaut Neil Armstrong in lunar orbit. Source: NASA

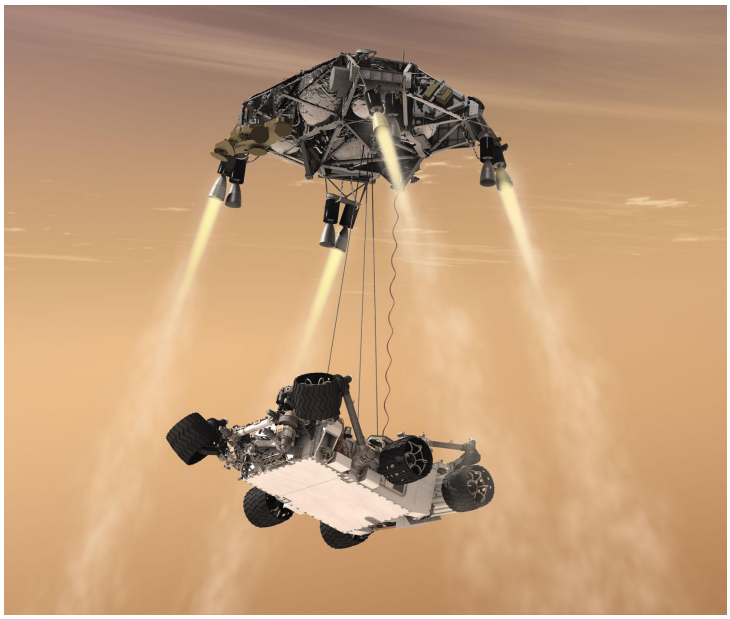

Figure 8. An artist's rendition of Curiosity being lowered during the "seven minutes of terror." While all Apollo astronauts opted to forego the automated landing system and land the LM manually, the Curiosity lander successfully utilized complex programming in order to success¬fully enter Mars' atmosphere, initiate a parachute descent, transition to a powered descent, and finally place the rover on the Martian surface via sky crane. Source: NASA

Apollo 17 Commander Gene Cernan on the LLTV's six degrees of freedom:

> "The LLTV was inherently less stable than the LM itself; and we also had to contend with gusts of wind that could cause problems. But, LLTV training was very valuable because it really put your tail out on the line. It was not a simulator you could make a mistake in and then reset. If you made a mistake, you busted your ass, quite frankly. It also really brought home the uniqueness of the problems that you get with six degrees of freedom. By six degrees of freedom, I mean that not only could you roll, pitch, and yaw the vehicle and change your thrust direction because of the main engine, you could also use the RCS thrusters and move it laterally up, laterally down, laterally left, laterally right, laterally fore, or laterally aft. You had a combination of all those things to do when you landed a lunar module, and that is why the LLTV was so realistic. It was a great training device, one of a kind and probably never will be seen or used again. The 'flying bridge.' The ugliest thing in the world; but it was an ingenious idea and an ingenious design, and I don't know how else you could have ever put yourself in a one-sixth gravity flying environment, with rocket engines, here on Earth, and still have six degrees of freedom.

Helicopters are just vertical flying machines, and they were nothing like this at all."

The final LLTV flight was on November 13, 1972 for pre-launch training for the final Apollo mission to the moon, Apollo 17.

Relevance to NASA

The LLRV development and research program finished as an excellent example of how individuals working in an aerodynamic environment can increase a measure of success of a spaceflight project through close cooperation and a complete understanding of differing engineering disciplines.

Throughout the Apollo missions, astronauts worked closely with designers and engineers to create optimal solutions for the Apollo capsule and LM—with design changes occurring both during the testing and operation phases. Many changes hinged on ease of use for the astronaut or operator.

The confidence and creative thinking of human operators is a persistent theme in the debate of human operation versus automation. From the LM *Eagle* to the Mars Science Laboratory *Curiosity* lander's "seven minutes of terror," technology has evolved from a passive tool used by operators to a highly independent agent that can eliminate mundane system subroutines from an operator workload or eliminate the operator and automate the entire system. However, total reliance on technology to eliminate the operator is not without its own problems. Lander failures like that of the Mars Polar Lander can be attributed to automation factors that have been highly subtle and difficult to anticipate or detect.

The Apollo Program decision to expose test pilots and astronauts to the risks necessary to master experimental vehicles seems easy to applaud in retrospect. Six human-piloted lunar landings validated the training risk as needful. However, it was the combination of brilliant subject matter experts and brave managers who made the technical case to build and fly the LLRV in 1961. Had those individuals lacked the right mix of knowledge and experience, they could have suffered failure of imagination, recommending conventional training with helicopters and static cockpit trainers. It would have been simpler for program managers to suffer failure of nerve and accept safer, low-fidelity training alternatives than persisting with LLTV training despite three crashes.

Today's challenge to land humans on Mars and return them safely to Earth faces even tougher mission and environmental hurdles. No Cold War politics drive competition or demand teamwork this time. The benefits of mission success deserve study equal to the well-publicized risks; otherwise how can technical brilliance and courageous leadership combine to find the level of needful risk to allow mission success?

Questions

- *Does the system being tested represent the flight configuration?*
- *Have all "heritage equipment" test and flight anomalies been resolved?*
- *Are all test anomalies fully understood?*
- *How are configuration changes tracked?*
- *Does the test inject sufficient off-nominal conditions to ensure the equipment is robust?*

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