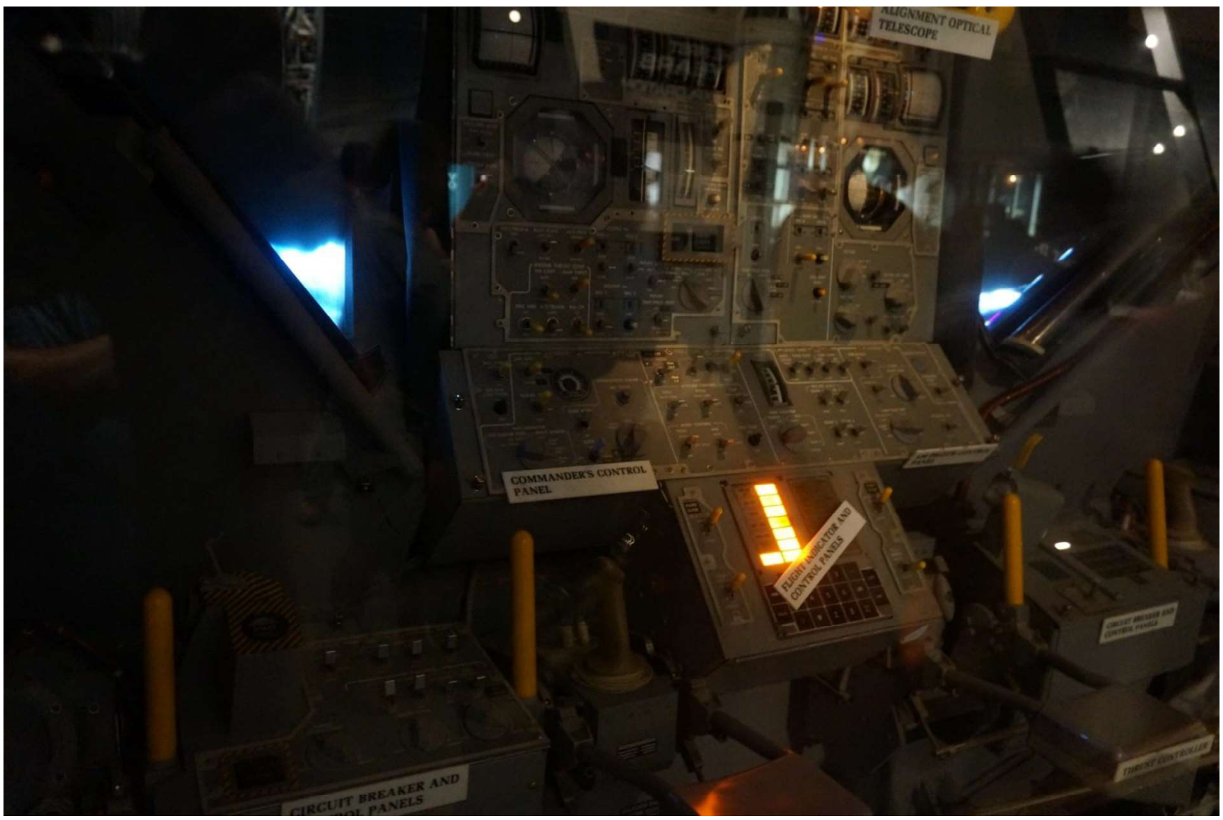
LM Interior, Main Control Panel [NASM]

[Note "DSKY" Data Entry Keyboard for PGNS Computer (center).]

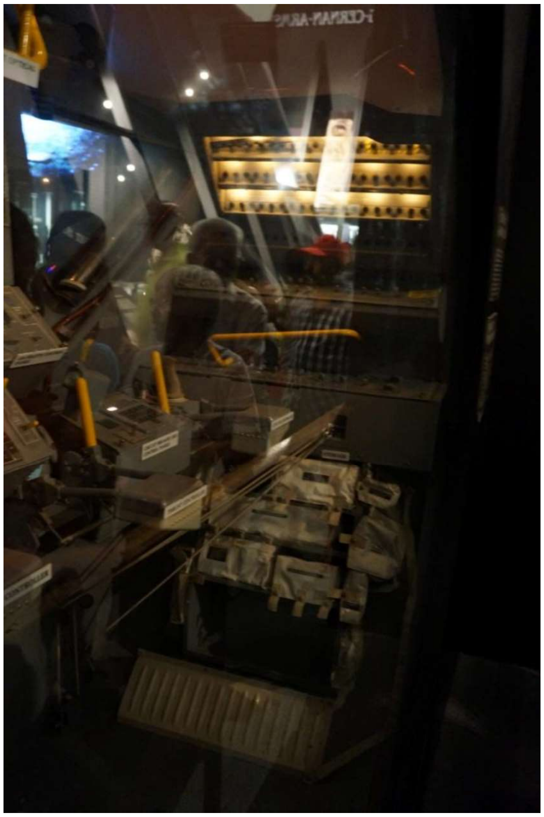


LM Interior, Commander’s Control Station (Port Side of Cabin)

[Note Hand Controller for Thrust (left) and Attitude “Joystick” (right).] [NASM]

LM Interior, Lunar Module Pilot's Control Station (Starboard Side)

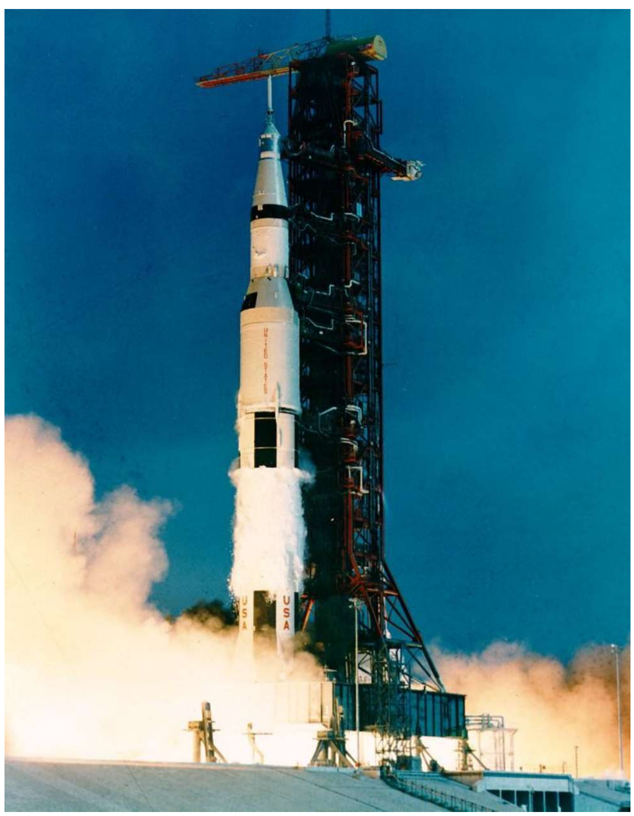
[Note Fuse Panel to LMP's Right, and AGS Data Entry Keyboard (center).] [NASM]



Another Son of Ohio, and American Hero:
Neil Armstrong, Commander, Apollo 11
(The First Human to Set Foot on the Earth's Moon)

The Apollo 11 Crew:
Commander Neil Armstrong, CMP Michael Collins, LMP Edwin Aldrin

The Apollo 11 Saturn V Space Vehicle Lifts Off on July 16, 1969



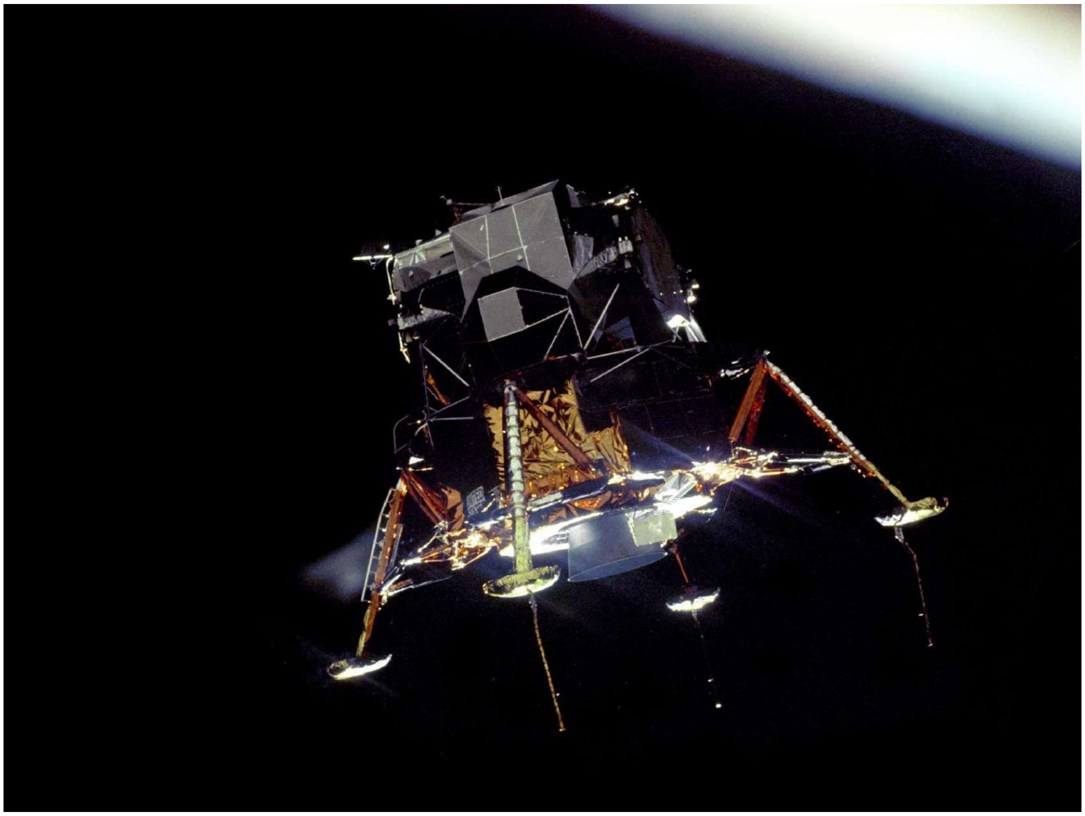
The Launch of Apollo 11 on July 16, 1969

(Taken from the top of the Launch Umbilical Tower, or LUT.)

The Lunar Module "Eagle" in Lunar Orbit Shortly Before Descent to the Lunar Surface

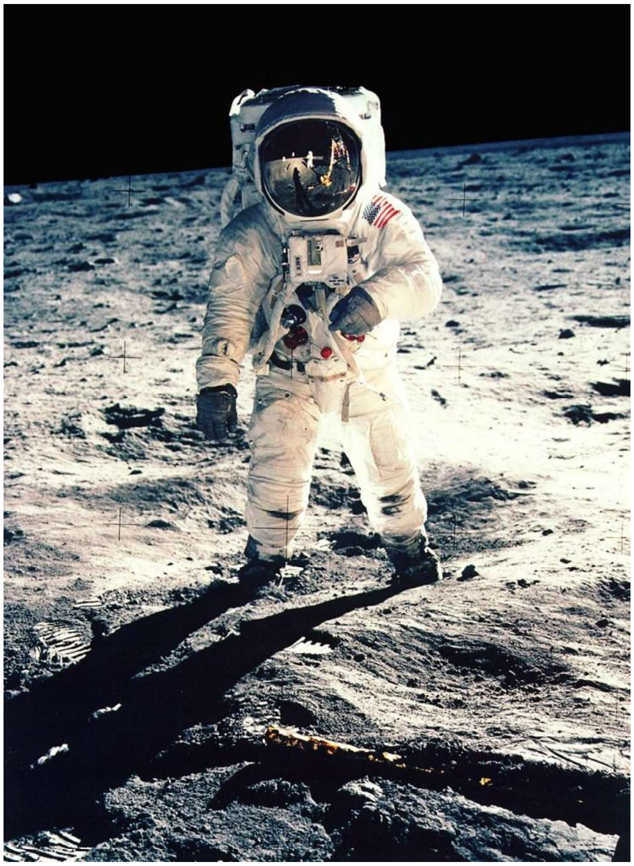
(Photo Taken by CMP Mike Collins During Visual Inspection)

[Note 6′ Long Surface Probes on 3 of 4 Footpads, Designed to Detect Lunar Contact and Stimulate Engine Shutdown.]



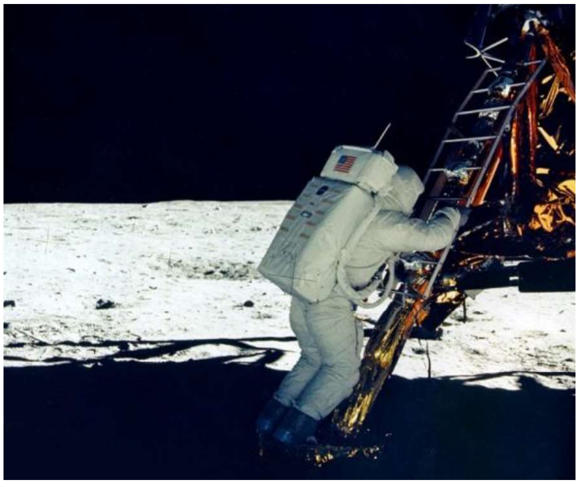
Apollo 11 Lunar Module Pilot Edwin "Buzz" Aldrin on the Moon, at the Sea of Tranquility

(Photo Credit: Taken by Mission Commander Neil Armstrong.)

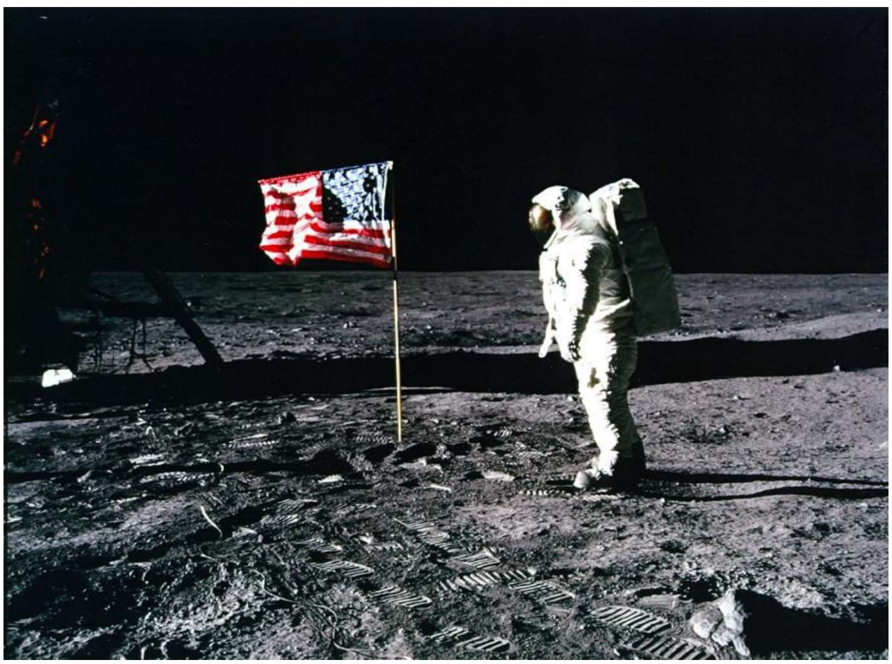


LMP "Buzz" Aldrin's Egress from "Eagle" on the Sea of Tranquility (July 20, 1969)

[Note Personal Life Support System, known as the "PLSS" backpack.]

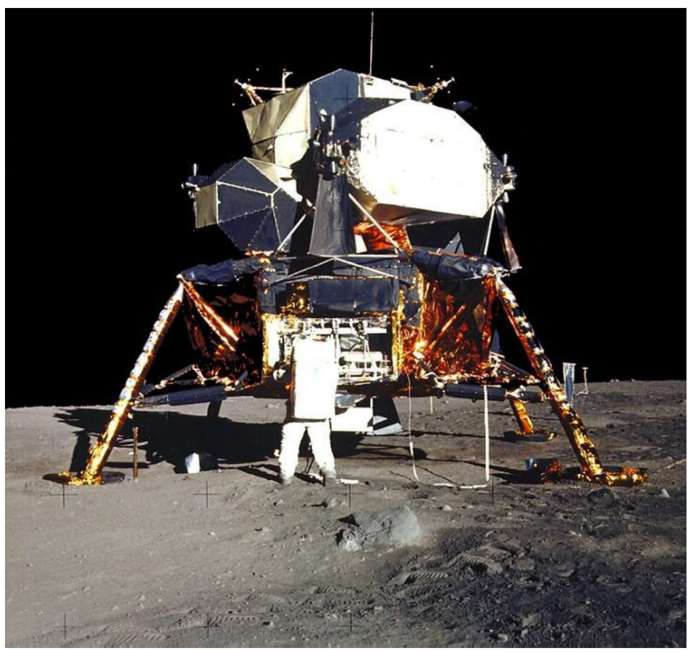


"Magnificent Desolation"



Lunar Module "Eagle" on the Sea of Tranquility

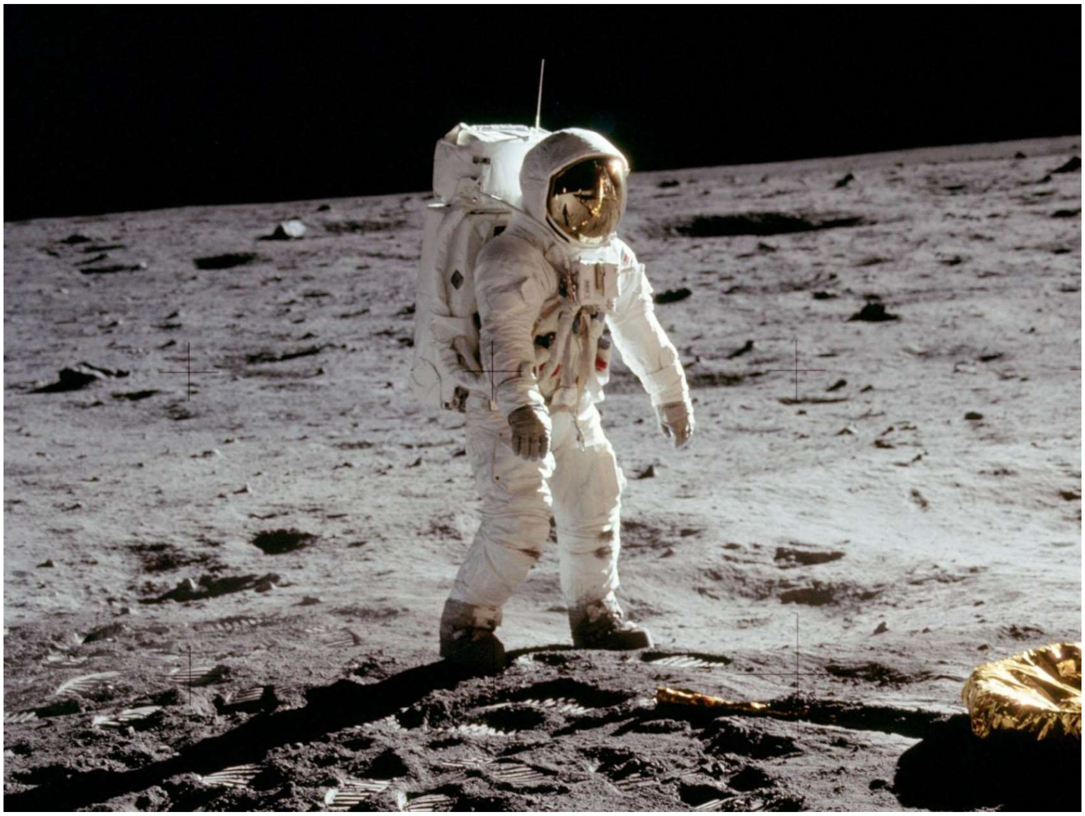
(Note Plume Deflectors Below "Quad" Thrusters, and the Battery Compartment on the Back of the Lunar Module's Ascent Stage.)



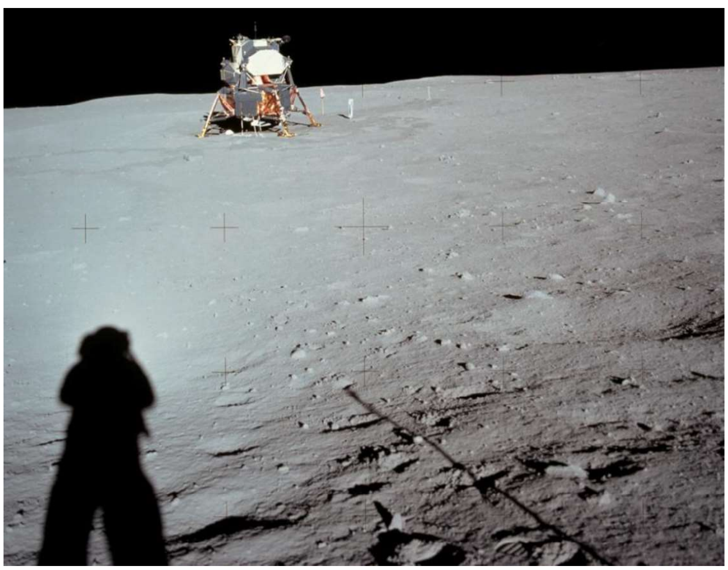
Close-Up of "Eagle's" Landing Leg and Bent Surface Probe

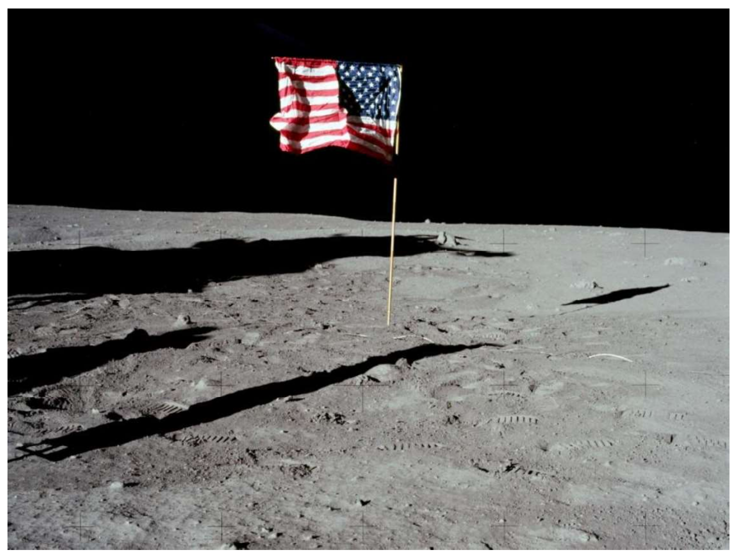
“Buzz” Aldrin on the Moon (Again)

(In his limited time using the camera on the lunar surface, Aldrin never took one close-up image of Commander Neil Armstrong.)



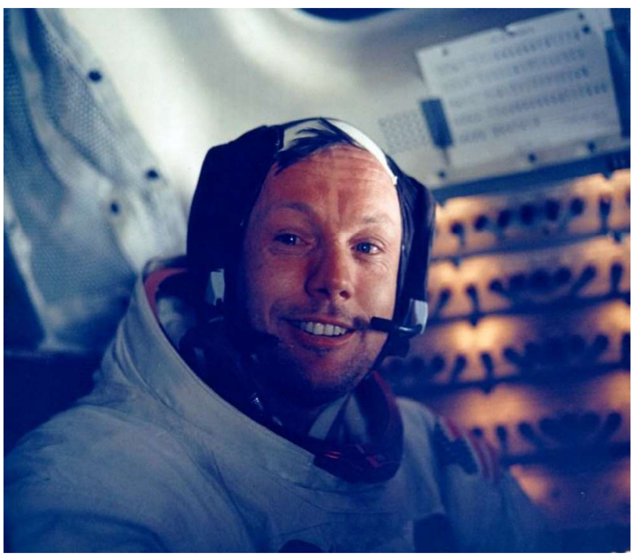
More “Magnificent Desolation”





Two Happy Apollo 11 Astronauts Inside Lunar Module "Eagle"

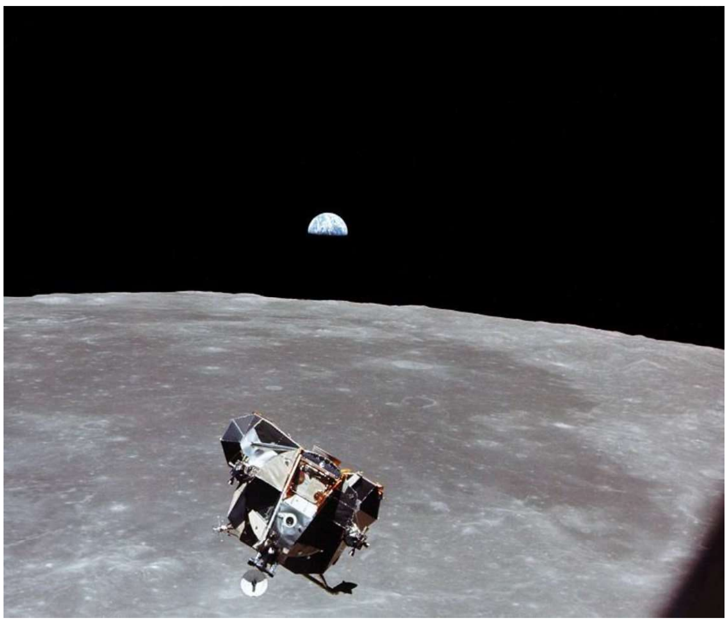
Commander Neil Armstrong, on the Lunar Surface: One Very Happy (and Relieved) Aviator



Lunar Module Pilot "Buzz" Aldrin, During LM Checkout Inspection On the Way to the Moon

Lunar Module "Eagle" Ascent Stage: Rendezvous with Command Module "Columbia"

(Photo Credit: Taken by CMP Mike Collins.)

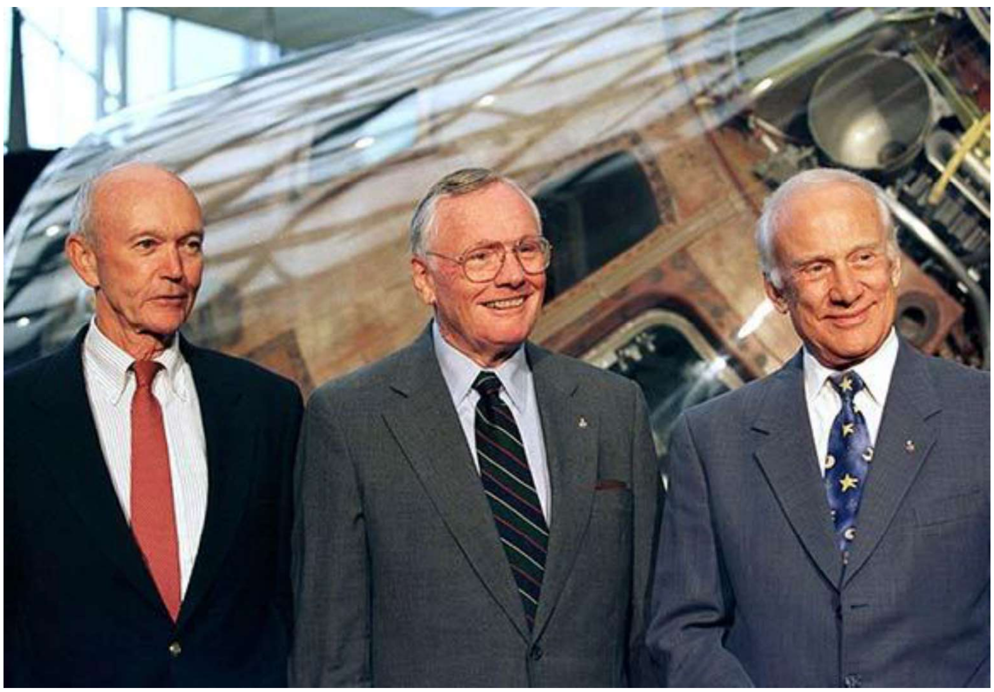


“Buzz” Aldrin’s Lunar Spacesuit at NASM (1 of 2)

“Buzz” Aldrin’s Lunar Spacesuit at NASM (2 of 2)
(Neil Armstrong’s Suit Has Been Stored for Preservation Purposes)

The Apollo 11 Crew 30 Years Later,
Standing Proudly in Front of Command Module "Columbia"

(At a 30th Anniversary Commemoration Ceremony at NASM, in 1999.)



How Did Apollo 11's Lunar Module Land on the Moon?
(Or, "A Nominal Lunar Landing Flight Profile")

- **The "TLI" Burn:** The **trans-lunar injection** burn **was performed by the J-2 rocket engine on the third stage of the Saturn V,** when it was ***reignited*** after about 1.5 orbits around the Earth:
  - The TLI burn was almost 6 minutes long, and placed the spacecraft stack on a ***free-return trajectory;***
  - It was commonly stated that the Apollo spacecraft stack had achieved **"escape velocity"** from the Earth following the TLI burn (accelerating from approximately 5 miles per second, to about 7 miles per second);
  - But this term "escape velocity" was actually a misnomer, since the TLI burn actually placed the Apollo spacecraft in an extreme elliptical orbit around the Earth; the spacecraft's orbit was simply intercepted by the Moon after about 3 days, and the Apollo spacecraft stack ***was then captured by Lunar gravity.***
- A **Mid-Course Correction** was usually required on the way to the moon after carefully tracking the spacecraft trajectory for about one day; it was usually of very short duration and **was most often performed by the powerful SPS engine** mounted on the aft end of the Service Module:
  - Apollo 11's mid-course correction enroute the Moon lasted only 3 seconds;
  - Minor mid-course corrections could alternatively be performed by burning selected attitude thrusters in the Service Module's "quad" thruster assemblies (for a longer period of time than an SPS burn, of course);
  - For Apollo 13-17, longer and more substantive mid-course correction burns were required, since their destinations on the Moon were not near the Moon's equatorial plane; ***these later burns took the Apollo spacecraft stack out of an automatic free-return trajectory.***
- **The "LOI" Burn:** The **lunar orbit insertion** burn (or "LOI-1") **was always performed by the powerful SPS engine on the Service Module;** it slowed down the Apollo spacecraft stack sufficiently so that it could be captured by lunar gravity, and begin orbiting the Moon. If the SPS engine had failed to fire on the Apollo 8, 10, 11, or 12 missions, the spacecraft stack would have remained on a free-return trajectory, meaning it would have automatically returned to Earth after performing a "figure 8" slingshot maneuver around the Moon.
  - The LOI burn for Apollo 11 was just under 6 minutes long (and slowed its velocity from 5,800 to 3,700 mph).
  - The LOI burn was always made at **PERICYNTHION** (a term used in celestial mechanics to describe the closest approach to the Moon by a craft from another celestial body); an alternate term is **PERILUNE.**
  - The LOI burn placed the Apollo spacecraft stack in **an elliptical orbit** about 110 kilometers (or 60 nautical miles) above the Moon; the low altitude chosen for the lunar orbit was dictated by the limited thrust of the Lunar Module's ascent engine when leaving the Moon.
  - The nominal lunar orbit for an Apollo spacecraft following LOI was 60 nm by 170 nm; ***for Apollo 11, the actual orbit achieved following LOI was 60.9 nm by 169.6 nm---a feat of remarkable accuracy.***
  - The guidance computer terminated all SPS burns based upon ***"delta v,"*** or changes in velocity, as measured by the IMU; the clock was not used because it was not accurate enough. ***A two-second error in shutdown of the SPS in lunar orbit could have resulted in a crash into the lunar surface one half-orbit later.***

Nominal Lunar Landing Flight Profile (2 of 5)

- **<u>Circularization Burn</u> (or "LOI-2"): Like the LOI-1 burn, this was always made with the SPS engine on the Service Module.** This burn was usually made a couple of orbits after the LOI, after Mission Control had evaluated the accuracy of the spacecraft's orbit following the LOI-1 burn.
  - <u>Apollo 11's LOI-2 burn lasted 17 seconds</u>;
  - Because the original LOI burn (at Pericynthion, or Perilune) only placed the spacecraft stack in an elliptical orbit, a second SPS burn (dubbed the "circularization burn") was always conducted ***on the opposite side of the Moon from LOI-1,*** at **APOCYNTHION** (the farthest point of the elliptical lunar orbit), or **APOLUNE.**
  - The intent was to <u>circularize the lunar orbit</u>, as much as possible, at approximately 110 kilometers (or 60 nautical miles).
  - Following an ideal circularization burn, the spacecraft orbit would be 60 nm by 60 nm. Apollo 11's orbit prior to LOI-2 was 168.8 nm by 61.3 nm; ***after LOI-2 Apollo 11's orbit was 66.1 nm by 54.4 nm.***

- **The <u>Descent Orbit Insertion</u> Burn (or DOI):** The purpose of the DOI burn was to lower the altitude of the Lunar Module one-half orbit later to only 50,000 feet (at which point <u>powered descent initiation</u>, or PDI, would occur). **For Apollo 10 through 12, the DOI burn was performed by the descent engine (or DPS) on the Lunar Module (after the LM had separated from the CSM); for Apollo 14-17, the DOI burn was performed by the SPS engine on the Service Module, while the LM was still mated with the CSM.**
  - The Lunar Landers for the Apollo 14-17 missions were significantly heavier than the LMs for the Apollo 10-12 missions, because they carried additional consumables for extended-stay missions, and because (for Apollo15-17) they also carried the <u>Lunar Roving Vehicle</u>. ***It was for this reason that the larger SPS engine on the Service Module was used for DOI on the last 4 landing missions---this saved propellant in the descent stage of the LM for landing a heavier Lunar Module.*** After the DOI burn for Apollo 14-17, the CSM performed a circularization burn.
  - **Apollo 11's DOI burn was performed by the descent engine (the DPS) on the Lunar Module "Eagle,"** 56 minutes after the "Eagle" separated from the "Columbia" CSM.
  - <u>The Apollo 11 DOI burn lasted about 30 seconds</u>, as follows: **a 15-second burn of the DPS at 10% thrust; followed by a 15-second burn of the DPS at 40% thrust.**
  - This gave the Lunar Lander "Eagle" a new Perilune, one half orbit later, of only about 15.3 kilometers altitude, at about 500 kilometers distance from the proposed landing site; English measurement equivalents for Apollo 11's new Perilume after DOI are 50,174 feet altitude, and 310 nautical miles from the landing site.

Nominal Lunar Landing Flight Profile (3 of 5)

- **The "PDI" Burn:** ***Powered Descent Initiation*** (or PDI) began at the new Lunar Lander Perilune of approximately 50,000 feet altitude, ***one half orbit following the DOI burn.*** The PDI burn lasted between 11.5 and 12 minutes, and **was a continuous burn of the DPS engine in the descent stage of the LM, from PDI initiation until landing.**

  – **Descent engine performance characteristics:** The **DPS engine** could be ***throttled;*** it could be throttled ***smoothly*** **between 10% and 65%** of its rated thrust (10,500 lbs.), or operated at its **"full power"** (or "fixed thrust") setting of **92.5%** of rated thrust. The descent engine could also be ***gimbaled,*** but this was not done for steering purposes; attitude control of the LM was the responsibility of the four (4) "quad" thruster assemblies on the LM's ascent stage. ***The DPS engine was gimbaled to ensure that its thrust vector was in line with the Lunar Lander's changing center of gravity, as propellants were burned.***

  – **PDI began** with a **10% burn** of the descent engine for the first 26 seconds; thereafter, "full thrust" of **92.5%** was engaged for about six full minutes, until about 6 min., 25 sec. into the PDI burn. At that point PGNS began to gradually ***throttle down the engine*** **(between 57% and 10%),** as necessary, to prepare for landing.

  – **Onboard "Eagle," Commander Neil Armstrong had chosen to begin the PDI burn "face down," looking at the lunar surface, so that he could eyeball landmarks on the lunar surface and compare them with the projected track. [The "face down" attitude created communications difficulties between "Eagle" and Houston following DOI, until 4 minutes into the PDI burn, when the LM rolled over and gave its high gain antenna a better lock on the Earth.]** *About 4 minutes into PDI, at 46,000 feet altitude, Armstrong rolled the LM over onto its back, placing the two astronauts "face-up"---so that the landing radar could be engaged.* **[On all other lunar landings, the PDI burn began with the astronauts "face up."] After Armstrong rolled the LM over at 46,000 feet, the astronauts were travelling "backwards" or feet-first, and "face up," looking out of their windows at outer space.** *They could not see the Moon's surface again until the "pitchover" maneuver, about 3 minutes prior to landing.*

  – **Numerous Computer Programs** were called up in the LM guidance computer (PGNS) **by number** during various phases of the landing, as follows:

    - **P63:** This program was called up by the astronauts about 1,400 kilometers away from the landing site, and about 22 minutes prior to landing. **The PDI burn was initiated automatically by PGNS [within program P63] when "Eagle" was about 500 kilometers from the landing site, a little more than 11.5 minutes prior to landing.** Once PDI began, the so-called **braking phase** commenced.

Nominal Lunar Landing Flight Profile (4 of 5)

- **Computer Programs Involved in Landing on the Moon (continued):**

  - **P64:** The astronauts entered **P64** at what was called ***"High Gate,"*** where the **approach/visibility phase** began, **about 3 minutes prior to landing**, when the Lunar Lander was about 7.5 kilometers away from the landing site, at about 2,200 meters in altitude (about 7,200 feet for Apollo 11).

    - **P64 immediately initiated the "pitchover" maneuver, in which the astronauts transitioned from flying on their backs, feet-first and "face up," to a position about 30 degrees from vertical.** This 60 degree change in orientation was dramatic, for ***after pitchover, the astronauts could see the lunar horizon and much of the lunar surface---they could finally see where they were going.***

    - During the **approach/visibility phase,** up until the landing, the Lunar Module Pilot (e.g., "Buzz" Aldrin) continuously updated the Mission Commander (e.g., Neil Armstrong) with oral readouts of:
      - **Altitude** (in feet), such as "100 feet;"
      - **Rate of Descent** (in feet per second), such as "three and a half down;"
      - **Horizontal Velocity** (in feet per second), such as "nine forward;" and
      - **Propellant Remaining** or "Fuel State" (as a percentage), such as "eight per cent."

    - **The LMP also relayed Landing Point Designator (or LPD) angles to the Mission Commander** to his left, who was actually flying the Lunar Lander. [The designator "Lunar Module Pilot" was a misnomer, utilized because none of these highly qualified and competitive test pilots wanted to be called a "co-pilot."] ***The LPD callouts worked as follows:***
      - Vertical and horizontal lines were inscribed onto the inner and outer window panes on the LM;
      - The horizontal lines on the inner and outer window panes were inscribed with LPD angles every 2 degrees, and numbered every ten degrees from 0 to 50 (e.g., 0, 10, 20, 30, 40, and 50);
      - If the LMP called out a PGNS-provided LPD angle of "42," the Commander (flying the LM) would look along the sight line created by the two horizontal lines representing "42 degrees" inscribed on the inner and outer window surfaces;
      - That sight line would direct his eyes toward the landing site that PGNS (the guidance computer) was leading him toward;
      - If the Commander liked the designated landing site along the sight line for the LPD he was given, he could simply allow the computer to continue aiming for that landing site; otherwise, he could select another landing site visually and redesignate a new LPD to the PGNS computer with either the "joystick" controller in his right hand, or the "DSKY" keyboard.

Nominal Lunar Landing Flight Profile (5 of 5)

- **Computer Programs Involved in Landing on the Moon (continued):**
  - **After Program P64: P65, P66, or P67? (One of these three options had to be selected)**
    - **P65 (never used)** would have allowed the guidance computer (PGNS) to land the LM automatically, without any human intervention.
    - **P67 (never used)** was an option which gave the Mission Commander ***FULL MANUAL CONTROL of both attitude and throttle (i.e., thrust).***
    - **P66 (used by all Apollo Mission Commanders)** was defined as manual control of ***attitude*** **with the right-hand "joystick" hand controller,** and the ability to override the computer's choice for ***throttle (i.e., thrust) by utilizing the "push/pull" controller in his left hand.***
- *"Low Gate"* was defined as the point (below 1,000 feet) where **approximately the last 200 meters (i.e., about the final 650 feet) of the descent began;** the **terminal descent/landing phase** of powered descent was defined as **the distance from *"Low Gate"* to touchdown.**
- **Program P66 (or P65, or P67) was selected just prior to reaching *"Low Gate."***
- **In actuality, Program P66 and *"Low Gate"* always began *lower* than the nominal 650 feet (sometimes much lower):**
  - **Apollo 11 (550 feet)**
  - **Apollo 12 (400 feet)**
  - **Apollo 14 (370 feet)**
  - **Apollo 15 (400 feet)**
  - **Apollo 16 (240 feet)**
  - **Apollo 17 (240 feet)**
- Ideally, the LM would descend almost vertically, like a helicopter, during the entire **terminal descent/landing phase. [This was not the case for Apollo 11; see next slide for explanation.]** The idea was to attempt to land the Lunar Module without any lateral movement (to avoid stressing the landing legs), or backwards movement (to avoid boulders or craters).
- **SUMMARIZING,** the **braking phase (in P63)** lasted about **8.5 minutes;** the **approach/visibility phase (in P64)** lasted about **1.5 minutes;** and the **terminal descent/landing phase (in P66)** lasted for about **1.5 minutes. (It took 11.5 minutes to land.)**
- **Contact Light:** When the first of the **5′ long probes** attached to three of the four Lunar Module landing pads contacted the lunar surface, the **ice-blue "Contact Light"** was illuminated on the LM control panel. This was intended to be the signal for the Commander to cut all thrust, and (theoretically) allow the Lunar Lander to drop the last few feet onto the lunar surface (thus compressing the aluminum honeycomb shock absorbers in the Lunar Lander's legs, lessening the distance from the ladder to the surface). **[Neil Armstrong on "Eagle" was unaware of the contact light, and did not cut thrust until touchdown; thus, for Apollo 11, there was no landing "bump" and little compression of the landing legs on the LM.]**
- **Three Stay/No-Stay Options:** If the LM was experiencing systems problems that dictated a quick lunar liftoff and rendezvous with the CSM, there were three accelerated options (which were the prerogative of Mission Control in Houston). Prior to each of these critical points in the timeline, the Houston MCC had to issue **"Stay/No-Stay"** commands to the Mission Commander on the LM, in regard to the following options (which were dictated by orbital mechanics and the position of the CSM in lunar orbit):
  - T-1 Option (liftoff 2 minutes after landing)
  - T-2 Option (liftoff 8 minutes after landing)
  - T-3 Option (liftoff 2 hours after landing)

Problems Experienced (and Overcome) During the Apollo 11 Flight

- **A Small Velocity Error Was Acquired By The Lunar Module during undocking from CSM in lunar orbit (but it placed the lunar landing in danger---the increased speed imparted to "Eagle" moved the Lunar Module halfway to its velocity abort limits):**
  - Increased velocity of the LM was caused by residual air pressure in CM/LM docking tunnel that had not been vented;
  - Commander Armstrong noted, 3 minutes into powered descent, that "Eagle" was going to land "long," since the LM passed over a key landmark (crater Maskelyne W) seconds early;
  - Lunar Module "Eagle" actually landed more than **four (4) miles downrange** of its intended landing site
- **There Were Five Guidance Computer (PGNS) Overload Alarms during descent to the lunar surface (three "1202" and two "1201" alarms), threatening a possible abort: [but because they were intermittent, and not continuous, an abort was not required]**
  - Computer overload was caused by the Rendezvous Radar being turned on at the same time the Landing Radar was being used; turning on the Rendezvous Radar was a new checklist item requested by LMP Aldrin that had never been simulated in training. The two radars were fed by different AC power supplies in the LM, and were therefore out-of-phase, and not in sync. This led to excessive computations by the computer, which intermittently exceeded the 15% overhead capability built into its design.
  - Theoretically, the Rendezvous Radar would only be needed in case of an abort, and ***could have been turned on AFTER an abort.***
  - Each computer overload was stimulated by LMP Aldrin's repeated tasking of PNGS to calculate "delta H," which was the difference between the computer's calculated altitude based on the IMU, and the spacecraft's actual altitude as revealed by the Landing Radar; PGNS could not calculate *both* "delta H" *and* process the Rendezvous Radar data in the same computational cycle.
  - PGNS repeated all of its tasks every two (2) seconds, and did not have enough time during each computing cycle to assimilate and process data from the Landing Radar (crucial), the Rendezvous Radar (not crucial), *and* calculate "delta H" (crucial).
  - A normal computer would have frozen up, and "crashed," but the Apollo guidance computer did not, because of the **"Executive Overflow"** feature designed into the computer by software engineer **Hal Laning at M.I.T. Under his "Interruptible Executive Design," the computer prioritized its tasks during each computing cycle (2 seconds long), and simply stopped performing the least important tasks when each computing cycle ended, and restarted, INSTEAD OF CRASHING AND SHUTTING DOWN.**
  - Neither the astronauts nor the Flight Director knew what the alarm codes meant, but two technicians in Houston **(Engineer Jack Garman and MCC Flight Controller Steve Bales)** did, because of simulations run in the days just prior to the Apollo 11 flight.
- **The PGNS computer was guiding the Lunar Module down into blocky terrain (consisting of boulders the size of Volkswagen Beetle automobiles) just short of the rim of a crater the size of a football field (West Crater), requiring Commander Neil Armstrong to exert manual control and alter the landing site:**
  - Landing "short" was considered by Armstrong to be more dangerous than landing "long," so he chose to land "long," and flew the LM *over* the blocky terrain short of the crater, and *over* **West Crater** itself; ***Armstrong then flew over a smaller, second crater.***
  - Instead of piloting the LM down vertically the last 650 feet, **Armstrong had to hold his attitude close to vertical and slow the PGNS descent rate---thus maximizing horizontal velocity to clear the crater---before hovering, and then setting down.**
  - These maneuvers contributed to a low fuel state onboard "Eagle"---lower than at any time during any simulations.
- **Low Fuel State---At the time of the landing, estimates were that the "Eagle" landed with only about twenty seconds of fuel left before reaching "Bingo" fuel state:**
  - **"Bingo" status** for the LM meant that only an estimated twenty seconds of fuel would remain in which to either land, or abort.
  - **Subsequently,** it was determined that **"Eagle" had more fuel available when it landed than thought at the time [enough for 50 more seconds of flight, vice 20 seconds];** the false low fuel state reading **["Quantity Light" = 5% fuel remaining = 94 second countdown to "Bingo" state]** was caused by the sloshing of propellant in the tanks, which made quantity measurements unreliable as the tanks emptied, and the sloshing increased.
  - The fix: NASA experimented with retrofitted fuel and oxidizer baffles in the propellant tanks on Apollo 12's LM, without much success. Accordingly, the propellant tanks in the descent stage of the LM were completely redesigned, and newly manufactured propellant tanks with proper baffles were installed in the LM descent stages for Apollo 14-17.
- **The plastic Engine Arm Switch on the LM control panel was inadvertently broken off by either Armstrong or Aldrin (probably by a bulky PLSS backpack) in the crowded Lunar Module cabin:**
  - The **Engine Arm Switch** breaker had to be closed to provide the electrical power to ignite the Lunar Lander's Ascent Engine;
  - **"Buzz" Aldrin provided a felt-tipped pen (fortuitously given to him by CM Pilot Mike Collins during trans-lunar coast) that was used by Neil Armstrong to close the Engine Arm Switch breaker immediately prior to liftoff from the Moon.**

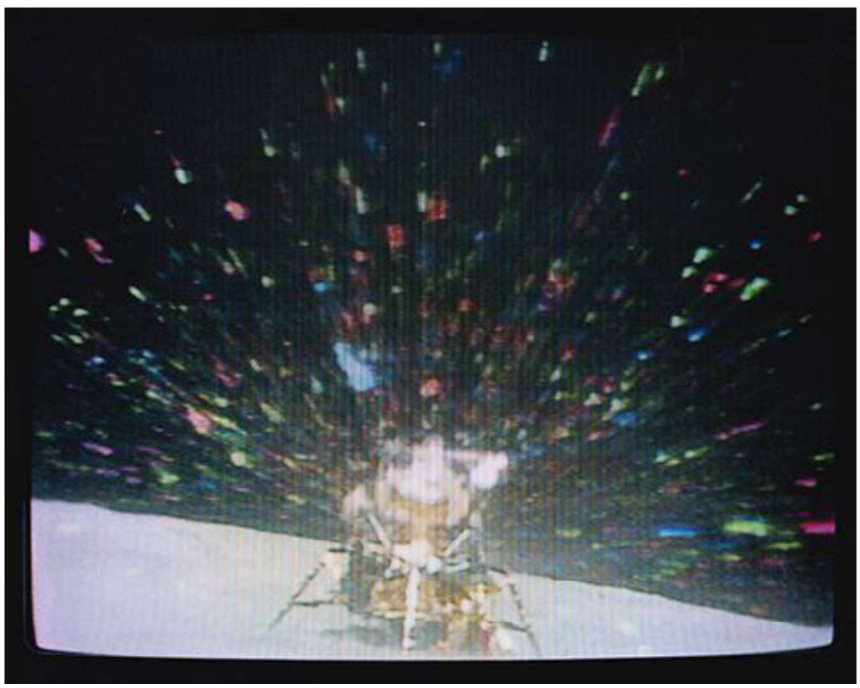
How Did the Apollo 11 Astronauts Return to Earth from the Moon? (Or, a Nominal Apollo "Return to Earth" Operational Profile)

- **Liftoff from the Lunar Surface in the Ascent Stage of the Lunar Lander**
  - The **LM Ascent Stage** was the active participant in the rendezvous with the CSM in lunar orbit. **It was the LM 's responsibility to lift off, attain lunar orbit, and then find, track, and pull up alongside the CSM.**
  - However, the Command and Service Module was always in the standby role of rescuer, in the event the Ascent Stage of the LM did not get a good burn.
  - **Once the rendezvous was completed in lunar orbit, the Command Module Pilot in the CSM executed the docking with the Ascent Stage.**
  - **The LM's ascent engine had a thrust of 3,500 lbs; it could not be throttled or gimbaled.** It provided "full thrust" all the way, and literally "jumped" off of the descent stage at ignition. **Acceleration: about one third of a "g."**
  - Almost immediately after liftoff from the lunar surface, **the Ascent Stage pitched over to 45 degrees from vertical,** providing the Commander and LMP with a rather dramatic (if not alarming) view of the lunar surface right below them.
  - The ascent engine burn always placed the upper stage of the Lunar Module in a low, very elliptical orbit around the Moon.
  - **The ascent engine burned for 7 minutes 45 seconds.**
  - **Apollo 11's Ascent Stage "Eagle"** reached an initial orbit around the Moon of **47.2 by 9.1 nautical miles.** Other Ascent Stage orbits were similar; for example, **Apollo 15's Ascent Stage "Falcon" reached a lunar orbit of 42 by 9 nautical miles.**
- **Rendezvous With the Command Module in Lunar Orbit (The Coelliptic Method, used by Apollo 11 and 12, took 3 hours, 25 minutes. The simplified Direct Rendezvous Method, used by Apollo 14-17, eliminated the first two burns discussed below [the CSI and CDH burns], took less than 2 hours, and was accomplished in less than one lunar orbit.)**
  - **After the ascent engine shut down, all subsequent burns necessary to rendezvous with the CSM were made with the reaction control system (RCS), i.e., the "quad" thrusters.**
  - **Four different burns with the RCS were required** for the Ascent Stage to rendezvous with the Command and Service Module (when using the Coelliptic Method employed by the Apollo 9-12 missions):
    - A "circularization burn," which NASA called the **CSI (coelliptical sequence initiation) burn,** occurred one half orbit after liftoff, at Apolune, the highest point of the initial elliptical orbit.
    - After another half orbit, what NASA referred to as the **CDH (constant delta height) burn** took place, in order to get the Ascent Stage flying 28 kilometers below the CSM's orbit.
    - After a 40-minute coast, the Ascent Stage performed what NASA called the **TPI (terminal phase initiation) burn,** in which the Ascent Stage raised its altitude up to that of the CSM, aiming directly for the Command and Service Module in the lunar "sky" above it.
    - Finally, the ***terminal phase final* burn** or "**braking maneuver"** ensured that the Ascent Stage did not overshoot the CSM---that the LM's upper stage ended up literally right next to the Command and Service Module, with the astronauts looking at each other out of their windows.
    - The Ascent Stage Rendezvous Radar tracked the CSM, once acquired, through use of a transponder on the Command and Service Module.

Liftoff from the Lunar Surface:

Television Image of Apollo 16 LM *"Orion"* Ascent Stage

(Taken by T.V. Camera on Lunar Roving Vehicle.)

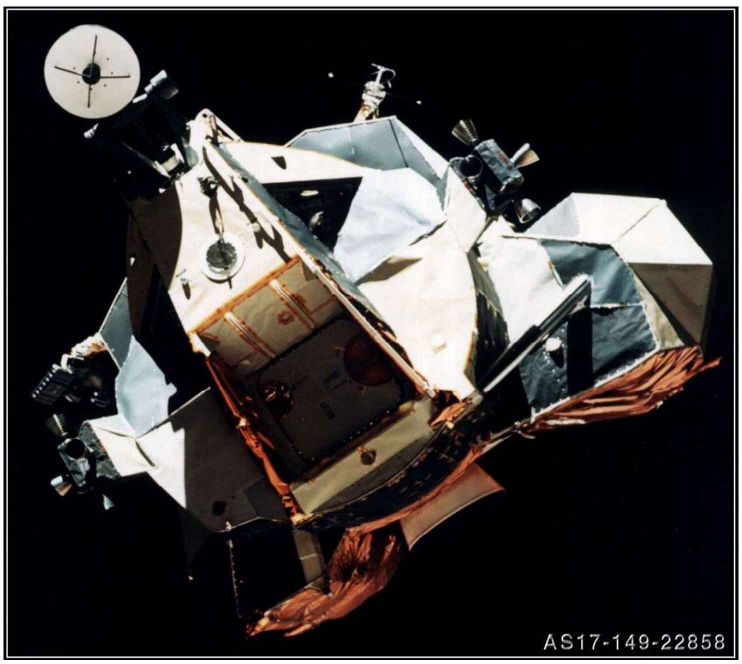


Apollo 17 LM "Challenger" Ascent Stage Lifts Off from Taurus-Littrow Valley

(Flight Controller Ed Fendell in MCC at Houston finally captured video of a complete lunar module liftoff on his last attempt; this is a freeze frame from the T.V. broadcast from the LRV's television camera.)

Ascent Stage of Apollo 17's LM "Challenger" After Rendezvous with CM "America"

(Photo credit: CMP Ron Evans.)



Nominal Apollo "Return to Earth" Operational Profile (2 of 3)

- **Docking in Lunar Orbit:**
  - The **Command and Service Module** was the active participant in the docking sequence;
  - Following a visual inspection of the Ascent Stage by the Command Module Pilot, the Mission Commander in the Ascent Stage aligned the **docking hatch** above his head with the **probe assembly** on the nose of the Command Module, and then ***rotated the Ascent Stage 60 degrees*** so that the COAS docking aids on the two spacecraft were in rough alignment;
  - **The Command Module Pilot then docked with the LM, just as he had following TLI, after leaving Earth orbit on the way to the Moon.**
  - Following transfer of moon rocks and film magazines from the LM to the CM, and various forms of refuse from the CM to the Ascent Stage of the LM, a ***pyrotechnic charge*** was used to cast off the Ascent Stage of the Lunar Module by severing the docking ring on the Command Module from the docking/transfer tunnel; ***when the LM was cast off, the docking probe from the CM went with the Ascent Stage.***
  - Most Lunar Module Ascent Stages were intentionally crashed into the Moon as a seismological experiment.

- **The "TEI" Burn: The Trans-Earth Injection (TEI) burn, using the large SPS engine on the Service Module,** took place on the far side of the Moon, directly opposite the near side of the Earth. Its goal was to gain enough additional velocity to escape the Moon's gravity and place the spacecraft on an S-shaped trajectory toward the Earth.
  - Apollo 11's TEI burn lasted 2.5 minutes.
  - The trajectory of the Command and Service Module became open-ended, or hyperbolic (not elliptical), allowing the spacecraft to literally fall back to the Earth;
  - Initially, as the spacecraft departed the Moon, its speed slowed down; but as the CSM neared the Earth, its speed accelerated dramatically, especially in the final one-half day of the three-day journey.

- **The Critical Re-Entry Window:**
  - **The Command Module had to enter the Earth's atmosphere at a shallow angle of 6.5 degrees, plus or minus one degree,** or it meant death for the astronauts. **This narrow two (2) degree window was crucial for a safe re-entry:**
    - If the CM hit the atmosphere at too shallow an angle, ***it would skip off into space;***
    - If the CM entered too steeply, ***lethal G-forces would quickly build up, and the spacecraft could incinerate.***
  - Occasionally, a minor mid-course correction with the SPS engine was required to stay within the critical two degree re-entry window.

Nominal Apollo "Return to Earth" Operational Profile (3 of 3)

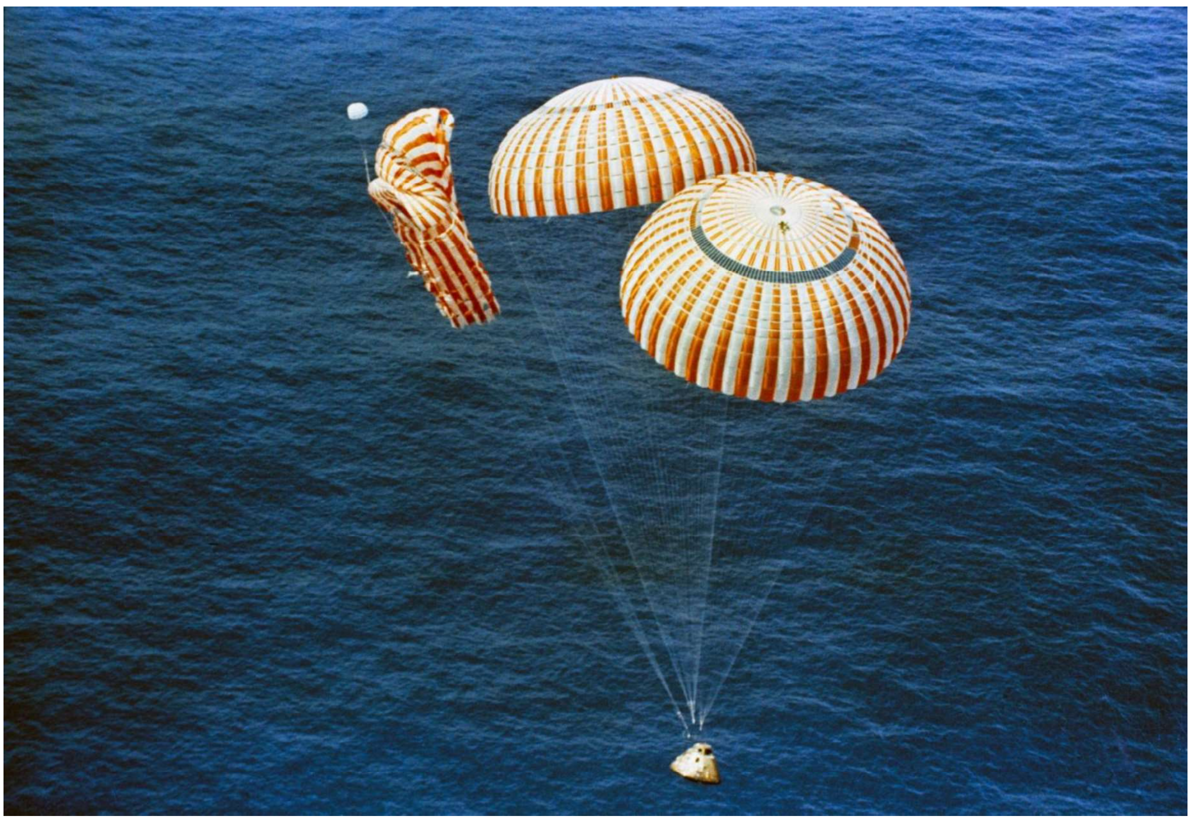
- **The Service Module Was Cast-Off by the Command Module About 15 Minutes Prior to Re-Entry:**
  - This was done at the last minute so that the Command Module could continue using electricity from the fuel cells in the SM, thereby conserving its batteries (which were needed during re-entry);
  - After the Command Module yawed 45 degrees from the flight path, pyrotechnic charges severed the three attachment points between the CM and the SM, as well as the many umbilical connections.
  - The Service Module was programmed to steer itself clear of the Command Module after it was jettisoned, through use of its "quad" RCS; soon thereafter the Service Module burned up in the Earth's atmosphere.
- **Atmospheric interface occurred at 400,000 feet altitude, at 0.05 gravity on the accelerometer. The speed of the Command Module at re-entry was approximately 25,000 mph, or 36,194 feet per second; and the heat generated by re-entry on the lower surface of the heat shield was about 5000 degrees F. (Max. re-entry "g" was 6.35.)**
- **Most Command Modules "flew" about 2,200 kilometers through the atmosphere from re-entry interface until splashdown;** Apollo 11 flew a longer distance (about 2,800 kilometers) because its landing site was changed to avoid bad weather. Apollo 11 performed a modified "skip maneuver" in the atmosphere, and instead of flying 1,187 nautical miles through the atmosphere, as originally planned, it flew about 1,500 nautical miles.
- **Atmospheric Maneuvering:** The center of gravity in the Command Module was intentionally off-center, which allowed the craft to be "flown" to a limited degree by using its roll thrusters; rolling right or left (up to 15 degrees) produced a limited amount of lateral lift. Nominally, PGNS "flew" the spacecraft during re-entry.
- **Parachutes:**
  - The **2 drogue parachutes** (16.5′ ea in diameter) opened at 24,000 feet, **at a speed of 320 mph;**
  - The **3 main parachutes** (83.5′ ea in diameter)---preceded by 3 small pilot chutes---were deployed at 10,000 feet, **with the Command Module traveling at about 160 mph;**
  - The Command Module hung from the parachutes at a **27.5 degree angle,** with the main hatch facing upwards, in the hopes that it would enter the ocean obliquely (and not pancake, as Apollo 12's "Yankee Clipper" did).
  - On one flight---Apollo 15's---one of the 3 main parachutes did not open properly; but the crew still landed safely.
  - Normal impact speed was intended to be at about 21 mph, or 31 feet/second; most of the astronauts said the water impact was more severe than they had expected.
- **Splashdown:**
  - **"Stable I"** was a "right-side-up" landing following splashdown; this occurred 7 times (out of 11 flights).
  - **"Stable II"** was the description given to a Command Module that capsized and ended up "upside down" after splashdown; this happened four times, to the Command Modules for **Apollo 8, 11, 12, and 16.** Ships that ended up in "Stable II" were eventually righted by the three inflatable air bags at the nose of the Command Module. It took 8-9 minutes for the three air bags to fully inflate.
  - Normally, the 3 air bags were inflated following splashdown regardless of whether or not the Command Module was upside down; in one case---Apollo 14---the Navy's splashdown recovery team arrived so quickly that the 3 air bags were not deployed.

Coming Home:
A View of Earth Taken by the Apollo 16 Crew
(Note Baja California, Mexico, Florida, and Cuba.)

Apollo 9 Command Module "On the Mains" After Re-entry
(Note 27.5 degree angle of suspension for CM "Gumdrop".)

Apollo 11 Command Module "Columbia" at Splashdown
(Note pilot chute visible above main parachute at left.)

One of Apollo 15 CM *Endeavour's* 3 Main Chutes Did Not Fully Deploy…



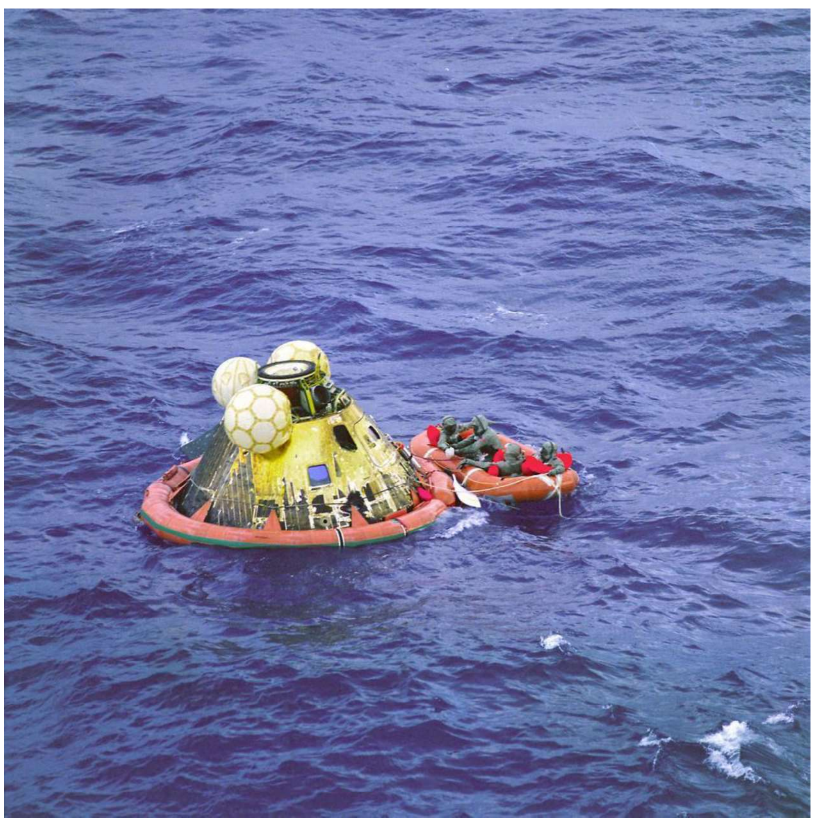
…Resulting in Some Additional Drama at the Moment of Splashdown

(Note the extremely hard water entry.)

Apollo 17 Command Module "America"
Brings the Apollo Lunar Landing Program to a Close

Apollo 11 Command Module *"Columbia"* Shortly After Spashdown

(July 24, 1969)

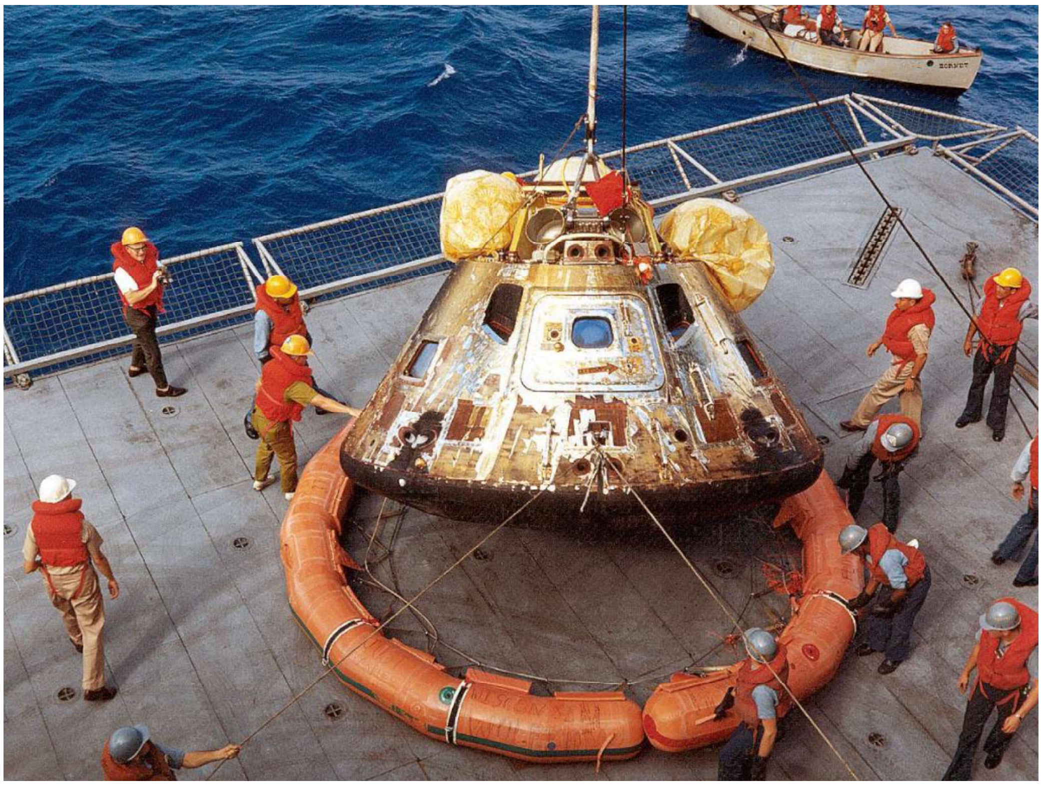


Closeup of Apollo 11 Crew from CM "Columbia"
Shortly After Egress

(Crew is wearing the "Bigs"---the biological isolation garments.)

Shipboard Recovery Commences for Apollo 11 Command Module "Columbia"

Shipboard Recovery of Apollo 11 CM *"Columbia"* Completed



Apollo 16 CM "Caspar"
Shortly After Splashdown

Lunar Module Pilot Ed Mitchell Exits Apollo 14 Command Module "Kitty Hawk"

(The Navy's splashdown recovery team was on the scene so quickly that the crew chose not to deploy the flotation bags.)

Apollo 13: *What Happened?* *(1 of 4)*

- **The following is a reconstruction---based upon the work of the Cortright Commission appointed by NASA---of what caused the disaster onboard the Apollo 13 Command and Service Module.**

- **Background:** Each CSM (for Apollo 7 through 13) contained two (2) oxygen tanks and two (2) hydrogen tanks, as well as three (3) fuel cells, in Bay # 4 of the Service Module. The fuel cells combined oxygen and hydrogen to produce 28 volt D.C. electricity (to power the spacecraft systems in the Command Module) and water (both potable water, and water for use in spacecraft cooling systems). An umbilical between the Service Module and Command Module transferred electricity, water, and telemetry to the Command Module; and electrical signals from the Command Module to Bay # 4, and to the SPS engine, also passed through the umbilical.
  - Both the hydrogen and oxygen were stored cryogenically, at very low temperatures, in a relatively small volume under high pressure.
  - The two SM oxygen tanks were each 26" in diameter and were made of Inconel (a nickel-steel alloy); each vessel was double walled, with a layer of teflon insulation in between the two pressure vessels. When filled, each tank held 320 lbs. of cryogenic liquid oxygen.
  - Through a "neck" in the dome of each oxygen tank (the weakest part of the pressure vessel) plumbing and electrical lines were passed into the tank; these included electrical lines providing power for two small fans, a large heating element, quantity and pressure sensors, and the various plumbing lines used to load and drain the tank prior to launch, as well as a line to send gaseous oxygen to the fuel cells. All of the electrical lines were insulated with teflon.
  - The cryogenic contents of the hydrogen and oxygen tanks---a kind of super-cooled slush---tended to get too cold; when that happened, insufficient amounts of gas would evaporate from the slush to properly feed the fuel cells. Furthermore, when too cold, the quantity readings from the cryogenic tanks were not accurate. **THEREFORE, Mission Control in Houston frequently asked the Apollo astronauts to perform a "cryogenic stir" of the oxygen and hydrogen tanks (using the fan installed inside each tank), and to turn on the heater inside each tank in conjunction with each stir.**

- **There was no single "smoking gun,"** or simple cause for the Apollo 13 oxygen tank explosion which nearly claimed the lives of three astronauts. Rather, a cascade of failures and mistakes---one exacerbating the other---led to the very serious state of *extremis* in which the Apollo 13 astronauts found themselves on April 13, 1970---more than two days after launch---when they were 200,000 nautical miles away from the earth, and on the moon's doorstep.

- Apollo 13's oxygen tanks had originally been installed in the Service Module for Apollo 10. Because of a technical upgrade, the two oxygen tanks in Apollo 10 were ordered removed so they could be replaced with the upgraded versions**. The entire shelf containing the two oxygen tanks and all associated wiring and plumbing was removed from the Apollo 10 Service Module by North American in Downey, Califonia on October 21, 1968.**

- During removal, an accident occurred during which **the entire shelf, which was being removed by crane, was inadvertently dropped a distance of 2 inches. Subsequent inspection revealed no apparent damage, and the oxygen tank assembly from Apollo 10 was recertified;** the upgrades were then installed in the removed subassembly; **and the oxygen tank subassembly removed from the Apollo 10 SM was then reinstalled in the Apollo 13 Service Module.**

Apollo 13: *What Happened?* *(2 of 4)*

- **UNBEKNOWNST to NASA**, **a small drain line used to vent oxygen tank # 2 following ground tests had been damaged when the oxygen tank shelf was dropped 2 inches at the manufacturer's facility on October 21, 1968. The subsequent inability of this drain line to properly empty oxygen tank # 2 following the Apollo 13 countdown demonstration test on March 27, 1970 led to the Apollo 13 disaster.** [More below]

- **MEANWHILE, ANOTHER PROBLEM---a design defect in *ALL* of the Apollo Service Module oxygen tank heater safety switches---had lain dormant since 1965, unrecognized by anyone and unlikely to cause a problem except under very unusual circumstances. Background follows:**
  - The CSM manufacturer, North American, subcontracted the design and manufacture of the Service Module cryogenic hydrogen and oxygen tanks to Beech Aircraft.
  - Beech Aircraft developed a design, and began manufacturing hydrogen and oxygen tanks that would utilize the **28 volt D.C. current in the Apollo spacecraft.**
  - However, **in 1965 NASA directed that all CSM systems must be compatible with the 65 volt D.C. ground test equipment at the launch pad; North American passed on this requirement to Beech Aircraft.**
  - Beech redesigned the heaters in the oxygen tanks to accommodate the higher 65 volt D.C. current at Pads 39A and 39B at KSC.
  - **BUT BEECH FAILED to replace a 28 volt D.C. heater safety switch for each heater with a safety switch that could accommodate the 65 volts used during ground testing.**
  - **Beech, North American, and NASA engineers all reviewed the redesigned cryogenic heater systems, and NO ONE detected the failure to replace the 28 volt D.C. heater safety switch with a 65 volt D.C. safety switch.**
  - **THUS, this design defect lay dormant in each and every cryogenic hydrogen and oxygen tank in every Apollo Service Module up until the Apollo 13 flight.**
  - NORMAL OPERATION of the safety switch meant that the safety switch remained closed when the heater was "on " ---thus allowing electric current to flow to the heater. Once the temperature reached 80 degrees F, however, the safety switch was designed to open, thus breaking the flow of electricity and shutting down the heater. (Normal cryogenic temperatures were well below **minus 300 degrees F;** no situation was foreseen in which the temperature of the slush would rise above 80 degrees F. Temperatures significantly above 80 degrees F were not desired inside the oxygen tank for fear of damaging insulation or other components.)

- **ON MARCH 27, 1970, during the standard pre-launch Count Down Demonstration Test (CDDT),** flight quantities of cryogenic hydrogen and oxygen were loaded into the Service Module under full pressure, and the spacecraft was operated under its own power (28 volts D.C.) for several hours atop the unfueled Saturn V launch vehicle. Following the test, it was normal procedure to immediately empty all cryogenics (hydrogen and oxygen) from the Service Module.

- **On this date, both hydrogen tanks, and oxygen tank # 1 all emptied properly, but oxygen tank #2 remained 92% full after three attempts to vent its contents.** Engineers studied the records and decided that the small drain line on the tank had probably been damaged when the oxygen tank shelf was dropped in 1968. **Accordingly, ground technicians decided to run the heater for oxygen tank #2 all night long---for 8 hours---and allow the remaining oxygen to boil off through the lines leading to the fuel cells.**

Apollo 13: *What Happened?* *(3 of 4)*

- **THIS PROCEDURE (running the oxygen tank heater all night long) <u>was not considered dangerous</u>**, since everyone knew that a **<u>heater safety switch</u>** was supposed to shut off the heater if the inside of the tank rose to 80 degrees F.

- **The bent drain line for oxygen tank # 2 was discussed with Commander Jim Lovell after the conclusion of the CDDT, and he concurred with running the heater in oxygen tank # 2 all night long to vent the oxygen. <u>Since the drain line was only used to vent the tank following ground tests</u>, neither Jim Lovell nor the ground technicians saw any need to replace the oxygen tank. (They were aware that doing so would delay the launch by one month.)**

- **UNFORTUNATELY, the temperature gauge monitoring the inside of the tank was not calibrated to show any temperature higher than 85 degrees F** since it seemed inconceivable that the temperature could ever rise any higher (because of the safety switch set to open at 80 degrees F). **Summarizing, the temperature gauge on the ground at KSC was pegged to show a max. of 85 degrees, NOT THE ACTUAL TEMPERATURE INSIDE THE TANK.**

- **WHAT ACTUALLY HAPPENED** on the evening of March 27-28, 1970, was that **the 28 volt D.C. safety switch in oxygen tank # 2 <u>fused shut</u>** while accommodating the ground-based power of 65 volts D.C. <u>throughout the night</u>, when it was no longer cooled by cryogenic slush. **Thus, when the temperature reached 80 degrees F inside the tank early that evening, the switch was unable to open and break the supply of current to the heater. TEMPERATURES INSIDE THE TANK REACHED APPROXIMATELY 1000 DEGREES F, burning off most of the teflon insulation on the many electrical wires inside the tank**---but the technician monitoring the heater system did not know that because his temperature gauge read only "85 degrees." **ALSO, <u>the monitoring technician did not notice that the electric heater in oxygen tank # 2 was still drawing power all night long, after exceeding 80 degrees F</u>.**

- The next morning, after running the heater for 8 hours, the ground crew noted that all of the liquid oxygen had indeed disappeared from oxygen tank # 2, as anticipated. No one foresaw any problems in flight.

- **ON APRIL 13, 1970, WHILE 200,000 MILES FROM EARTH, Apollo 13 Command Module Pilot Jack Swigert complied with a routine request from Mission Control to perform a "cryo stir" on both hydrogen and oxygen tanks.**

- **UNKNOWN TO HIM,** there were many bare wires inside oxygen tank # 2 when he activated the fans. Sixteen seconds after Swigert threw the switch initiating the cryo stir, **<u>a short occurred, and the ensuing spark inside the partially empty tank ignited the remaining teflon insulation on the damaged wiring, as well as teflon insulation at the top of the tank's dome</u>.** The heat from the intense oxygen-fed fire quickly raised the temperature, and accordingly the pressure, inside oxygen tank # 2.

Apollo 13: *What Happened?* (4 of 4)

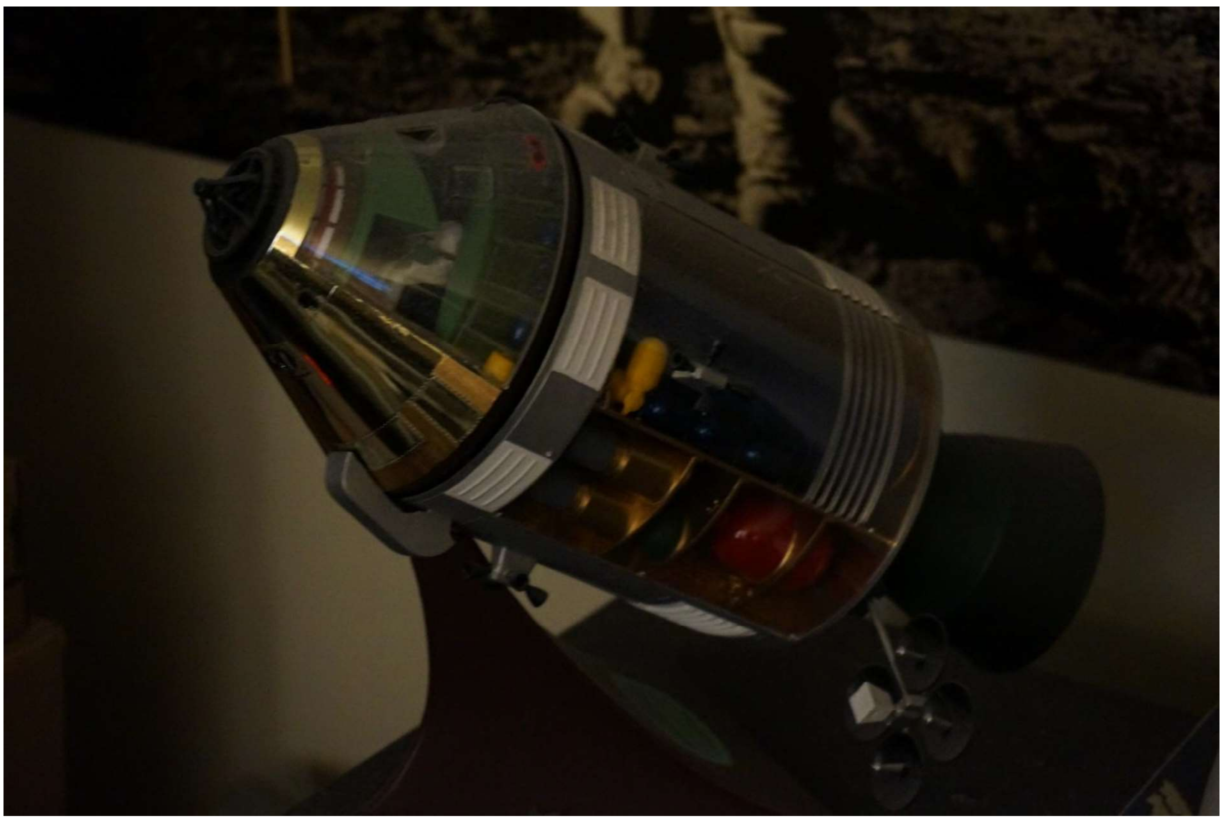
- Twenty-four seconds after the teflon insulation began burning, the neck and/or dome of oxygen tank # 2 blew off, striking the shelf above it, upon which sat the 3 fuel cells, with a force of 86g for 11 microseconds. **After the event, NASA preferred to call this event a "tank failure," and not an "oxygen tank explosion."** This is a distinction without a difference.

- **IN RAPID SUCCESSION, SEVERAL THINGS HAPPENED:**
  - **The remaining 300 lbs. of oxygen in tank # 2 flashed instantly to gas, and filled the compartment of Bay # 4 in the Service Module;**
  - **The teflon insulation in-between the two pressure vessels of the oxygen tank began to burn, and acted as a torch, igniting the mylar blanketing covering all surfaces inside Bay # 4;**
  - **The surface panel (the skin of the Service Module) outside Bay # 4 blew off, striking the high gain antenna and causing it to gyrate and wobble dangerously; the high-gain antenna, the primary means of communication with Mission Control, was nearly torn off;**
  - The shock of one or both of these events caused the valves serving several of the attitude control rockets in the Service Module's 4 "Quads" to close; **thereafter the "Quads" on the Service Module were partially disabled, resulting in a loss of attitude control of the spacecraft stack.**

- **WE ALL KNOW THE REST OF THE STORY:** With breathable oxygen supply rapidly dwindling, the Apollo 13 crew was forced to use the Lunar Module as a lifeboat, and eventually (and just barely) made it back to Earth safely. Tremendous teamwork and ingenuity by Mission Control personnel saved the lives of three astronauts.
- **THE FIXES:** The safety switches in all the cryogenic tanks were replaced, of course, with switches that could accommodate the 65 volts D.C. used in ground testing. **Apollo 14 travelled to Fra Mauro on the Moon (Apollo 13's original destination) with an extra oxygen tank installed in its Service Module; and the Apollo 15-17 missions all had *both* an extra oxygen tank, *and* an extra hydrogen tank, installed in a different equipment bay of the Service Module from the other hydrogen and oxygen tanks.**
- **THE WHAT-IFS: The disaster could have been much worse; consider these scenarios---**
  - **The explosion(s) might have broken the three tension ties between the Command Module and Service Module (severely impacting communication with earth right after the event, and losing the option of burning the SPS engine to return to earth);**
  - **The explosion(s) might have cracked the Command Module's heat shield (resulting in the fiery death of all three astronauts during re-entry);**
  - **The explosion(s) might have occurred during a "cryo stir" while the Lunar Module was on the surface, and with the Command Module in orbit around the Moon; this would have led to the quick asphyxiation of the Command Module Pilot in lunar orbit, and the somewhat slower, but equally cruel death of the two astronauts on the lunar surface, who would have had "nowhere to go."**
  - **The explosion(s) might have occurred during the CSM's return to earth after a successful lunar landing, with no Lunar Module available as a lifeboat (resulting in 3 deaths due to asphyxiation).**

Oxygen Tanks # 1 and 2 in the Service Module Are Painted Green in the Model

(Note: Fuel Cells # 1-3, above the 2 Oxygen Tanks, are Grey; Hydrogen Tanks # 1 and 2, below, are Red.)



Another View of the Service Module’s 2 Oxygen Tanks (Green in Model); The 3 Fuel Cells Above Them Are Grey, and the 2 Hydrogen Tanks Below Them Are Red