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The Apollo flights: a brief history

AN ALPHABET OF MISSIONS

Owen Maynard, one of the engineers who had been designing manned spacecraft for NASA from the beginning, reduced the task of reaching the Moon to a series of missions that, one by one, would push Apollo's capability all the way to the lunar surface. These missions were assigned letters of the alphabet: A, B, C, etc. Managers believed that if the lunar goal was to be realised, each mission would have to be accomplished, with some missions possibly involving more than one flight.

- An A-mission would be an unmanned test of the Saturn V rocket to rate it for manned flight and test the ability of the Apollo command module to re-enter Earth's atmosphere safely.
- A B-mission would take an unmanned lunar module up into space for a workout. It would be launched by a Saturn IB launch vehicle.
- A C-mission would be an Earth orbital test of the CSM with a crew, again using the Saturn IB.
- A D-mission would be a full manned test in Earth orbit of the CSM and LM Apollo system, launched by a Saturn V.
- An E-Mission would see NASA move away from the Earth with another full test of both spacecraft, this time in an orbit that would reach much higher than any manned spacecraft had previously flown, in order to test the combination away from Earth where navigation, thermal control and communications would be different.
- An F-mission would be a full dress rehearsal of a flight to the Moon, carrying out every manoeuvre except the actual landing. This would give crews in the spacecraft and the people in mission control their first operational experience of lunar orbit.
- The G-mission would attempt to land on the Moon. Its goal would not extend much beyond the landing itself, as the two-man crew of the lander would take only one short walk on the lunar surface.

W.D. Woods, *How Apollo Flew to the Moon*, Springer Praxis Books,
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This was the plan, but circumstances altered the manner in which these mission were achieved. Three further mission types were later envisaged by the planners.

- An H-mission would maximise the capabilities of the basic lander to enable a crew to make two forays outside their craft on foot, and to deploy a suite of science instruments on the surface.
- An I-mission would have used only the CSM for a month-long stay in an orbit whose ground track would include the lunar poles. Cameras and other remote-sensing instruments built either into the side of the service module, or aboard an instrumented module docked onto the CSM, would have mapped the entire Moon. However, no such mission was ever flown.
- A J-mission was the final type to enter the planners' lexicon and would use an uprated Saturn V and LM to extend surface operations to three days. In the event, the CSM included remote-sensing instruments and the LM delivered a little electric car to enable its crew to venture much further around the landing site and explore areas with multiple scientific objectives.

When Kennedy's challenge was made, NASA had barely dipped its toe into space with the Mercury programme. Before an advanced spacecraft like Apollo could head for the Moon, the agency had to address a lot of basic questions about how to fly in space. The Gemini programme was its classroom. Across two hectic years of 1965 and 1966, ten increasingly ambitious flights were launched at bi-monthly intervals to test techniques for Apollo; in particular controlled re-entry, rendezvous, docking, spacewalking and long-duration flights. Its achievements placed America ahead in the space race for the first time, and as 'Go-fever' gripped the agency, NASA looked forward to getting the Apollo programme flying in the new year of 1967.

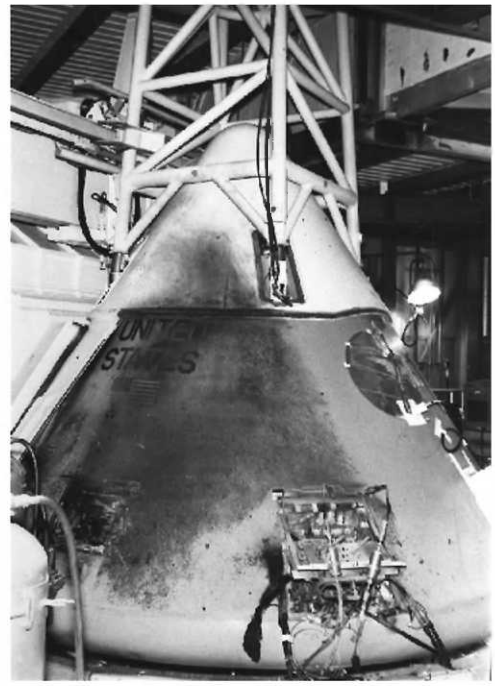
The bulk of this book deals with the steps involved in flying to the Moon rather than the sequence of the flights themselves. However, to give the reader a historical perspective the following is a resumé of what each flight achieved.

FAILURE OF IMAGINATION

As soon as the world learned of Sputnik's launch, it was clear that the United States lagged behind the Soviet Union in the lifting capacity of their launch vehicles. But this was no failing of their designers. Rather, most rocket research to this point had been in support of both nations' nuclear weapons programmes and because US designers were better at building smaller, lighter weapons their rockets were smaller. The Atlas missile used for the Mercury orbital flights and the Titan for the Gemini programme were really delivery systems for nuclear weapons, and struggled to lift their manned payloads. It became habitual for designers to minimise payload weight as they strove to maximise the capability of their spacecraft within the constraints of the available rockets. One decision to save weight would have tragic consequences for what was to have been the first manned Apollo mission.

On Earth, the atmosphere consists of four-fifths nitrogen and one fifth oxygen, the latter being the gas that sustains life. To save the substantial mass of the

equipment required to supply two gases in a manned spacecraft, NASA decided that the cabins of its spacecraft would be filled with 100 per cent oxygen, but at a low pressure to ensure that the crew received only the concentration of oxygen molecules to which their lungs were accustomed. This single-gas arrangement worked well throughout the Mercury and Gemini programmes, and was a sound engineering decision, but as the first Apollo crew were preparing their spacecraft for flight, this nearly ended the programme.



CM-012 scorched by the intense heat from its internal conflagration. (NASA)

On 27 January 1967, the AS-204 mission was three weeks away from its planned launch. It was so designated because it was to use the fourth vehicle in the Saturn IB series. Informally, it was dubbed Apollo 1. The Apollo spacecraft, CSM number 012, was a Block I type and was sitting on top of an unfuelled launch vehicle. Its crew of three were strapped in for a 'plugs out' countdown simulation in which the ability of the entire space vehicle to function on its own power would be tested. The cabin had been deliberately overpressurised with pure oxygen in order to test for leaks, as had been done in ground tests for the Mercury and Gemini programmes. Five and a half hours into a simulated countdown that had made only halting progress, a fire began near the commander's feet. In the super-oxygenated environment, this quickly grew into an intense conflagration that ruptured the hull of the spacecraft and asphyxiated the three crewmen – Gus Grissom, Ed White and Roger Chaffee.

NASA sustained heavy criticism from the press and the political classes for this tragedy. Some was directed at the manufacturer, North American Aviation, with accusations of sloppy workmanship. North American rebutted, pointing out that as it tried to build the spacecraft, NASA had insisted on interfering with the process by ordering a multitude of changes. In congressional hearings on the fire, astronaut Frank Borman appealed for support from the lawmakers. "We are confident in our management, our engineering and ourselves. I think the question is: are you confident in us?"

NASA learned many lessons from this accident and applied them to the rest of the Apollo programme. Some commentators have argued, convincingly, that there was a very real possibility that, had the fire not occurred, NASA would never have realised

its lunar dream. They point out that the shock of the deaths spurred all those involved in the programme, especially at NASA and North American, to make the Block II spacecraft into the great spacefaring ship it became. Without the changes imposed by the tragedy, casualties may have occurred later in the programme, possibly in space. At the very least, the development problems of the Block I Apollo spacecraft would probably have crippled the programme at a later stage had they not been brought into sharp focus so early on.

Although NASA wanted to keep this unflown mission's name as AS-204, it acceded to the widows' requests that the name Apollo 1 be reserved for their dead husbands' flight. Crews had been in training for Apollos 2 and 3, scheduled for later in 1967, but they were cancelled.

Meanwhile, a few months after the Apollo fire the Soviet Union grieved at its first loss of a cosmonaut during a test of the new Soyuz spacecraft. Both nations therefore had to cope with setbacks in their race to the Moon.

BACK IN THE SADDLE: APOLLO 4

NASA resumed Apollo operations on 9 November 1967 with Apollo 4. It was an A-mission to test the Saturn V launch vehicle. As so often happens with new, complex systems, getting this vehicle ready for flight proved to be a slow, difficult affair. Its S-II stage repeatedly exhibited cracks during inspections, and the unmanned Block I spacecraft, CSM-017, tested modifications called for by the investigation into the AS-204 fire.

The Saturn V launch vehicle turned the normal procedures of rocket development upside down. Traditionally, engineers undertook a careful, progressive programme of testing a rocket stage to ensure that it worked before setting another stage on top, and testing that. To test the entire configuration at once – so-called *all-up* testing – was deemed too risky. However, when George Mueller became head of NASA's Office of Manned Space Flight in 1963 he argued that the incremental approach to testing rocket stages not only wasted expensive

The launch of Apollo 4, the first flight of the Saturn V. (NASA)

flight-capable stages, it also wasted precious time. He ordered that the engineering and ground testing of the rocket's components should be of such a quality that all stages of the vehicle could be flight tested at the same time. Apollo 4 would prove to be a triumphant vindication of this strategy. The launch issued a noise like nothing that had ever been heard at the Kennedy Space Center, and this blew away much of the lingering pessimism from the spacecraft fire. As the acoustic and thermal energy was enough to cause substantial damage to the launch tower, NASA had subsequently to make modifications to the launch pads in order to suppress the extreme conditions.

As well as testing the entire rocket system, Apollo 4 placed its CSM payload into a high ballistic arc. From here, the SPS engine powered the command module into a high-speed dive into the atmosphere to test its heatshield by re-entering at the speed it would have if it were returning from the Moon. The CM was recovered from the Pacific Ocean after an 8½-hour flight that, in all important respects, was a complete success.

THE LUNAR MODULE FLIES: APOLLO 5

Launched on 22 January 1968, Apollo 5 is the flight that history treats almost as a footnote. It was neither manned nor did it have the remarkable Saturn V as its launch vehicle. It used the AS-204 launch vehicle that had been intended to lift Apollo 1, but it is important to the story because, as a B-mission, it tested the first Apollo lunar module, LM-1. The test allowed engineers to verify the lunar module's structure and its response to the launch environment, and it gave them their first opportunity to test the spacecraft's two engines in the space environment.

In the case of the ascent engine, it was NASA's first opportunity to try out a fire-in-the-hole burn when they ignited the ascent engine just as the descent stage was being jettisoned. In their effort to give crews the best possible chance of escape from any reasonable failure of equipment, the LM's designers planned that if the descent engine should fail while a crew were descending to the Moon, the ascent engine should fire and lift the crew back to the safety of an orbit. For this to happen, its engine would have to ignite while the descent stage was still in place. Despite some problems, the legless module successfully demonstrated everything that was asked of it,

Lunar Module-1, without landing gear, being mated to its adapter. (NASA)

and a second B-mission was cancelled. The second test lander, LM-2, is now on display at the National Air and Space Museum in Washington DC. The next spacecraft to fly, LM-3, would be entrusted with the lives of two men.

THE SATURN BALKS: APOLLO 6

By the spring of 1968, with two flights completed, the Apollo programme seemed to be hitting its stride. It had demonstrated all three stages of the Saturn V worked, the command module had survived its high-speed re-entry, and an early version of the lunar module had performed satisfactorily. Before the Saturn V could be declared fit to carry astronauts, a second A-mission was required. This flight was named Apollo 6 and, once again, events unfolded that threatened to stop the programme in its tracks.

After a successful lift-off on 4 April 1968, the first problem appeared towards the end of the S-IC's flight. Rockets have always been prone to vibrations along their length, but for about ten seconds immediately before the first stage was to shut down, the longitudinal shaking of the entire vehicle (known as pogo) became alarming. Meanwhile, at the front end of the rocket, a conical aerodynamic shroud that would normally protect the lunar module (not carried on this flight) was losing chunks of its outer surface. Since this section had to support the mass of the CSM multiplied by the g-forces of acceleration, its structural integrity was of some concern.

Halfway through the flight of the S-II stage, one of its five J-2 engines began to falter, prompting the instrument unit to shut it down. As it did so, another engine that had been showing no distress also shut down, causing the thrust from the other three to be applied asymmetrically. Considering that the Saturn's control system had been programmed only to deal with a single-engine failure, it did a remarkably good job of compensating for the off-axis thrust and burned the remaining engines for longer on the residual propellant. The first burn of the S-IVB third stage successfully put the vehicle into orbit, but a subsequent command to restart the engine failed. Some of the flight's objectives were met, but if the problems could not be fixed, NASA would not dare to put men on top of the next Saturn V, as was being considered instead of a third A-mission test.

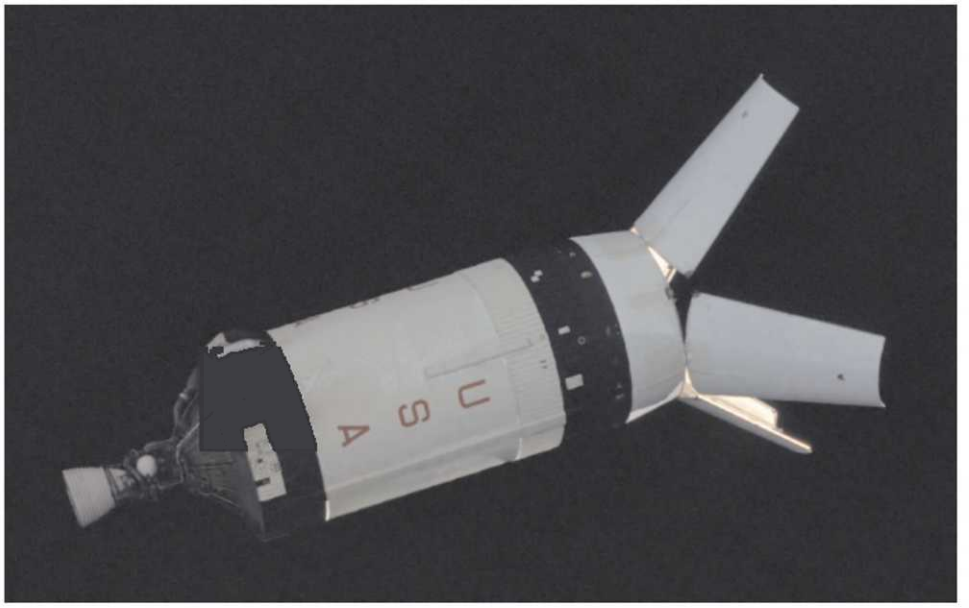
In the event, engineers managed to find solutions for all these problems. The first stage vibrations were suppressed by the addition of helium gas to cavities in the LOX feed lines, which damped out pressure oscillations. Elaborate tests on the J-2 engine discovered a design fault in a liquid hydrogen fuel line that had not only caused one of the engines on the S-II to shut down but also prevented the S-IVB from restarting. Compounding the S-II problem, a wiring error had sent the shutdown command from the Saturn's instrument unit to the wrong engine, shutting it down unnecessarily. The aerodynamic shroud had failed because frictional atmospheric heating as the rocket went supersonic caused trapped moisture and air within its aluminium honeycomb sandwich skin to expand, in turn causing the skin to peel off in sheets. This problem was remedied by making small ventilation holes in the shroud's skin and adding cork insulation.

The launch vehicle issues apart, the CSM-020 spacecraft successfully performed a number of remote-controlled manoeuvres and was recovered from the Pacific Ocean. Preparations for Apollo 7 continued because it would use a Saturn IB launch vehicle. It was decided that if this mission went well, the third Saturn V would indeed carry a crew.

TESTING THE BLOCK II: APOLLO 7

The Apollo programme became a juggernaut towards the end of 1968 as flights were launched every two or three months in the race to achieve Kennedy's deadline. The C-mission of Apollo 7 gave the Block II spacecraft, without a lander, its first manned test. It began on 11 October 1968 with a launch by the smaller Saturn IB vehicle. Its crew of Wally Schirra, Donn Eisele and Walt Cunningham spent 11 days orbiting Earth, which was more than enough time for a mission to get to the Moon and back, and it proved the CSM to be a worthy, spacefaring ship.

As soon as the spacecraft achieved orbit, the crew separated it from the S-IVB second stage and attempted to practise the type of turnaround manoeuvre that would be required of future flights, when the lander would have to be plucked from inside its protective shroud. As soon as he saw the S-IVB, Schirra noticed that one of the four hinged petals of the shroud had not fully deployed. He cancelled a simulated approach manoeuvre for fear of it hitting the spacecraft, and later recommended that the panels be jettisoned instead.



Apollo 7's S-IVB and its deployed shroud petals in Earth orbit. (NASA

The Florida peninsula as seen from Apollo 7. (NASA)

Throughout the early part of the mission, the crew concentrated on achieving their most important goals: firing the main engine repeatedly to make rendezvous passes with the S-IVB (whereupon it was noted that the balky shroud petal had properly deployed) and proving the operation of their navigation system. With these tests satisfactorily performed, the crew spent their remaining time carrying out secondary tests of the Apollo system and completing a programme of Earth photography.

Despite the operational success of the mission, history tends to remember it for the breakdown in relations between the crew and flight controllers in mission control. A dose of the common cold made its normally wise-cracking commander increasingly grumpy. In weightlessness, the symptoms of cold are exacerbated by the inability of the congested head to drain itself. The other two crewmen, both rookies, were drawn into the soured atmosphere with the result that, having irritated management, neither man flew in space again. Schirra had already announced his retirement from space flight.

GUTSY DECISIONS: APOLLO 8

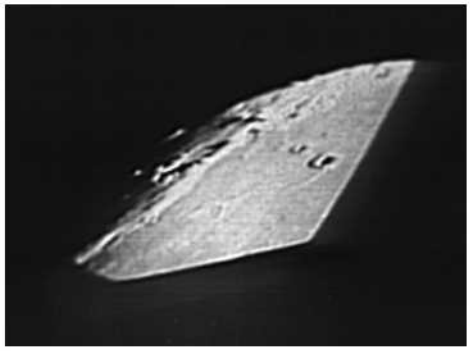
Even before Apollo 7 was launched, managers were dreaming up something special for Apollo 8: an audacious six-day flight to the Moon in a hastily arranged mission which turned an otherwise unfavourable set of circumstances into a blessing.

Apollo 8 had originally been planned as the D-mission, a test of the entire Apollo system including a lunar module in low Earth orbit, on the assumption that Apollo 7 would successfully carry out the C-mission. However, the first man-capable LM was not ready for flight owing to a litany of problems: stress fractures had appeared in some of its structural components; the type of wiring used on the intended spacecraft

The Moon's far side, photographed from Apollo 8 after it departed for Earth. The distinctive dark-floored crater is Jenner, 71 kilometres in diameter. (NASA)

was prone to breakage; and the engine for the ascent stage was prone to combustion instability. Bereft of a LM, managers were unwilling simply to repeat Apollo 7, so they altered the mission sequence and brought the deep-space goals of the E-mission forward, but without a lander.

Furthermore, they took the gutsy decision to send the CSM all the way to the Moon and place it into lunar orbit. Although this would fulfil some of the goals of the E-mission (deep-space tracking, deep-space thermal control, lunar navigation), the fact that it would be a CSM-only flight prompted NASA to label it the C-prime-mission. Although it would provide operational experience needed to manage lunar missions, its unstated purpose was to reach the vicinity of the Moon before the Soviet Union. Intelligence reports suggested that the Soviets were preparing to send a crew on a flight that would loop around the back of the Moon and head straight



TV image of the Moon's sunrise terminator as seen through a spacecraft window, broadcast as the Apollo 8 crew read from the book of Genesis. (NASA)

back to Earth, and the propaganda value of such a circumlunar mission would be immense. On the other hand, if the Americans could get there first, and enter orbit around the Moon, they could claim to have essentially won the space race as long as the Soviets did not achieve a landing.

On the morning of 21 December 1968 Frank Borman, Bill Anders and Jim Lovell rode a Saturn V away from Earth to become the first people to swap the Earth's gravitational hold for that of another world. The three-day long coast out to the Moon gave Jim Lovell plenty of time to practise monitoring the ship's trajectory by taking sightings of Earth, the Moon and the stars. On 24 December 1968, Apollo 8 took its crew around the lunar far side where they fired its SPS engine to enter lunar orbit to begin 10 revolutions, each lasting two hours. As they coasted 110 kilometres above the cratered surface, the crew closely examined two sites that were being considered for the first landing and, along with tracking stations on Earth, practised techniques for navigating while orbiting the Moon. Much of Earth's population with access to television watched with amazement when the crew made an extraordinary Christmas-time black-and-white television broadcast made on the penultimate orbit, during which they read the first few verses from the Bible's *Book of Genesis* while the stark early morning landscape of the Moon passed in front of the camera.

If their burn to enter lunar orbit had failed, the crew would have simply slingshot around the Moon and returned to Earth with little intervention – just as the Soviets intended to do – but the burn had been performed successfully and the spacecraft had entered orbit. It was Apollo 8's next manoeuvre that really scared the managers. Although the SPS engine had been designed for reliability, everyone was aware that its failure would doom the crew to stay forever in the Moon's grasp. Worse, because the engine burn would take place around the Moon's far side, no one on Earth would be able to monitor its progress, and instead would have to wait until the spacecraft re-emerged, hopefully on a path for home. Shortly after midnight in Houston, Texas, on Christmas Day, Apollo 8 reappeared around the Moon's eastern limb exactly on time, with Jim Lovell's playful words to mission control, "Please be informed, there is a Santa Claus."

Apollo 8's voyage to the Moon raised the morale of the many thousands who were working brutally long hours to achieve the landing goal, and by allowing navigation, thermal control and communication procedures to be tested it gave NASA the operational experience it needed to make future lunar trips. On a philosophical level, the flight gave the human race its first glimpse of its home planet as seen from another world. In addition to television views of Earth from a vantage

The first image of Earthrise taken by a human. Bill Anders's Apollo 8 photograph was taken a few seconds before more famous colour images were snapped. (NASA)

point between the two worlds, while orbiting the Moon the awed astronauts photographed their home planet rising over a barren lunar horizon. These photographs would later become a catalyst for the rise of the environmental movement and were true icons of the age.

A COMPLETE SYSTEM TEST: APOLLO 9

By now NASA had confidence in the Apollo CSM, but no one had yet flown inside the flimsy lander that was to take crews to the Moon's surface. NASA ticked the D-mission box by flying the entire Apollo system, consisting of the main spacecraft and a fully configured lander, LM-3, in Earth orbit as Apollo 9. It was to rehearse all the manoeuvres that a Moon flight would require. It also marked the first time astronauts would entrust themselves to a spacecraft that had no heatshield and therefore would not be able to bring them home in an emergency, but it was a trust that would have to be gained if the LM was to take their colleagues to the Moon's surface.

After a successful launch on 3 March 1969, the crew followed a ten-day timeline roughly similar to a lunar mission but without leaving low Earth orbit. This began with retrieval of the LM from its station on top of the S-IVB stage, one of many

firsts achieved in this crammed mission. Controllers on the ground then commanded the now discarded booster to reignite its engine and leave Earth's vicinity, as if dispatching an Apollo mission to the Moon. The spent stage eventually escaped Earth's gravity to enter its own independent orbit around the Sun. After a number of firings of their SPS engine to set up the correct orbit, Jim McDivitt and Rusty Schweickart entered the LM, call sign *Spider*, and powered it up. David Scott remained behind in *Gumdrop*, the CSM. The names selected by the crews simply reflected the shapes of their spacecraft.

Schweickart was to venture out of the LM's front hatch in order to test the type of

Rusty Schweickart's view from the porch of lunar module *Spider* looking along CSM *Gumdrop* with David Scott working out of its side hatch on Apollo 9. (NASA)

spacesuit and back pack that crews were to use on the Moon and demonstrate that, in the event of an unsuccessful docking or a blocked tunnel, a crewman could make his way from one spacecraft to another by using external handrails, but this spacewalk was reduced in scope when Schweickart suffered a bout of space adaptation sickness on the day prior to his task. Managers still had little experience of this condition and allowed him only to move out onto the LM 'porch' to prove the space-worthiness of the suit and back pack, while Scott stood in *Gumdrop*'s hatch to retrieve experiments from the skin of his own spacecraft.

Four days into the flight, McDivitt and Schweickart sealed the tunnel between the two vehicles and undocked *Spider*. After a visual inspection by Scott, they fired the LM's descent engine to move 185 kilometres away from *Gumdrop* and set up the conditions for a lunar-type rendezvous. After the descent stage had been jettisoned, they flew the ascent stage back to the command module, as would happen on a lunar mission, and eventually docked and transferred back to the company of Scott without difficulty.

For the remainder of the flight, the crew practised navigation techniques, made multiple adjustments to their orbit with their dependable SPS engine, and carried out experiments including multispectral photography of Earth in support of future Earth resources satellite programmes and the manned Skylab orbital workshop. Although less glamorous than the missions to come, Apollo 9 was a highly successful overture to Apollo's climax: flying to the Moon.

A DRESS REHEARSAL: APOLLO 10

Most of the major components and procedures required for a Moon landing had been tested, though not always in the context in which they would be needed during a lunar flight. In order to minimise the surprises that might face the landing mission, NASA wanted to practise a complete lunar mission as far as they dare, short of beginning the final descent to the Moon. This dress rehearsal flight, the F-mission, was accomplished by Apollo 10, flown by Tom Stafford, Eugene Cernan and John Young. Their spacecraft were named after characters in Charles Schulz's popular cartoon strip *Peanuts*, who had also featured in NASA campaigns to promote quality control in the programme. The CSM was therefore named *Charlie Brown* while the LM took the name *Snoopy*.

Launch took place on 18 May 1969 and, for the first time, all the functions of the CSM to take a lunar module to an orbit 110 kilometres above the Moon had to work. Once the two docked spacecraft had successfully entered a lunar parking orbit, the crew settled down for their first night in the Moon's vicinity as their ship hurtled above its surface at 5,800 kilometres per hour. Next day, Stafford and Cernan entered *Snoopy*'s cabin, separated from Young in *Charlie Brown*, and took the LM into the same low orbit from which a landing mission would make its final descent. This orbit brought *Snoopy* down to an altitude of less than 14,500 metres above the lunar terrain from where Stafford photographed and described the approach to the landing site that had been selected. The most important task was to prove that lunar

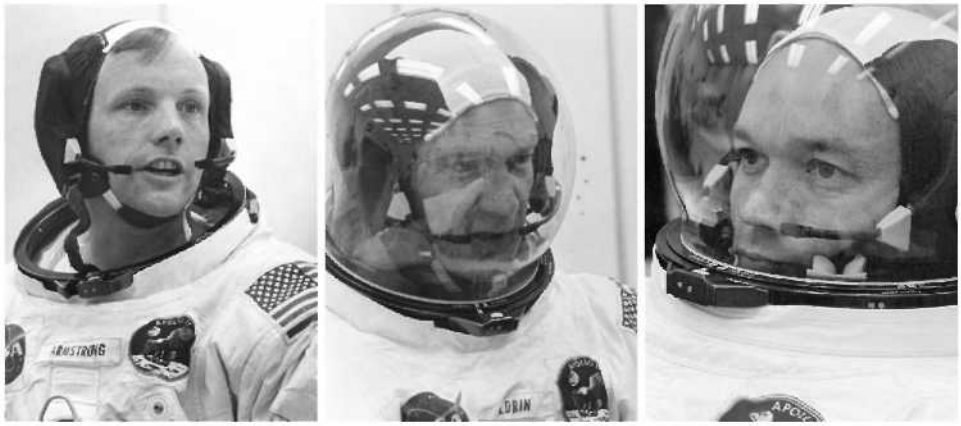
Waypoints to a landing. Left, crater Moltke at 6-km diameter. Right, the Apollo 10 CSM *Charlie Brown* flies above a triangular feature named 'Mount Marilyn' by Jim Lovell. Both features led to way to the Apollo 11 landing site. (NASA)

orbit rendezvous would work as planned. After they jettisoned the descent stage, the ascent engine was used to set up an orbital situation similar to that which would be presented after lift-off from the Moon. NASA's management had once been wary of the idea of two speeding craft being brought into close proximity while in orbit around another world, and they wished to prove that their techniques worked prior to committing a lander to the surface. This successful rendezvous and docking finally cleared the way to a landing attempt.

Thanks to the usual predictability of the gathered media, Apollo 10 is more often remembered for the 'son-of-a-bitch' language Cernan used when a pilot error caused the LM to gyrate unexpectedly as the descent stage was being jettisoned. The journey home was uneventful except for the unprecedented colour television coverage of a receding Moon that was beamed to Earth soon after *Charlie Brown*'s SPS engine was fired. Stafford had promoted the importance of TV on Apollo, not only to the public, but also to engineers and lunar scientists. The 8-day flight of Apollo 10 put NASA on the home straight, leaving the G-mission with no unknowns except the landing itself.

TASK ACCOMPLISHED: APOLLO 11

Apollo 11 departed the Kennedy Space Center in the early morning of 16 July 1969 on a mission that would culminate in an attempt to land on the lunar surface. It is widely quoted that over a million people gathered in the vicinity of Cape Canaveral to witness the start of what promised to be a defining event in human history. For the first four days, its crew of Neil Armstrong as commander, lunar module pilot Edwin 'Buzz' Aldrin and the command module pilot Michael Collins followed a path



The Apollo 11 crew during suiting-up operations before their flight. Neil Armstrong, Buzz Aldrin and Michael Collins. (NASA)

blazed by their predecessors. They even took time out to give viewers to the TV networks an extended tour of their lunar module, *Eagle*, with an improved colour camera.

On the fourth day, Armstrong and Aldrin left the command module, *Columbia*, in the charge of Collins, undocked, and fired *Eagle*'s descent engine to enter the descent orbit around the Moon. As communications proved to be somewhat troublesome, Armstrong reorientated the LM slightly in order to improve reception. On approaching the point where they were to reignite the engine for the landing phase, Armstrong timed the passage of landmarks to determine whether their trajectory was as it should be, and saw that they seemed to be a little ahead. The engine was ignited on time, and after several minutes of continuing to monitor the passage of the landscape below they rotated the LM to allow its radar to take altitude and velocity measurements.

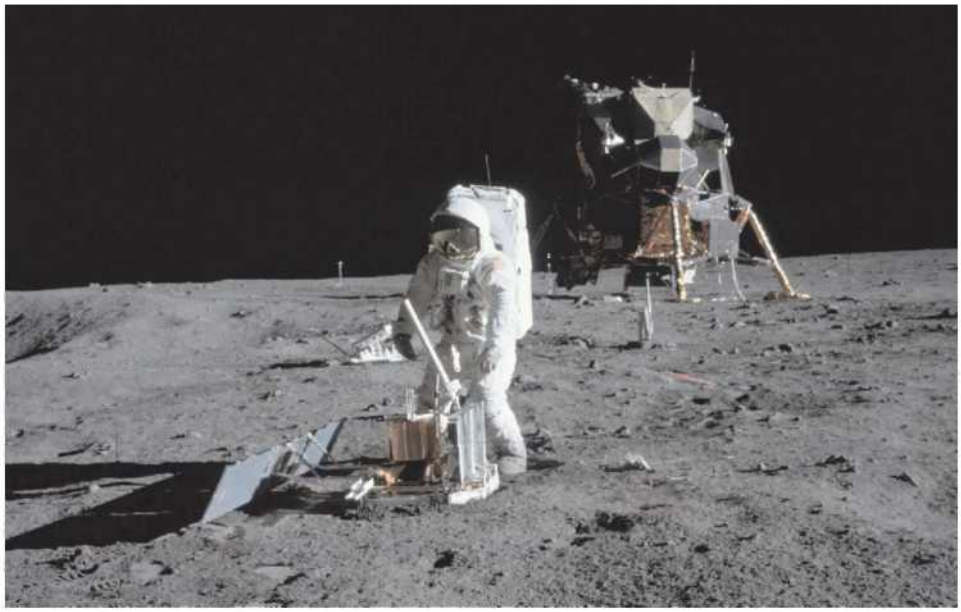
At this point, things became hair-raising, especially for the flight controllers in Houston who lacked the crew's situational awareness. Thanks to a subtle flaw in the spacecraft's electronic systems, the computer began to complain of being overloaded. It displayed debugging codes that were never meant to be seen during a flight and which most people at mission control, as well as the two men in the spacecraft, had little knowledge of. However, just two weeks before the mission, the LM computer experts had studied a large number of such codes, including those that the crew were seeing. Given that the vehicle was otherwise operating normally, they recommended that the descent continue.

Armstrong was able to monitor where on the lunar landscape the computer was guiding them as Aldrin read out relevant numbers. When he saw that their destination appeared to be a boulder field near a large crater, he put himself in the control loop earlier than planned, and manoeuvred to smoother ground 300 metres further along the flight path. Meanwhile, mission control began to worry about a shortage of propellant. When only 15 seconds remained before mission control

would have advised the crew to abort the landing attempt, *Eagle* successfully realised John F. Kennedy's goal on 20 July 1969 by touching down in the southwest corner of Mare Tranquillitatis.

In the minds of the crew the difficult part of Apollo's goal had been achieved, yet the public was more eager to witness an event whose scale was much more human and personal. This was the moment when a man made a boot impression in the lunar dust. Armstrong later pointed out that the moonwalk carried far fewer dangers than manoeuvring seven tonnes of flimsy spacecraft loaded with explosive propellants down onto an unknown rocky surface on the end of a rocket flame, while surrounded by a hard vacuum. Nonetheless, it was inconceivable that a crew would land on the Moon and *not* walk on the surface!

Over the subsequent hours, in one of the most memorable television events in human history, Armstrong and then Aldrin descended the ladder onto the lunar surface. Observed by a black-and-white television camera whose mode of operation gave them a ghostly appearance, they took photographs, collected samples and set up three simple scientific experiments: a small seismometer, a laser reflector and a solar wind collector. The social significance was not forgotten when the flag of the United States was raised on behalf of the nation that had paid for the venture. Additionally, a plaque was unveiled to inform any future visitors to Tranquillity Base that its first visitors "came in peace for all mankind" and the two explorers took a telephone call from President Richard Nixon. After 2½ hours, the moonwalk ended. Armstrong and Aldrin took their exposed film and a box of lunar samples up to the ascent stage, repressurised the cabin and tried to get some fitful sleep before



Buzz Aldrin deploys a seismometer at Tranquillity Base on Apollo 11. (NASA)

performing lift-off for the second time in less than a week. Their return to Collins in *Columbia* and the trip back to Earth were uneventful, concluding with a landing in the Pacific Ocean on 24 July.

The Apollo programme had been designed to be aggressive from the outset, with launch facilities at KSC constructed for multiple or closely spaced launches. Now, with the moonlanding successfully accomplished, and America's spending on the Vietnam War draining the nation's purse, the scale of lunar exploration was cut back by Congress. Nevertheless, the sheer momentum of the programme brought another landing attempt only four months later.

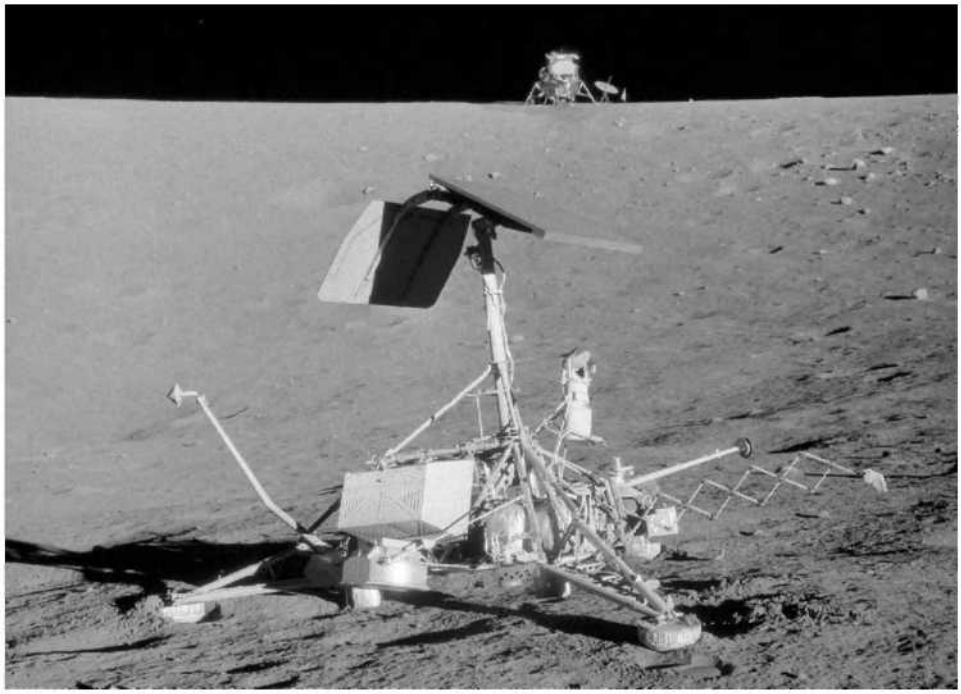
LIGHTNING STRIKES: APOLLO 12

By concentrating almost single-mindedly on the goal of a manned lunar landing, secondary considerations like landing accuracy and science had taken a back seat. In the event, Apollo 11 had landed about seven kilometres beyond its planned site and for some time, no one knew exactly where they were. Not even Mike Collins had been able to see *Eagle* through his sextant – a powerful optical instrument built into *Columbia*'s hull. The science payload had been severely limited by mass constraints and lack of time. Future missions would make amends because the United States had invested heavily in the infrastructure to support Apollo and wanted to see results. It also demanded justification for the continuing costs. Fittingly, science became that justification.

To gain knowledge from the Moon, NASA had to go to sites where Earth-based and orbital imagery suggested that answers to questions might lie. However, given the limited walking range of an astronaut on the lunar surface, the ability to land 'on target' became paramount. Although Apollo 12 was not sent anywhere of particular geological importance, it was given a very small target to aim for. Specifically, it was to land within walking distance of Surveyor 3, a small robotic lander that NASA had sent to Oceanus Procellarum in April 1967.

The mission courted disaster in its first minute when the vehicle flew through a rain cloud and invoked a lightning strike. Regardless, the crew continued to the Moon amid fears that their command module may have been damaged by the surge of power that had passed through it. In the event, the CSM *Yankee Clipper* proved to be unharmed, and on 24 November 1969 Charles 'Pete' Conrad and Alan Bean landed their LM *Intrepid* some 1,500 kilometres west of where *Eagle* had landed and a mere 200 metres from Surveyor 3. This demonstrated that ground controllers and crew could bring a lunar module down exactly where they wished. Richard Gordon, orbiting overhead, confirmed their position by spotting both the LM and the Surveyor on the surface through his sextant.

Since Apollo 12 was an H-mission, Conrad and Bean made two moonwalks. On the first they laid out an ALSEP which was an autonomous scientific station that operated on the lunar surface for many years after they left. The next day they hustled across the surface taking a circular route of over a kilometre, pausing at preplanned points of interest on the way to visit the Surveyor probe. After examining



The unmanned spacecraft, Surveyor 3, with the Apollo 12 LM *Intrepid* beyond. (NASA)

and photographing the probe, they removed pieces to enable researchers to study how well the hardware had survived 31 months of exposure to the lunar environment. In terms of public relations, the low point for this fun-loving crew was when their television camera was ruined early in the first moonwalk by being inadvertently pointed at the Sun. TV networks struggled to provide a visual accompaniment to the crew's voice communication and audiences quickly became bored of listening to indistinct and often arcane yakking by the two guys on the surface. Nonetheless, like every crew after them, Conrad's and Bean's two joyous forays out on the surface yielded samples of greater bulk than the previous mission, and the scientists were more than happy with what they brought back. In particular, tiny grains of a very slightly radioactive rock type began to lift the lid on important aspects of the Moon's early history.

Despite concern that it may have been damaged during launch, *Yankee Clipper*'s successful splashdown concluded a successful, if charmed 10-day mission that was marred only by the loss of the TV coverage.

THE SUCCESSFUL FAILURE: APOLLO 13

Now that NASA knew how to land accurately on the Moon, it could pursue its science goals with increased vigour with a view to finding out how the Moon formed

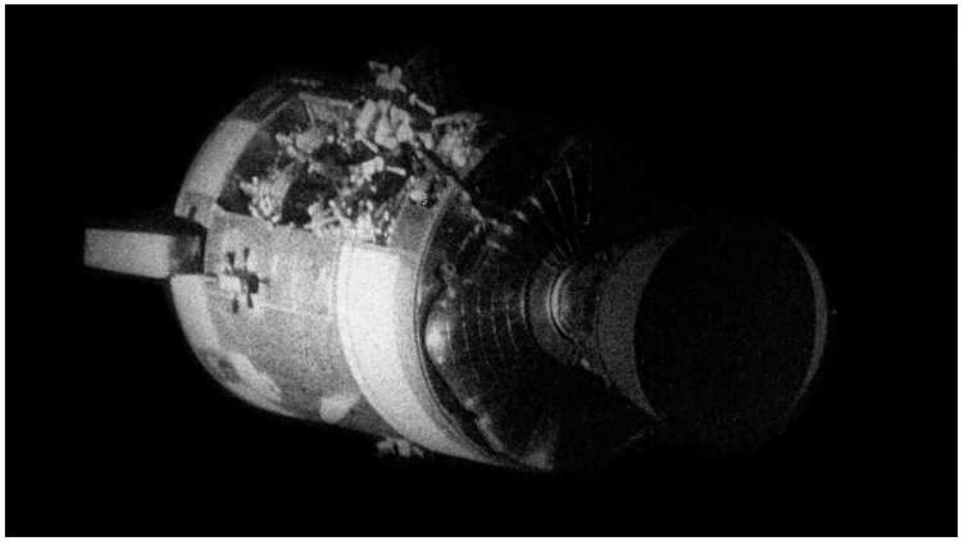
although whether the tax-paying American public wanted to know this information is a moot point. Lunar studies before Apollo had focused upon one large feature as perhaps being a key to understanding much of the visible lunar landscape. This was Mare Imbrium, a lunar 'sea' that is readily visible from Earth. In reality, it is a vast circular structure, fully 1,300 kilometres in diameter, that was formed by the impact of an asteroid early in lunar history. The resultant depression was subsequently filled with dark lava. Like any impact structure, the Imbrium Basin would have been surrounded by a blanket of material ejected during its formation. The cadre of lunar scientists involved in Apollo believed that much could be learned by sampling this ejecta blanket, which appeared to dominate the near side. To sample it, they proposed a landing site for Apollo 13 in hummocky terrain just north of the crater Fra Mauro, and Apollo 12 took pictures to assist in planning.

Apollo 13's first problem occurred several days before its 11 April 1970 launch, when command module pilot Ken Mattingly had to be replaced by his backup, Jack Swigert, owing to a possible exposure to rubella. The glitches continued soon after launch when one of the five engines in the second stage of the Saturn V shut down prematurely. However, these issues were as nothing compared to what occurred almost 56 hours into the mission. When Swigert operated fans to stir the contents of an oxygen tank in response to a request from mission control, the tank violently burst. The resultant shock blew out one of the skin panels of *Odyssey*'s service module and damaged its oxygen system sufficiently to cause most of the spacecraft's supply of this vital gas to leak out to space. At that time, Apollo 13 was 328,300 kilometres from Earth and 90 per cent of the way to the Moon.

This traumatic event deprived the spacecraft of electrical power and began a four-day feat of dedication, ingenuity and endurance by the crew, the flight control team and thousands of support staff to effect a safe return to Earth. Every system in the SM was rendered inoperable by the blast itself, by the lack of power, or by concern that it may have been damaged and represented part of the problem rather than part of the solution. The CM had to be powered down very quickly to save its remaining consumables, as they would be needed for re-entry into Earth's atmosphere. This left the LM *Aquarius* as the only means of sustaining the crew while the two joined ships flew around the Moon for a slingshot back to Earth. It also became the sole means of manoeuvring to speed up the return trajectory and control the accuracy of its arrival.

Without power, the interior of the spacecraft soon cooled to around 6°C. In these uncomfortably low temperatures, the crew grew increasingly exhausted as they took refuge in the LM while nursing their dead CSM to the safety of Earth, its command module being the only way to pass through the atmosphere. During the long fall to Earth, they had to construct devices to remove toxic carbon dioxide from their air, work through complex checklists to fire the LM's main engine, and also improvise a means of firing it for the correct duration while ensuring that it was correctly pointed. They found themselves carrying out difficult and often completely new procedures without having slept for days.

In the flight's final moments on 17 April as it re-entered Earth's atmosphere, the world was gripped by the tension of not knowing whether *Odyssey*'s heatshield had been damaged by the blast. A safe splashdown in the Pacific Ocean ended a failed



Apollo 13's shattered service module. (NASA)

The exhausted crew of Apollo 13 after their recovery from the Pacific Ocean. Left to right; Fred Haise, Jim Lovell and Jack Swigert. (NASA)

mission that became perhaps the finest hour for a spacecraft's crew, its ground control team and their supporting organisations. It showed that in spaceflight, and in the face of terrible odds, toughness and competence could win through.

Despite the superstition that surrounds the flight number, and knowing with hindsight that the spacecraft left Earth with a flaw on board, Apollo 13's oxygen tank rupture occurred at just about the most opportune time. Much earlier and their coast to the Moon and back would have been too long for the LM to sustain them. Much later, and they might not have had a LM available to act as a lifeboat. In fact, it was a case of *lucky* 13.

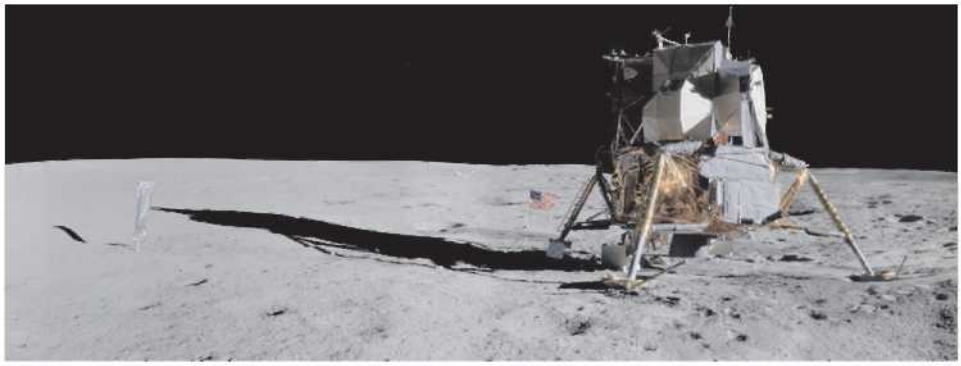
TRY AGAIN: APOLLO 14

With Apollo 13, NASA had dodged a bullet. The flight had very nearly killed its crew and, as always happens when it is hit by traumatic events, NASA needed a hiatus to investigate and understand what had disrupted *Odyssey*'s service module. Although there were calls from both inside and outside the administration to end Apollo before anyone else got killed, its managers kept faith with it. The programme of exploration which they instituted, now almost forgotten, visited immensely beautiful sites with spectacular vistas. Enhanced equipment allowed crews to explore further from the LM, and although the results from these missions had little political impact, their scientific findings now underpin our understanding of the early history of the solar system.

Apollo 14 returned the programme to the Moon to achieve what its predecessor had set out to do: visit the Fra Mauro area to gain insight into the formation of the Imbrium Basin. The precise target for the lunar module *Antares* was near a relatively fresh impact feature dubbed Cone Crater. The scientists' interest in Cone arose from a useful property of crater formation whereby, when an impactor hits the ground, it removes the target rock in such a way that the most deeply excavated material ends up at the rim of the crater and material from successively shallower depths is deposited at increasing distances in an ejecta blanket. By having the surface crew of Alan Shepard and Edgar Mitchell radially sample this blanket as they walked towards its rim, geologists hoped to use Cone Crater as a convenient 25-million-year-old 'drill hole' to sample down through the ejecta blanket of the Imbrium Basin impact itself, which is now thought to have occurred 3.91 billion years ago.

The launch from Earth on 31 January 1971 was successful, and once they were on course for the Moon command module pilot Stu Roosa separated CSM *Kitty Hawk* from the S-IVB, turned around and attempted to dock with the LM *Antares*. For reasons that have never been clear, the docking was unsuccessful, and five further attempts were required to capture the lander. At the Moon, just before *Antares* was due to begin its powered descent to the surface, an intermittent short circuit threatened to abort the mission as soon as its engine ignited. A virtuoso engineering effort between mission control and the crew reprogrammed the computer, instruction by instruction, to work around the problem.

Being the last of the H-missions, the surface crew were scheduled two excursions



Apollo 14's LM *Antares* and the landing site at Fra Mauro. (NASA)

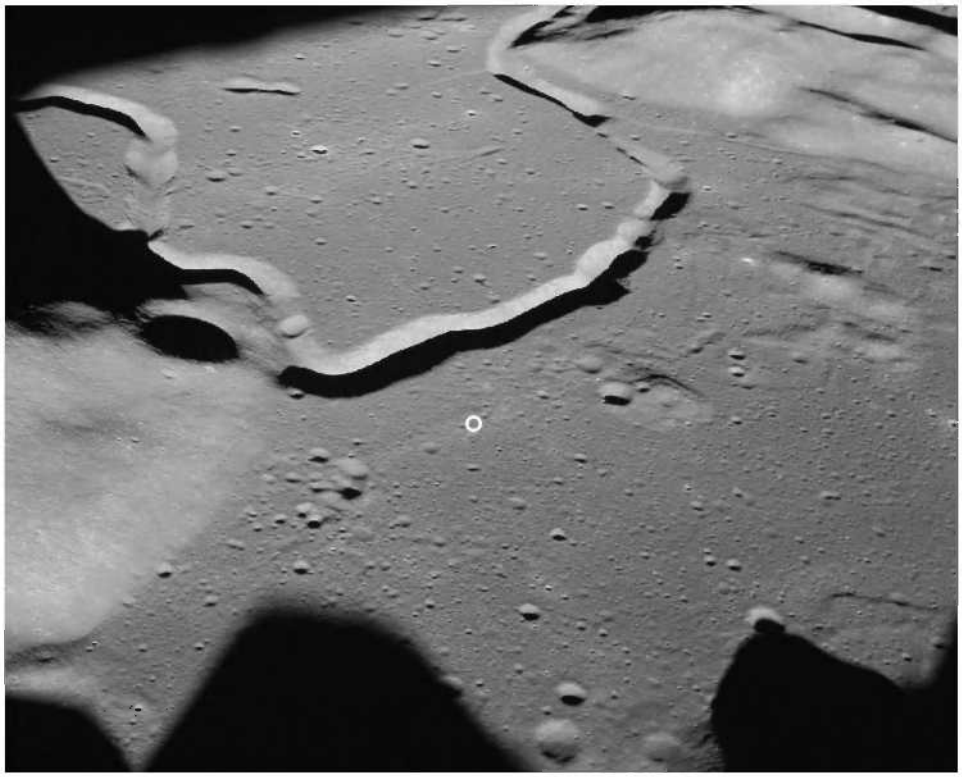
outside. On their first day, Shepard and Mitchell set up a second ALSEP science station and explored their locale. On their second day they were to undertake a trek of over a kilometre across the hummocky plain and up a shallow ridge to approach the 370-metre-diameter Cone Crater. The climb proved to be tiring and, as they neared the summit, they experienced difficulty in locating the crater. They had come 400,000 kilometres to get to this rim but were reaching the safe limits of their oxygen supply. With time running out, they collected a clutch of samples and turned back. Analysis later showed that they had navigated to within 30 metres of the rim, which was near enough for their samples to represent material from deep within the Imbrium ejecta.

Back at the LM, Shepard pulled off a famous stunt by attaching a genuine golf club head to the shaft of one of his tools and hitting golf balls he had smuggled to the Moon. Meanwhile, in lunar orbit, Roosa had planned an aggressive campaign of orbital photography with a high-resolution mapping camera attached to the hatch window. When the instrument failed early on, he was able to accomplish some of his photographic assignments by clever flying and using handheld cameras.

Apollo 14 was a highly successful mission that restored NASA's confidence and prepared it for the triumphs of exploration and science to come. It was also the last time lunar explorers were required to undergo a period of biological isolation after landing on Earth. The returned rocks allowed geologists to probe the nature of the ejecta from the formation of the Imbrium Basin. They could apply the principle of superposition, whereby one feature can be seen to overlie another, to distinguish between pre-Imbrium and post-Imbrium landforms.

EXPLORATION AT ITS GREATEST: APOLLO 15

The final three flights of the programme took Apollo to new and worthy heights of exploration, science and discovery. Since the engineering had been largely proved, science became the driving force behind the choice of landing site and the equipment to be carried. Both the LM and CSM were upgraded to carry more supplies and



The Apollo 15 landing site (circled) next to the 1.5-km-wide Hadley Rille. (NASA)

increase their endurance. To further facilitate this final push for knowledge, a small fold-up electric car was carried on the side of the lunar module and a suite of sensors and cameras were fitted into an empty bay of the service module. The capabilities of the Apollo system were pushed ever further by extending the J-missions to 12 days.

Scenically, Apollo 15 had everything. Its target was an embayment of a lunar plain bounded by the stunning mountains of the Apennine range and a meandering channel called Hadley Rille. It was well north of the equatorial band to which Apollo had heretofore been restricted, but the relaxation of operational constraints made such a mission viable. It was an enchanting site for exploration, where the story of the Moon's most ancient time began to be revealed.

Apollo 15's launch from Earth on 26 July 1971, while as spectacular as any, gave no surprises. The coast to the Moon was punctuated by a fault in the main engine's control circuits and a leak in the CM's water supply, both of which were dealt with successfully. Once they had landed at Hadley Base, the crew of the LM *Falcon*, David Scott and Jim Irwin, depressurised the cabin to allow Scott to survey the site by poking his head out of the top hatch of the lander. The following three days saw the two explorers carry out a relentless programme of exploration that sampled the rocks of both the mare beneath them and the adjacent mountains beside them. A

ground-controlled TV camera on their rover allowed their audience to accompany them as they visited landscapes that Capcom Joe Allen described as "absolutely unearthly". The presence of the rover changed the rules of lunar exploration. Instead of working near the LM for the first part of a moonwalk, then going on an excursion, a rover-equipped crew jumped on board and made tracks as soon as they could so that, if it failed, they would have adequate reserves of oxygen to walk back to the safety of the LM.

The TV view along Hadley Rille described as "absolutely unearthly". (NASA)

Their first excursion took them on a drive to where Hadley Rille ran below Mount Hadley Delta. Scott said the vehicle was somewhat sporty to drive, but both crewmen benefited from the rest gained while driving between stops. Upon their return, they set up a third ALSEP science station and in trying to emplace sensors for a heat-flow experiment Scott had difficulty in drilling into the lunar soil. Although the material was an unconsolidated mass of powder and debris, over a period of billions of years it had become so compacted as to be as hard as rock. The drill had to be redesigned for the next mission.

In their second excursion they drove up the lower slopes of Mount Hadley Delta, where they hoped to find fragments of the original lunar crust. Near a fresh crater they collected a likely candidate which the press instantly dubbed the 'Genesis Rock' because scientists said they hoped the sample would yield insight into the Moon's earliest era. Back at the LM, Scott battled once more with the balky drill. Although he managed to obtain a core that was more than two metres long, he found he could not pull it out of the ground. With the surface mission far behind the planned timeline, the third moonwalk was shortened. On their final outing, and with Irwin's help, Scott managed finally to extract the deep core. Then they drove to the edge of Hadley Rille where they could see layers of lava exposed in the opposite wall. As a final flourish, this time in the name of science rather than golf, Scott carried out a simple experiment in which he simultaneously dropped a hammer and a falcon feather in order to prove the theories of Galileo and demonstrate that objects of differing mass fall at the same speed in the absence of air.

While the surface crew redefined lunar surface exploration at Hadley Base, Alfred Worden operated the apparatus built into CSM *Endeavour*. As it orbited the Moon, large swathes of terrain were photographed with modified reconnaissance cameras, and the surface was surveyed with instruments that could determine the composition of the lunar material. A laser altimeter measured the varying elevation of the ground passing beneath, obtaining data which quickly demonstrated the relationship between the highlands and lowlands and, along with how their composition differed, insight into the Moon's history. Before departing for Earth, the crew deployed a

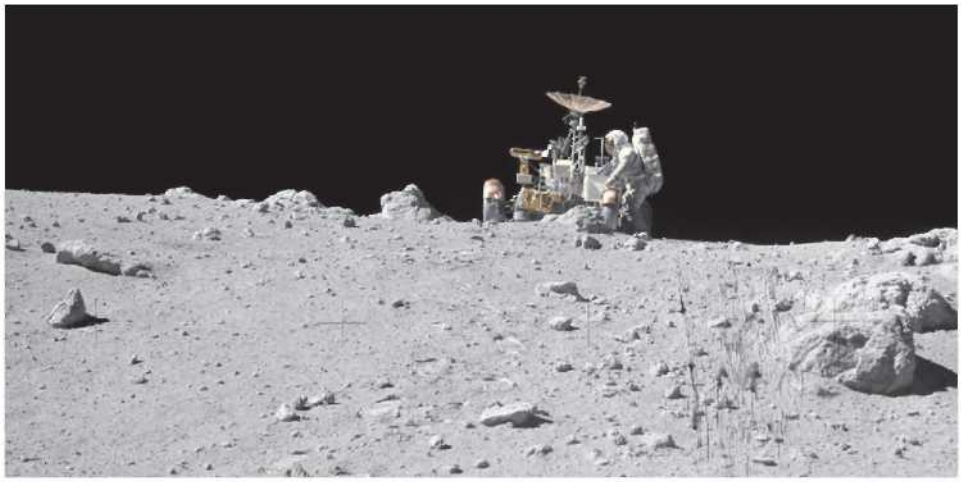
subsatellite that reported measurements of the Moon's environment for seven months.

The knowledge gained from Apollo was beginning to tell a story of an ocean of molten rock whose surface cooled to form an aluminium-rich crust. This was then punctured by massive asteroid impacts whose wounds were later filled in as iron-rich lava welled up through deep fractures. It was a story that would also tell of Earth's earliest years.

NEW KNOWLEDGE: APOLLO 16

The scientific feast continued with Apollo 16, launched on 14 April 1972 to explore what were believed to be 'highland volcanics' within the rugged hills near the crater Descartes towards the centre of the Moon's disk. Its crew of John Young, Charlie Duke and Ken Mattingly nearly had to abort their mission some hours before landing. When Mattingly tried to test the back up steering system of the main engine on board the CSM *Casper* preparatory to a scheduled burn, it began to wobble violently. Once this glitch had been overcome, Young and Duke made a successful landing six hours late in their LM *Orion*.

After a night's sleep, they stepped onto the surface, immediately prepared their rover, and set up their ALSEP science station. Although Duke had no difficulty drilling into the surface for the heat-flow experiment, Young inadvertently disabled the instrument by tripping over its cable. Their first traverse was a short one to craters where they only found breccia or 'instant rock', made in the high-energy environment of an impact event when fragments were bound together by the melting of powdered rock. Their second and third days also concentrated on traverses, seeking signs of the expected volcanism but finding only beat-up rocks of a vast



Charlie Duke works at the lunar rover near North Ray Crater during Apollo 16. Contamination to the film acquired during the mission is visible to the right. (NASA)

John Young and the lunar rover next to Plum Crater during Apollo 16. (Panorama by Erik van Meijgaarden from NASA images.)

ejecta blanket. In orbit, Mattingly continued the same type of observations that Apollo 15 had made, but over a largely different swathe of terrain.

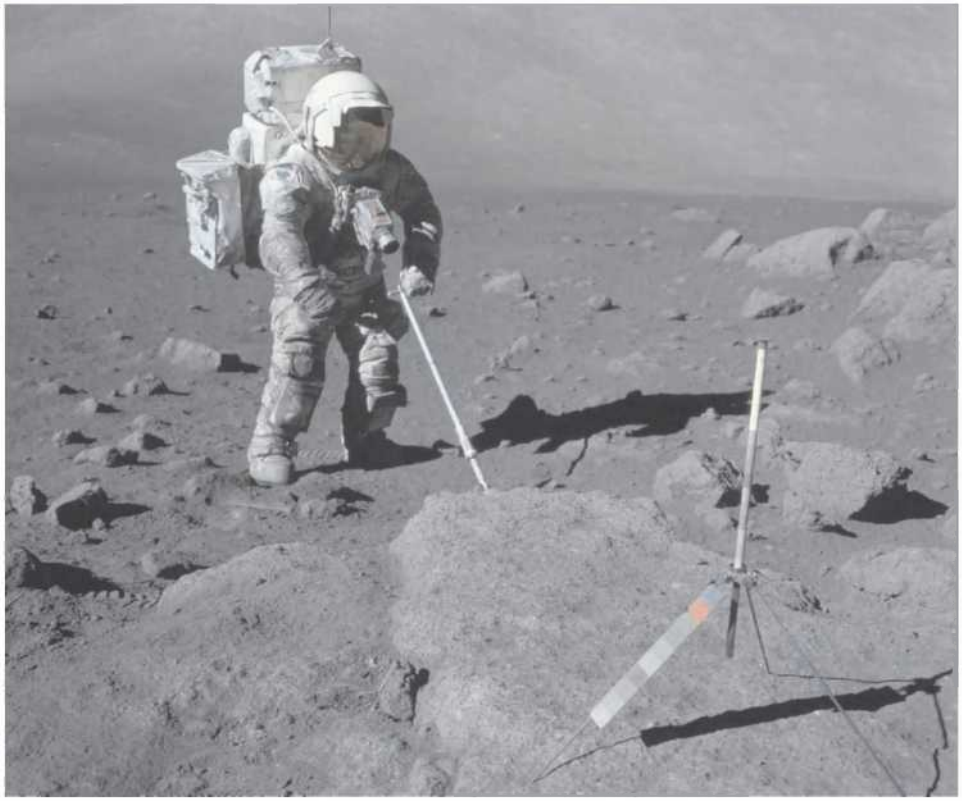
The surface crew returned to the CSM and then, in view of the problem with their engine's steering, departed lunar orbit a day early. Apart from being unable to release their subsatellite into the correct orbit, this curtailment of the Apollo 16 flight barely impinged on the quantity and quality of its results.

It was an example of classic scientific research. A hypothesis had been proposed by geologists to explain the origin of light-toned plains that were visible across some areas of the lunar highlands. Part of Apollo 16's brief was to test this hypothesis, and with samples and observations to hand, the theories were proved wrong. However, this is how scientific progress is made, because it prompted a new hypothesis and a better understanding of the Moon's evolution as a planetary body.

THE LAST HURRAH: APOLLO 17

Apollo's final lunar mission took advantage of behind-the-scenes lobbying by the lunar science community to have a professional geologist visit the Moon. Many of the astronauts, whose backgrounds were usually in the fighter-pilot/test-pilot milieu, believed that a dangerous environment such as an experimental spacecraft in the vicinity of the Moon was just not the place to take someone who was not already inculcated in the philosophies surrounding aviation. Indeed, it was a requirement for the five scientist/astronauts recruited by NASA in 1965 that they learn to fly jets. Only one of them, Harrison 'Jack' Schmitt, was a geologist, and he proved a worthy representative when he flew with Eugene Cernan and Ron Evans on the Apollo 17 mission to explore a region of unusually dark soils in a valley near the shores of Mare Serenitatis.

The interest in this site was stirred by Al Worden's observations during Apollo 15 of dark halo craters on the floor of the valley which looked like a possible source of continuing lunar volcanism. Apollo 17's launch on 7 December 1972 was notable by

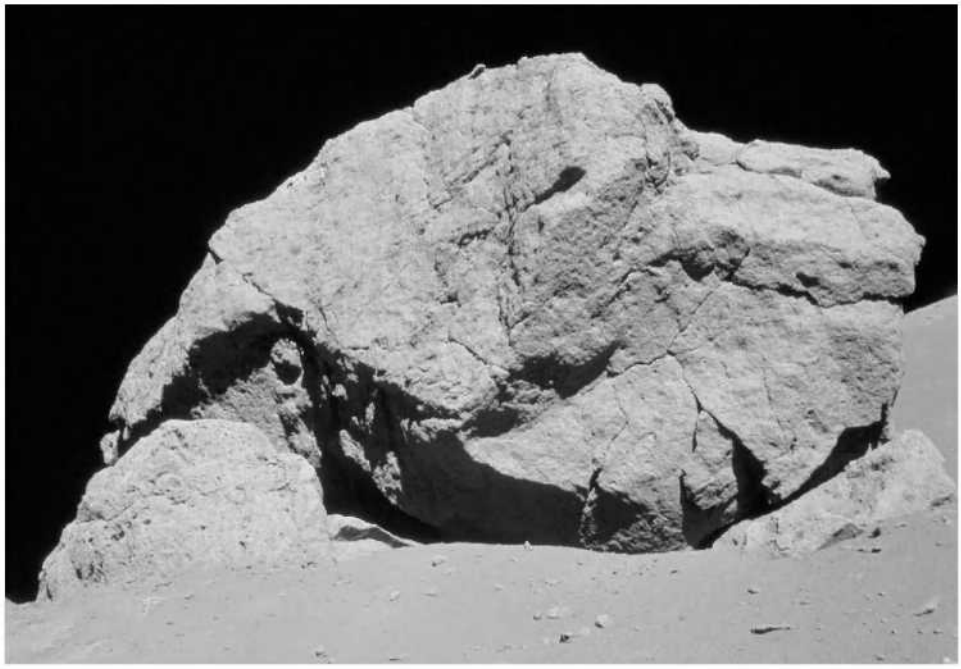


Jack Schmitt, his suit grimy from two days' work on the Moon, conducts geology at Camelot Crater. (NASA)

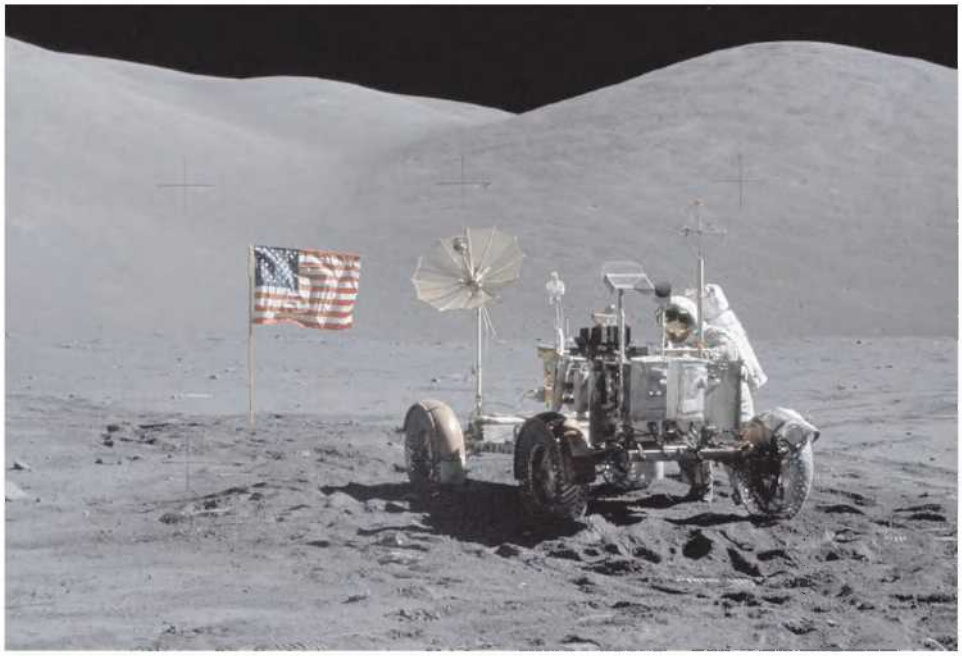
being the only night launch in the programme, with the Saturn V's fire rising like an artificial sun to illuminate the eastern coast of Florida. To reach the landing site, the spacecraft had to adopt a Moon-bound trajectory that took longer than any previous mission. The subsequent orbital dance around the Moon was the most involved of all the missions. Having landed, Cernan and Schmitt immediately began preparations to exit the LM *Challenger*, deploy their rover and set up their ALSEP science station. As had Scott on Apollo 15, Cernan had difficulty extracting the deep core drill from the ground, despite having a special jack to aid him in the task. The extra time taken meant that a planned drive to a nearby crater had to be curtailed.

On their second day, during a moonwalk that lasted over 7½ hours, they drove over seven kilometres west to the base of a mountain. Here they sampled boulders whose tracks indicated that they were from outcrops further uphill, thereby enabling the astronauts to collect rock from sites that were well beyond the rover's reach. On the way back they stopped at a crater that was later named 'Ballet' because Schmitt lost his footing while sampling, and performed wild gyrations in an attempt to regain his balance.

A frisson passed through those conducting the mission, both on Earth and Moon,



Eugene Cernan and Jack Schmitt's split boulder. (NASA)



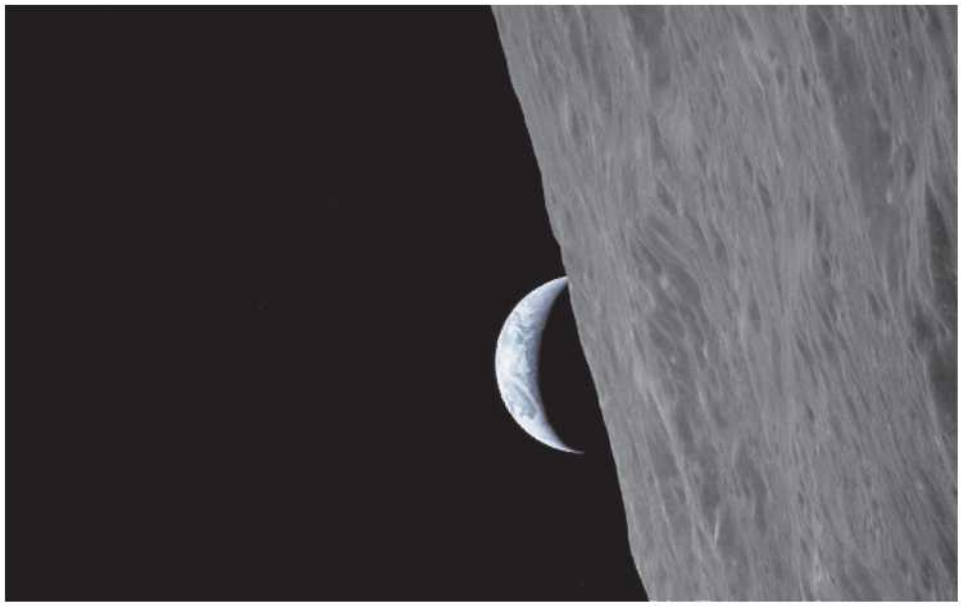
Eugene Cernan at the rover during Apollo's final moonwalk. (NASA)

when deposits of orange soil were found on the rim of one of Worden's dark halo craters. Nothing like it had ever been seen on previous missions, and its colour suggested iron oxidation or rusting, something that normally requires water – a substance notable by its apparent absence on the Moon. Subsequent analysis of the material showed that it was certainly due to volcanism, but of an ancient variety when spectacular fire fountains had sprayed droplets of molten rock hundreds of kilometres into the sky some three billion years ago. It had simply been excavated by the impact that made the crater.

A productive range of stops on the final moonwalk of the Apollo era included a visit by Cernan and Schmitt to another mountain where a split boulder had come to rest. Schmitt's expert eye spotted the signs of alteration that showed how more than one massive impact had worked and reworked the Moon, and by implication, Earth during their infancy.

Evans, working in the CSM *America*, was not idle either. The complement of instruments built into the side of his service module had been changed compared to what Apollo 15 carried because its orbit would repeat much of *Endeavour*'s swathe. As with the two previous missions, thousands of high-resolution images of the Moon were taken on giant rolls of film that Evans retrieved during the coast back to Earth by exiting the hatch and manoeuvring hand-over hand along the SM.

The visit of Apollo 17 to a site nearly as grand as Hadley was the peak of a spectacular mission that brought the initial human exploration of the Moon to a highly successful close.



The view of Earth as Apollo 17 came around the Moon. (NASA)

GOODBYE APOLLO

Although Apollo 17 ended the lunar phase of the Apollo programme, America's investment in its hardware and infrastructure continued to pay back for three more years. A spare S-IVB stage became an orbital workshop called Skylab. This massive 77-tonne space station was launched by a Saturn V on 14 May 1973 and serviced by three crews riding modified Apollo CSMs launched by Saturn IBs. The crews stayed on board for one, two and three months respectively. The final Apollo flight was also to Earth orbit as part of the Apollo-Soyuz Test Project in 1975, again using a Saturn IB, when an American Apollo and a Soviet Soyuz spacecraft met and docked in space as a political act of detente, thereby ending the 'space race' amicably. The two remaining Saturn Vs were turned into lawn ornaments.

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