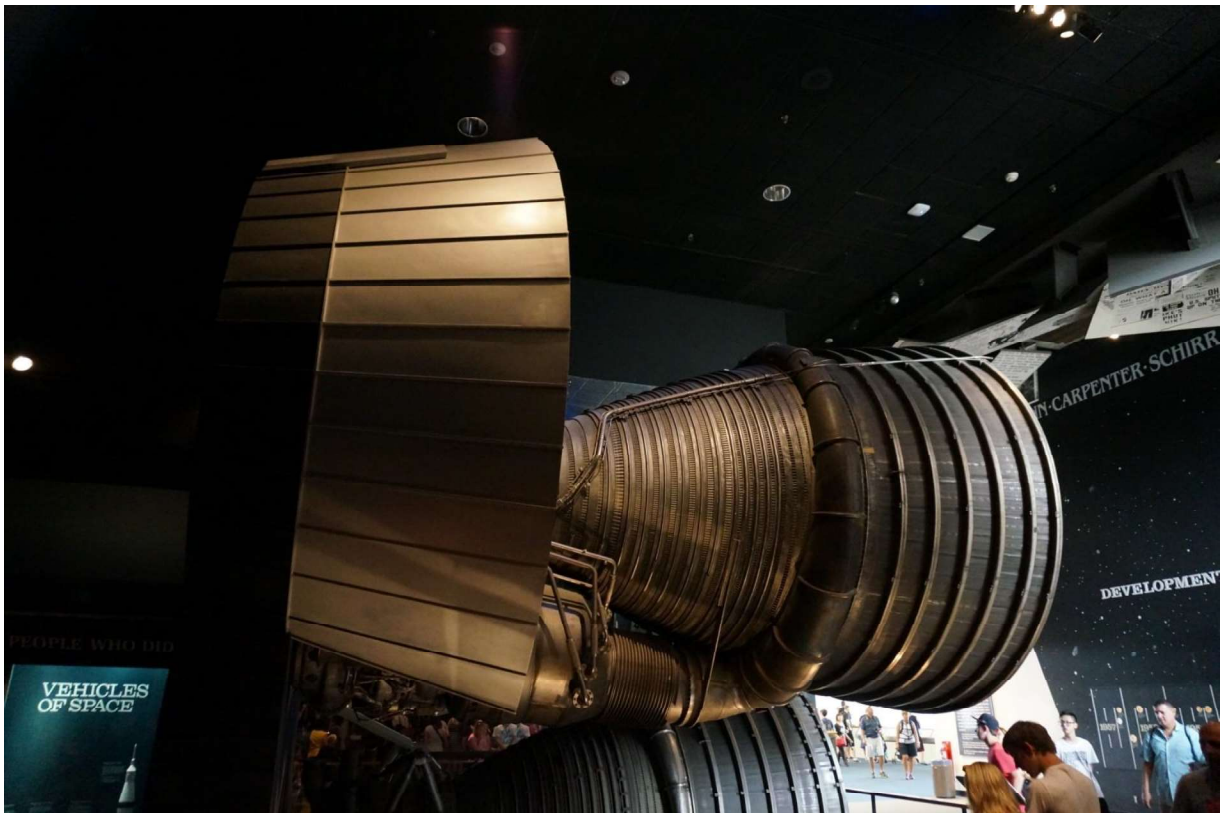


F-1 Engine on Display at NASM, Washington, D.C.
(Note Thrust Chamber, Heat Exchanger, Turbopump Exhaust Manifold, and Nozzle Extension or “Skirt”)



The Mighty F-1 Engine (1 of 4)

- Built by Rocketdyne, a subsidiary of North American Aviation.
- Origins:
 - A USAF contract in 1955 called for the development of a rocket engine that would generate one million pounds of thrust;
 - The fledgling NASA inherited the contract from the Air Force and on January 19, 1959 formally assumed responsibility, upgrading the desired thrust to 1.5 million pounds.
- Dimensions: the F-1 engine was **18.5 feet tall**, and the nozzle extension (or “skirt”) was **12.2 feet wide at its base**. The engine’s **exit-to-throat-area ratio was 16:1**; the nozzle extension expanded the exit-to-throat-area ratio in the basic engine (without the “skirt”) from 10:1 to 16:1, making the engine much more efficient. The weight of the F-1 engine (flight configuration) was 18,500 lbs.
- Propellants: **Fuel was a refined kerosene called “RP-1” (rocket propellant one) and the oxidizer was liquid oxygen, commonly referred to as “LOX.”**
- **The oxidizer-to-fuel ratio was 2.27 (plus or minus 2%) to 1**; this is the principal reason why the oxidizer tank in the S-IC stage was so much larger than the fuel tank for the RP-1 kerosene.
- **The specific impulse of the F-1 engine was 265 seconds**; specific impulse is defined as the ratio of the engine’s thrust over the weight of the propellants consumed in one second. *In comparison, the specific impulse of the cryogenic J-2 engine (which burned liquid hydrogen as fuel and LOX as the oxidizer) was 424 seconds; the J-2 was a much more efficient engine. But the F-1 still produced much more thrust than the J-2, since it was so much bigger.*

The Mighty F-1 Engine (2 of 4)

A Thirsty Engine: Each F-1 engine at full thrust (or “main stage”) consumed **.8 metric tons of RP-1 fuel per second, and 1.8 metric tons of oxidizer (LOX) per second.** [Conversion factor: One metric ton equals 1.1023 tons in imperial units.] The total run time for the four outer engines, at “main stage,” was 166 seconds. (The run time for the center engine was only 136 seconds; it was shut down thirty seconds prior to the four outer engines so that the acceleration of the Apollo-Saturn V Space Vehicle did not exceed 4 gravities; this was done in deference to the delicate structure of the Lunar Lander.) The five F-1 engines ran for one full second at full thrust prior to hold-down arm release and “liftoff;” only when the Instrument Unit sensed that all five F-1 engines were at full thrust, did it signal hold-down arm release and permit liftoff. (Note: the I.U. would not shut down any of the F-1 engines for the first 30 seconds of operation, for any reason, to ensure that the tower was cleared and that the rocket was clear of the launch pad.) Liftoff appeared quite slow at first; although it took about 10 seconds to clear the Launch Umbilical Tower, the Saturn V was traveling at about 56 mph by then.

A separate **Mark 10 F-1 Turbopump**, an exquisite blend of precision and brute force engineering, fed each one of the five F-1 engines. This extremely robust device generated 55,000 brake horsepower, and operated at 5,500 RPM. It was a direct drive unit consisting of a two-stage turbine, a fuel pump, and an oxidizer pump, all mounted on a single shaft. RP-1 fuel was used to lubricate the bearings. Overall, about **2.9% of the propellant load** in the S-IC stage was burned in a **gas generator**, and those exhaust gases drove the 5 turbopumps. RP-1 fuel not only lubricated the turbopump’s bearings, but it served as the hydraulic fluid that gimballed the 4 outer F-1 engines during flight. The capacity of the fuel and oxidizer pumps was as follows:

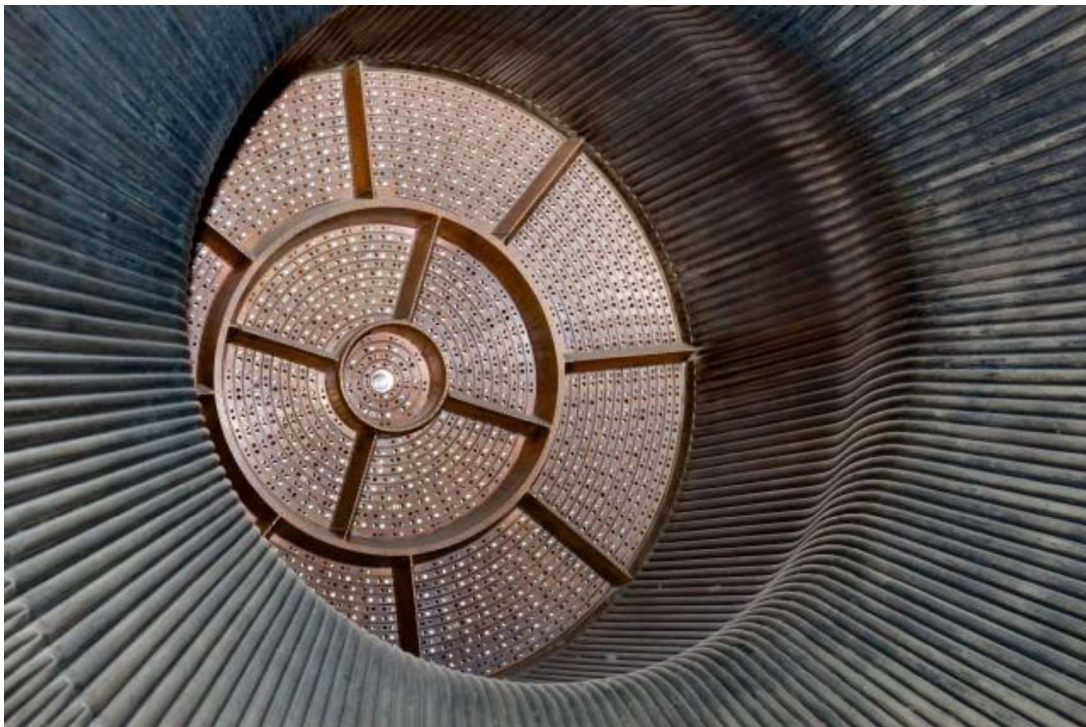
Fuel pump: 15,471 gallons per minute

Oxidizer pump: 24,811 gallons per minute

The Mighty F-1 Engine (3 of 4)

- More About the **Gas Generator** for each F-1 engine:
 - It was a single-walled vessel;
 - It burned a **fuel-rich mixture** of RP-1 and LOX, at a ratio of 0.416 LOX to RP-1, so that the exhaust gases were *relatively* “cool” to keep the walls of the gas generator from melting; the temperature of the gas generator exhaust was about 1,465 degrees F (or 796 degrees C).
 - F-1 engine thrust chamber operating temperatures, in contrast, were about 5,970 degrees F (or 3,299 degrees C). [The oxidizer-to-fuel ratio in the F-1 was 2.27 to 1 for maximum efficiency, and produced a lot of heat.]
- A large, circumferential **Exhaust Manifold** directed the turbopump exhaust to the top of each nozzle extension (or “skirt”) where the exhaust gas entered in-between the outer and inner walls of the “skirt.” The relatively “cool” turbine exhaust [1,465 degrees F versus 5,970 degrees F] exited into the main combustion exhaust plume through openings (slots) in the “shingles” which comprised the inner walls of the nozzle extension. **This cooler turbine exhaust prevented the nozzle “skirt” from melting during “main stage” ignition.**
- **Regenerative Cooling** in the walls of the *thrust chamber* (i.e., above the “skirt” or nozzle extension) prevented the thrust chamber from melting; some 70% of the RP-1 fuel that was eventually burned, circulated first through the piping that constituted the walls of the F-1 thrust chamber. This Inconel X-750 alloy tube bundle, through a form of welding called furnace brazing, constituted the solid wall of the engine (above the nozzle extension). The remaining 30% of the RP-1 entered directly into the engine through the injector plate.
- A **Heat Exchanger** located *in between* the Turbopump itself, and the Exhaust Manifold, heated both helium and LOX, respectively, to keep the kerosene fuel and oxidizer tanks pressurized during the flight of the S-IC stage.
- An **Injector Plate**, about 3 feet in diameter and 4 inches thick, was located at the top of the engine in a barrel 36” wide and about 30” long. Drilled into this injector plate were 2,600 LOX orifices and 3,700 RP-1 orifices; through these openings the fuel and oxidizer streamed at extremely high pressure, at precise angles of impingement, to maximize efficient combustion inside the combustion chamber. The opening of the barrel below the injector plate was called the “throat” of the F-1 engine. The orifices in the injector plate for the fuel and oxidizer were drilled into copper circular bands held in place in a stainless steel body by *gold-plated steel lands* to insure good welds that would not come apart during the intense heat of combustion. The otherwise flat face of the injector plate was interrupted by 14 circumferential and radial thick copper baffles that prevented runaway combustion and ensured stable burning inside the rocket engine.

Photo of **F-1 Engine Injector Plate** and “**Throat**” of the **Combustion Chamber**; note **Regenerative Cooling Tubes** Comprising the **Thrust Chamber**. [The 14 radial and circumferential thick copper baffles can be seen on the surface of the Injector Plate.]



The Mighty F-1 Engine (4 of 4)

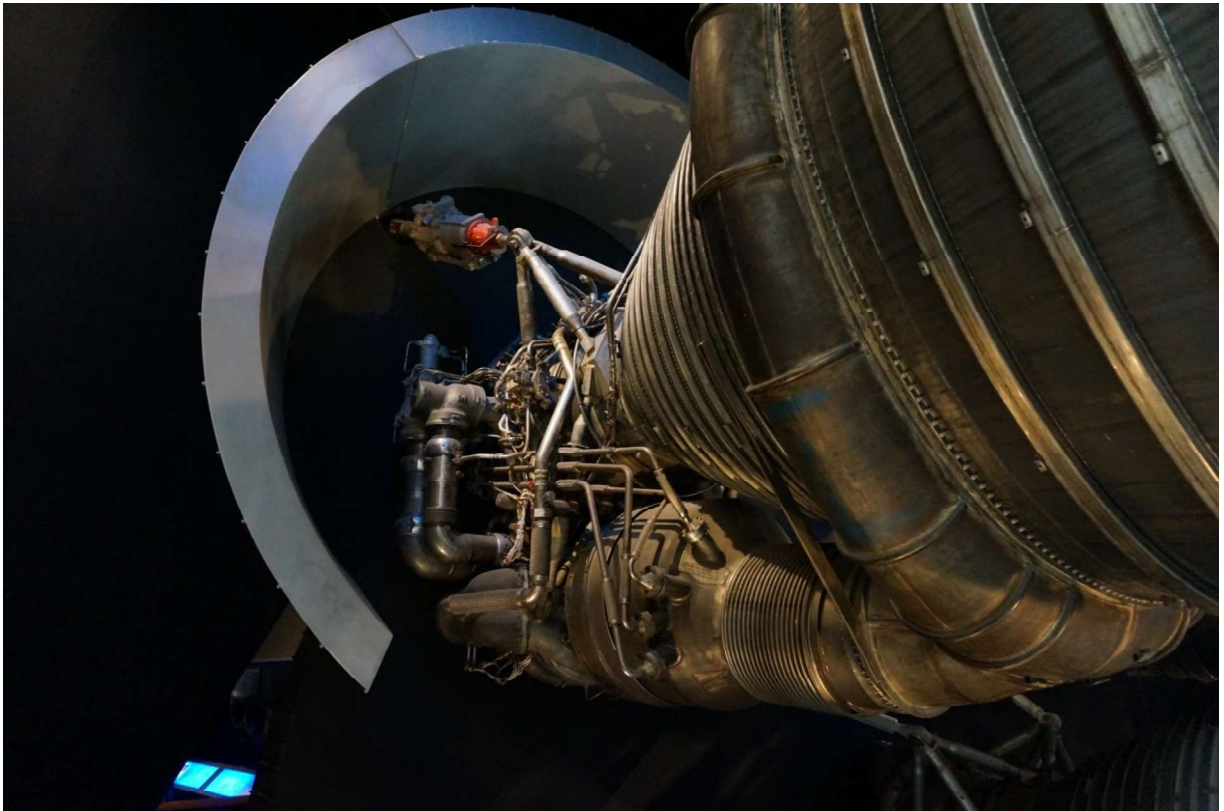
- **F-1 Engine Insulation:**

- A “cocoon” of insulation was required on the outer surface of each F-1 engine to protect them from both the intense heat buildup during the ignition sequence when the rocket was stationary, and during flight.
- During flight, maximum temperatures of up to 2,550 degrees F were experienced around the engines because *as atmospheric pressure rapidly diminished during ascent, the exhaust plumes from the clustered engines expanded to envelop the F-1 engines with a backlash stream of hot gases* against the outer surfaces of the engines. (This backwash of engine exhaust can clearly be seen in launch films, as it slowly also climbs up the first stage of the Saturn V, enveloping the thrust structure.)
- The insulation was installed on the launch pad by workers standing on the large, 45-foot square **engine servicing platform** mounted on the mobile launcher’s surface around the five F-1 engines. The engine servicing platform was removed from the mobile launcher after installation of the insulation “cocoon.”
- The insulation consisted of Inconel X-750 foil batting, and asbestos blanketing covered by foil; the insulation packages were made in the factory, and then shipped to KSC for installation on the pad.

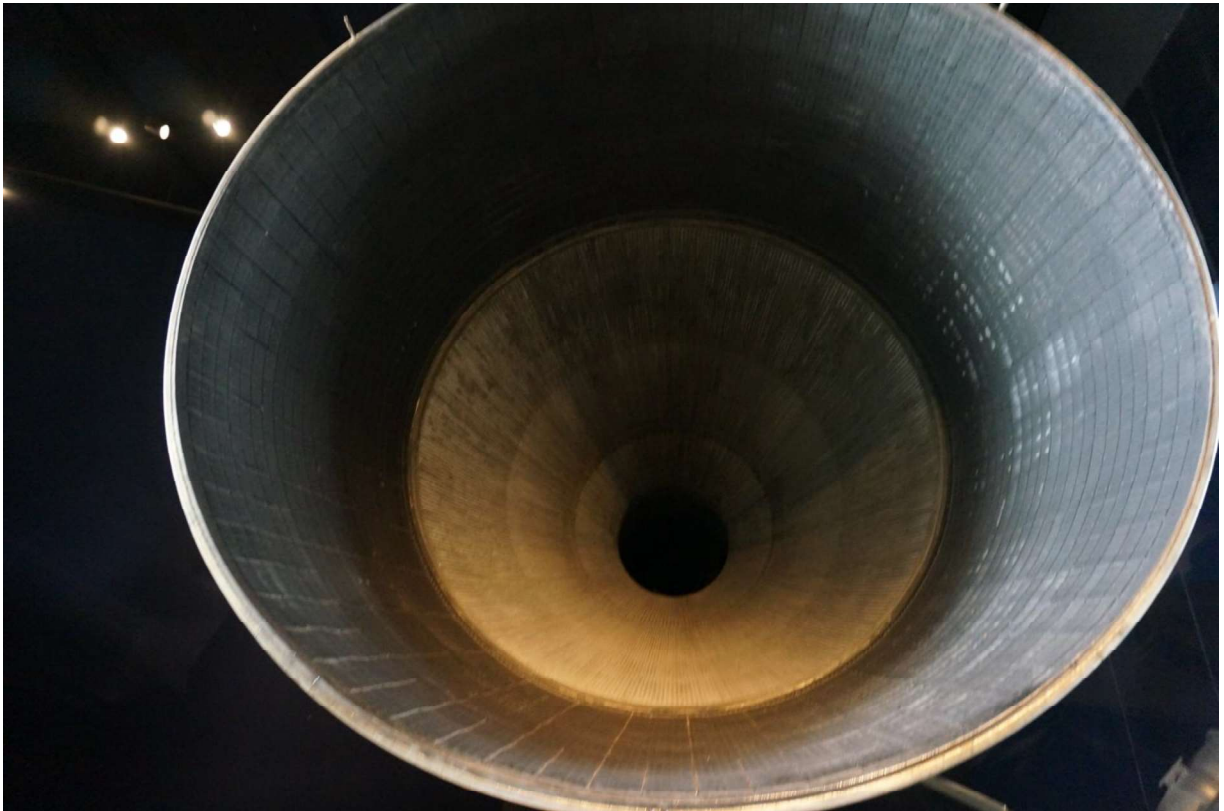
- **F-1 Engine Development Problems:**

- **Combustion Instability** destroyed several F-1 engines during testing. This problem was solved by: (1) a trial-and-error process of changing the impingement angles of the propellant streams coming out of the injector plate into the combustion chamber; and (2) installation of *circumferential and radial copper baffles* on the face of the injector plate. Solving the combustion instability problem would have been impossible without model cooperation between government, private industry, and academia.
- **“POGO”** was the name for excessive longitudinal axis vibrations that seriously threatened the structural integrity of the vehicle during the second unmanned test launch of the Saturn V (AS-502); the POGO was caused by *resonance* between the engines’ vibration and the booster structure’s natural vibration frequencies. This was resolved by introducing gaseous helium into the five LOX prevalues above the F-1 engines prior to the introduction of LOX into the turbopumps or the LOX dome above each engine; the gaseous helium in the prevalues served as a “shock absorber,” greatly ameliorating the POGO problem.
- **The Mark 10 Turbopump** absorbed more design effort and time for fabrication than any other component of the F-1 engine. [Eleven turbopumps were destroyed during testing until they “got it right.”]

F-1 Engine at NASM, Washington, D.C.
(Note Gimbal Outrigger Arm, Turbopump, Heat Exchanger,
and Exhaust Manifold)

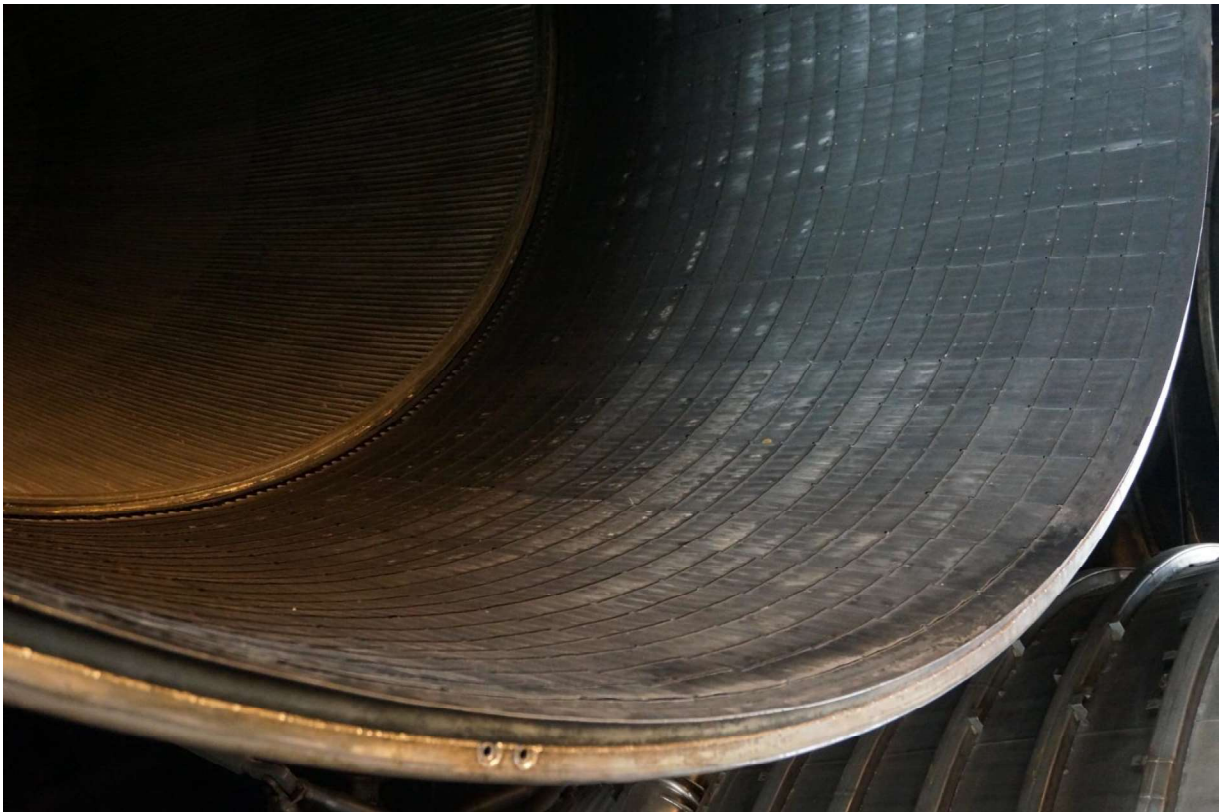


F-1 Engine at NASM, Washington, D.C.
(Note nozzle extension; thrust chamber; and “throat” of engine)



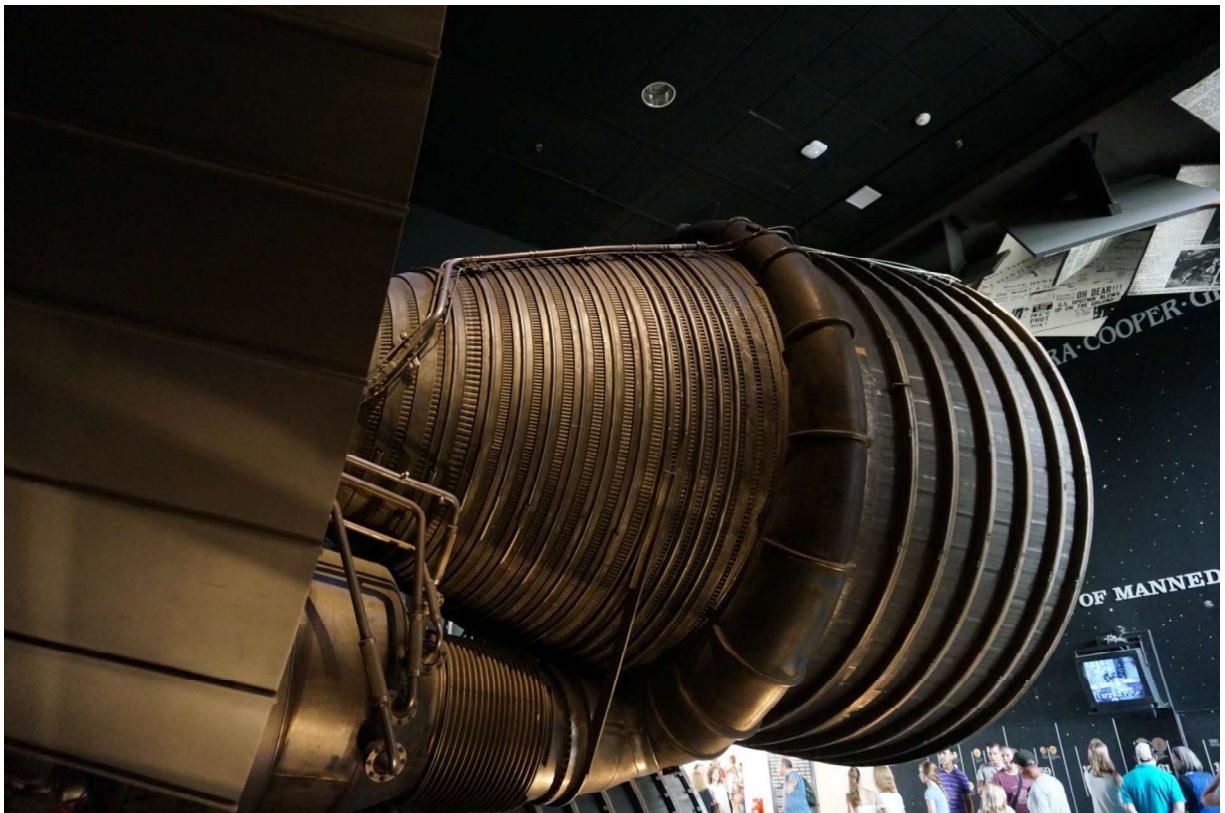
F-1 Engine at NASM, Washington, D.C.

(Note detail of “shingles” that constitute inner layer of nozzle “skirt,” and regenerative cooling tubes that make up the thrust chamber)



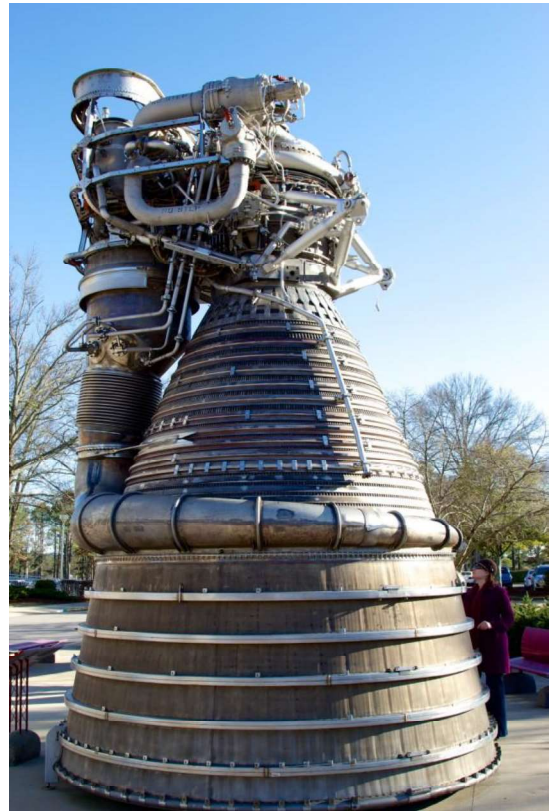
F-1 Engine at NASM, Washington, D.C.

(Note Helium and LOX lines---2 each---leading from Heat Exchanger back to the 1st stage propellant tanks to maintain pressurization)



F-1 Engines, Showing Human Scale

(Note Exhaust Manifold linking the *Heat Exchanger* with the *Nozzle Extension*)
The F-1 Remains the Largest Rocket Engine Ever Built



Saturn V First Stage (S-IC) Ignition Start (Simplified) [1 of 2]

- At T-8.9 seconds (eight seconds prior to liftoff), “**ignition sequence start**” was activated by the Terminal Launch Sequencer (a solid-state clock, not a computer) in the Mobile Launcher. Commencing with *liftoff*, the Saturn V’s I.U. took over command of the booster’s engines.
- **The “engine start” actions for the five F-1 engines were staggered**, to lessen the shock on the *thrust structure* of the S-IC stage.
- The centerline F-1 engine, no. 5, was started first; followed about .25 seconds later by the diagonally opposite engines no. 1 and 3; and about another .25 seconds later by diagonally opposite engines no. 2 and 4. (Opposite engine starts approximately, *but not exactly*, same time.)
- There were **five (5) igniters per engine**: 4 spark plugs, and one hypergolic chemical igniter.
 - Two (2) electrical igniters were located inside the Gas Generator;
 - Two (2) electrical igniters were located in the Nozzle Extension;
 - The **Hypergol Cartridge (85% Triethylborane and 15% Triethylaluminum)** was located above the injector plate and thrust chamber.
 - Upon receipt of the “engine start” command, the **four (4) electrical igniters** for that engine were lit off, *and burned for about 6 seconds each*.
- **LOX began flowing into the combustion chamber.**
- **Propellants, under tank pressure, began flowing into the Gas Generator combustor and were ignited by the two spark plugs inside the Gas Generator.**
- **Combustion gas from the Gas Generator passed through the Turbopump, Heat Exchanger, Exhaust Manifold, and Nozzle Extension.**
- **Fuel-rich turbine combustion gas**, exiting the slots in the inner wall of the Nozzle Extension, **combined with LOX**, *and was ignited by the two spark plugs in the Nozzle Extension*. This produced a *ragged, bright orange flame* that exited each Nozzle Extension.
- The MK 10 Turbopump rapidly accelerated, causing RP-1 and LOX pump pressures to increase.

Saturn V First Stage (S-IC) Ignition Start (Simplified) [2 of 2]

- Increasing fuel pressure caused the Hypergol Cartridge (the one chemical igniter per engine) to rupture, spewing its contents into the thrust chamber through special orifices in the injector plate.
- The hypergolic fluid from the ruptured Hypergol Cartridge, RP-1 fuel, the glycol pre-stored in the injector plate, and LOX, all mixed inside the combustion chamber and ignited inside the “throat” of the engine.
- All preceding actions in each engine took about 6 seconds to accomplish.*
- Transition to “Mainstage” (combustion of RP-1 and LOX leading to full rated thrust) commenced shortly after the opening of the RP-1 main fuel valves. The staggered “mainstage” transition of the five (5) F-1 engines commenced as follows (based upon their staggered ignition start times):
 - **Engine no. 5**, at about **T-3.0 seconds**;
 - **Engines no. 1 and 3**, at about **T-2.75 seconds**; and
 - **Engines no. 2 and 4**, at about **T-2.5 seconds.**
- It took a little more than one second (about 1.25 to 1.5 seconds) after the main fuel valve for each engine was opened for the engine to build up to full thrust.
- Once the thrust pressure switch sensed a thrust chamber pressure of 1060 psi, a **“Thrust OK”** signal was sent to the Instrument Unit.
- After the I.U. received a **“Thrust OK”** signal from **ALL FIVE ENGINES for one full second**, it sent the **“let me go” signal** to the four (4) Hold-Down Arms at the base of the S-IC stage, and **Liftoff** occurred at “first movement.”
- Umbilical connections for the last 5 Swing Arms in the LUT** were commanded by the sequencer in the Mobile Launcher to rapidly retract after the Saturn V had moved 1.5” (4 cm) off of the pad.
- During the Saturn V’s slow, ten second ascent past the Launch Umbilical Tower, *the I.U. gimbaled the four (4) outer F-1 engines* to execute a *“yaw maneuver”* of 1.25 degrees to the south (away from the vertical and the LUT), to avoid LUT contact in the event of a gust of wind. This initial gimbaling of the F-1 engines was very noticeable, and somewhat disconcerting, to the astronauts all the way at the top of the Space Vehicle.

Apollo 16 Launch (Note commencement of the “Yaw Maneuver”---
the 1.25 Degree Tilt to the South, Away from the Launch Umbilical
Tower)



**A More Dramatic View of the “Yaw Maneuver”
During the Launch of Apollo 1 in November of 1967**

(The 1.25 degree tilt of the Saturn V away from the LUT seems quite pronounced)



Controlled Fury: **The Launch of a Saturn V Space Vehicle**

(Almost 15 tons of propellant were consumed by the first stage each second, for over 2 minutes, 15 seconds.)



The J-2 Engine: A Cryogenic Marvel (1 of 2)

- **Origins:** America's first *cryogenic* rocket engine (both fuel and oxidizer were stored at subzero temperatures) was the **RL-10**, producing a modest thrust of "only" 15,000lbs.; it was designed in 1958-59, and manufactured in the early 1960s by Pratt and Whitney. It was made to propel the *Centaur* upper stage rocket (which was intended primarily for use with the Atlas booster), and was the direct precursor to the J-2 engine. The *Centaur* upper stage utilized two RL-10 engines; and the early S-IV second stage (used with the Saturn I first stage) used six (6) RL-10 engines. After the development of the RL-10 demonstrated that cryogenic technology worked, the NASA Lewis Center encouraged the development of a much larger cryogenic stage. In September of 1960, **Rocketdyne** won a competitive contract to develop a 200,000 lb. thrust J-2 engine; it would use the same Liquid Hydrogen and LOX propellants that the RL-10 employed. (Thrust was later upgraded to 225,000; and then to 230,000 lbs.)
- **Advantages of using Liquid Hydrogen as fuel:** It was much more efficient than kerosene (RP-1). For example, the specific impulse of the F-1 engine was 265 seconds, whereas the specific impulse of the J-2 was 424 seconds. [Specific impulse is the ratio of an engine's thrust over the weight of the propellant consumed in one second.]
- **Disadvantages of using Liquid Hydrogen as fuel:** Because Liquid Hydrogen is *much less dense* than a non-cryogenic fuel such as RP-1, it requires very large propellant tanks; for this reason it was ruled out for use in the first stage of the Saturn V (i.e., the fuel tanks would have been too large, making the first stage of the booster too fat). Furthermore, insulating liquid hydrogen fuel at its extremely low temperature of -423 degrees F (-253 degrees C) proved to be a major challenge, since the nearby LOX oxidizer, maintained at a temperature of -300 degrees F (-184 degrees C), tended to "warm up" the Liquid Hydrogen. This was unacceptable, since the Liquid Hydrogen could not be allowed to turn into a gas inside the fuel tank!
- **Dimensions:** The J-2 engine was much larger than the relatively modest RL-10:
 - **RL-10 dimensions:** 5.67 feet tall (68"); 3.25 feet wide (39") at the nozzle exit
 - **J-2 dimensions:** 11.1 feet tall; 6.8 feet wide at the nozzle exit; 27.5 to 1 exit-to-throat-area ratio; flight weight: 3,480 lbs.
- In its exterior appearance, the J-2 engine seemed very similar to the F-1 engine because it, too, had a wraparound exhaust manifold halfway down the engine bell; however, the J-2's turbine exhaust gas was **not** sent into the thrust chamber for cooling purposes---it was instead burned inside the exhaust plume, increasing the engine's thrust. Generally speaking, the J-2 engine was a more complex machine than the F-1. There were differences between the two engines in regard to their turbopumps, injector plates, and in the nature of the regenerative cooling for the thrust chamber.
- **Regenerative Cooling in the J-2:** The Liquid Hydrogen fuel turned into gas halfway through its journey through the J-2's cooling tubes, and was injected into the J-2 thrust chamber as a gas, not as a liquid. **Combustion temperature of J-2: 5,750 degrees F.**
- **Oxidizer-to-Fuel Ratio in the J-2 Was Variable:** In the F-1 engine, the oxidizer-to-fuel ratio remained constant at 2.27 to 1; however, in the J-2, this ratio could be changed somewhat by varying the flow of the LOX in an attempt to more evenly balance the use of both fuel and oxidizer, so that they were both depleted at about the same time. The J-2 engines on the S-IVB stages were operated at mixture ratios (MRs) of 4.5 or 5.0 to 1. The early J-2s in the S-II stages (through the Apollo 13 flight) operated at MRs of 4.5:1, 5.0:1, or 5.5:1; starting with the Apollo 14 S-II stage, and beyond, the J-2s only used two MRs, of either 4.8 to 1, or 5.5:1. The valve that controlled LOX flow to the J-2 engine, thereby adjusting the mixture ratio, was called the propellant utilization valve. This function was controlled by the I.U. on the Saturn V, which sensed propellant levels in the tanks and acted accordingly.
- **An Augmented Spark Igniter** provided a constant ignition source at the center of the injector face in each J-2 engine after spark plugs were used to begin combustion during the engine start sequence, and ensured that the cryogenics continued to burn after the two spark plugs burned out.

The J-2 Engine: A Cryogenic Marvel (2 of 2)

- **The J-2 Turbopumps:** Because Liquid Hydrogen and LOX had such different densities, they each required a *separate turbopump*; this was considered more reliable than gearing down the drive from a single turbine. The two J-2 turbopumps were mounted on opposite sides of the J-2 thrust chamber.
 - A *much higher turbine speed* was required to propel Liquid Hydrogen (which is much less dense than LOX) into each J-2 engine.
 - A common gas generator ran both turbopumps, with the Liquid Hydrogen pump accepting the gas generator exhaust first; the LOX pump utilized the leftover exhaust gas, by design.
 - The Liquid Hydrogen fuel pump operated at 27,000 RPM and produced 7,800 brake horsepower;
 - The LOX oxidizer pump ran at 8,600 RPM and was rated at 2,200 brake horsepower;
 - Together, they drove about a quarter of a metric ton of combined propellants, per second, into each J-2 engine.
 - Each turbopump was lubricated by its own liquid (Liquid Hydrogen and LOX, respectively);
 - A heat exchanger converted liquid to gaseous oxygen to maintain pressure in the LOX tank; it warmed helium to keep the Liquid Hydrogen tank pressurized.
- **The J-2 Injector Plate was very different from that in the F-1 engine:**
 - **It was not a solid plate of metal; instead, it was porous**, allowing about 3.5% of the gaseous Hydrogen fuel (warmed from a liquid to a gas during regenerative cooling) through the fine mesh to cool the injector plate;
 - Unlike the F-1 injector plate, the orifices and flow of the fuel and oxidizer were *not angled* in the J-2 engine;
 - **The J-2 injector plate featured 614 co-axial injector tubes**, through which LOX was passed under pressure; each of the 614 LOX tubes *was surrounded by a circular gap through which gaseous Hydrogen flowed*. The LOX was atomized as these two flows met, while exiting the injector plate.
 - Although Hydrogen and Oxygen are very reactive, they are not hypergolic, so the Augmented Spark Igniter was required to produce a steady flame in the middle of the injector plate that would ensure smooth and steady combustion inside the thrust chamber.
- **J-2 Restart Capability** existed only for the J-2 Engines in the S-IVB Stage (it was needed for the TLI burn); a complex series of actions was required that had to begin **9 minutes and 38 seconds** prior to commencement of the translunar injection burn. These actions included repressurization of propellant tanks, and chill-down of both turbopumps to prevent the cryogenic propellants from turning into gas inside the turbines.
- **In both the S-II stage and the S-IVB stage, instead of being stored in separate propellant tanks, both the Liquid Hydrogen and LOX were in one single tank that shared a “common bulkhead;”** while this made each stage shorter and saved weight, it presented severe challenges in regard to developing appropriate insulation to keep both the LOX and the Liquid Hydrogen at their respective temperatures.

Typical Apollo-Saturn V Launch Profile

<u>Stage</u>	<u>Duration of Burn</u>	<u>G Forces</u>	<u>Altitude, End of Burn</u>	<u>Speed After Burn</u>
First Stage (S-IC)	2 min., 45 sec.	Max of 4 g	39-40 nm	6,100 mph
Second Stage (S-II)	6 min., 30 sec.	.75 to 1.8 g	116 nm	15,600 mph
Third Stage (S-IVB) #1	2 min., 22 sec.	.5 to .75 g	Same (LEO)	17,170 mph
Third Stage (S-IVB) #2	Almost 6 min.	.5 to 1.5 g	N/A	24,200 mph

(Note: The S-IC's center engine cutoff was specifically designed to prevent the Apollo-Saturn V stack from exceeding 4 gs; its acceleration reached about 4gs at center engine cutoff (2 min., 15 sec.), and then reached 4gs again---for the second time---at the time of outer engine cutoff (2 min., 45 sec.). The beneficiary was the LM, which had an exceedingly delicate construction.

The F-1 engines provided about 31% of the speed needed to reach Earth Orbit; the J-2 engines in the S-II stage provided about 53% of the speed needed to reach Earth Orbit; the S-IVB (burn # 1) provided about 11%; and the earth's rotational velocity (toward the east) provided the remaining 5% of the speed needed to reach Earth Orbit. The mighty F-1 engine was the "heavy lifter," but the elegant J-2 engine produced most of the velocity required for Earth Orbit, and all of the velocity required for translunar injection, or TLI.)

Kennedy Space Center (KSC): America's Moonport (1 of 2)

- **KSC employed almost 24,000 workers at the height of the Apollo program (civil service and contractor).**
- **Principal facilities at Launch Complex 39 (and nearby):**
 - **Vehicle Assembly Building (VAB)**
 - World's largest building (in terms of volume) when completed;
 - High Bay (for Saturn V stacking) and Low Bay (for receipt of individual stages and manned spacecraft from MSOB).
 - **Launch Control Center (LCC)**
 - 4-story building with four "firing rooms;" 3 used for launches, 1 used for planning meetings.
 - **Turning Basin and Barge Terminal** (adjacent to VAB and LCC)
 - Banana River provided access to turning basin; S-IC and S-II stages delivered by barge and thence taken directly into VAB Low Bay area.
 - **Crawlerway** (from VAB to launch pads)
 - About 3.5 miles long, from VAB to Pad 39A; a 5-6 hour trip for the Mobile Launcher (carried by the Crawler-Transporter), traveling at an average speed of one mph when loaded with the Saturn V)
 - **Launch Pads 39A and 39B**
 - Pad 39A used for all Saturn V launches except one (see below);
 - Pad 39B only used for the Apollo 10 launch;
 - Each launch pad notable for large flame trench for rocket exhaust, running north-south;
 - Two (2) large flame deflectors were built for each launch pad.
 - **Manned Spacecraft Operations Building (MSOB)**, renamed "Operations and Checkout Building"
 - Located in the KSC Industrial Area, just south of Merritt Island and Launch Complex 39;
 - High Bay and Low Bay; also included **two full sized altitude chambers** that could each accommodate a CSM or LM, so that tests of each manned spacecraft could be run in a very low pressure (near vacuum) environment;
 - **The Command and Service Module (CSM) and Lunar Module (LM) for each flight underwent about 3 months of concurrent testing and checkout in the MSOB**, prior to being shipped over to the VAB for stacking on top of the Saturn V booster;
 - **CM and LM simulators, and astronaut living quarters** (for use immediately prior to flight and/or simulations) were located at the MSOB.

America's Moonport: A Bird's Eye View

**(Note VAB, LCC, Crawlerway, Mobile Launcher/LUT, and Barge Canal and Turning Basin Used to Deliver Saturn V Stages.)
[Mobile Service Structure and Pad 39A Visible in Distance]**



Kennedy Space Center (KSC): America's Moonport (2 of 2)

[Conversion Factors: one meter = 3.281 feet; one metric ton = 1.1023 tons]

- Vehicle Assembly Building (VAB)
 - Could accommodate the stacking of four (4) Saturn V launch vehicles at one time; **on some occasions, there were 3 launch vehicles in various stages of assembly and checkout at one time in the VAB.**
 - Dimensions: 160 meters high; 218 meters long; 158 meters wide;
 - Four (4) different doors could be used for the egress of the Apollo-Saturn V Space Vehicle on the mobile launcher; **door dimensions were 139 meters high;** 45 meters in width at the base; and 22 meters wide at the top.
 - Volume: over 3.6 million (3,665,000) cubic meters;
 - Total volume was almost as much as the Pentagon and Chicago Merchandise Mart, *combined*.
 - Total area: 32,500 square meters (about 8 acres)
- Flame Deflectors (four were constructed---two per launch pad; only one used per launch)
 - **635 metric tons each;**
 - Dimensions: 13 meters high; 15 meters wide; 23 meters long.
 - Placement: **moved on rails, and placed directly beneath the bottom of the Saturn V rocket,** so as to disperse the rocket exhaust east and west along the flame trench axis.
 - Steel skin over a strong framework of girders; **outer surface was covered by a 10 cm. layer of ceramic material which could be replaced.**

KSC Hardware Supporting Apollo-Saturn Launches: Engineering Marvels (1 of 2)

- Mobile Launcher, and its associated Launch Umbilical Tower (LUT)
 - **Three (3) were built; the Apollo-Saturn Space Vehicle was stacked (assembled), and transported to the launch pad, on the mobile launcher.**
 - Each mobile launcher carried not only the Apollo-Saturn V Space Vehicle, but also a bright red Launch Umbilical Tower affixed to the surface of the launcher;
 - Dimensions of Mobile Launcher:
 - **Two-story platform**, 7.6 meters high; 49 meters long; 41 meters wide; with a 14-meter-square opening directly underneath the Saturn V for rocket exhaust to pass through; the 14-meter-square engine servicing platform (around the five F-1 engines) was removed prior to launch.
 - Supported by six (6) steel pedestals 7 meters high; the mobile launcher sat on these six pedestals inside the VAB and on the launch pad.
 - Weight: 5,715 metric tons (includes unfueled Apollo-Saturn Space Vehicle).
 - Features of Mobile Launcher:
 - **Four (4) hold-down arms at its base**, weighing over 18 metric tons each; dimensions of each were 3.35 meters high; almost 2 meters wide; and almost 3 meters long.
 - **The 4 hold-down arms supported the entire weight of the Saturn V, and also held the rocket down to the pad during thrust build-up**, during the 8.9 seconds prior to liftoff.
 - **Three (3) tail service masts** at the base of the Saturn V furnished electrical cables, propellant loading lines, hydraulic lines, and pneumatic lines to the S-IC stage.
 - Housed the Terminal Launch Sequencer (a solid state clock), and an RCA 110A computer connected to an identical computer at the Launch Control Center; these three electronic devices, all crucial to each countdown, interfaced with the Apollo-Saturn V Space Vehicle.
 - Dimensions and Features of Launch Umbilical Tower:
 - 136 meters from base of tower, to top of hammerhead crane, at its top;
 - **18 levels, two (2) high-speed elevators, nine (9) swing arms** providing electric, propellant, pneumatic, and instrumentation lines to the space vehicle;
 - **Swing arms** varied in weight from 15,900 kg to 23,600 kg each; four (4) were retracted prior to launch, and five (5) had to quickly move out of the way, and then brake to a stop, immediately after the booster's first motion at liftoff. **Swing arms 1 thru 8 retracted 73 degrees to the right.**
 - **Swing arm 9** connected the **White Room** at its extreme end to the Command Module, and was used for astronaut loading. **Swing arm 9 retracted 135 degrees to the left prior to launch.**

KSC Hardware Supporting Apollo-Saturn Launches: Engineering Marvels (2 of 2)

- Crawler-Transporter

- **Two (2) of these behemoths were built;** their function was twofold: to carry either a Mobile Launcher/LUT to the launch pad, or afterwards, to carry the enormous Mobile Service Structure (see below) to the launch pad.
- **The Crawler-Transporter moved underneath the Mobile Launcher in the VAB and picked it up with four enormous jacking mechanisms; carried it to the launch pad with the Apollo-Saturn Space Vehicle on top; and then moved out from underneath, after depositing the Mobile Launcher at the launch pad; afterwards, the Crawler-Transporter would then pick up the Mobile Service Structure from its parking area, and transport it to the launch pad as well.**
- Weight: 2,700 metric tons;
- Design: rectangular in shape, with **four (4) double-tracked tread assemblies** (one at each corner); these four double-tracked “crawlers” were each 3 meters high, 12 meters long, with **57 “shoes”** in each of the eight (8) tread assemblies. **Each of these “shoes” weighed about 900 kgs.**
- The Crawler-Transporter had two control cabs (one on each end, facing opposite directions);
- Propulsion: Two (2) 2,750 hp diesel engines ran generators, which provided electric power to 16 traction motors which moved the treads.
- **Speed: one mile per hour when loaded;** typical trip from the VAB to the launch pad took 5-6 hours.
- **Four (4) “jacking cylinders”** (near the corners of the Crawler-Transporter) were employed to keep the top of the Apollo-Saturn V Space Vehicle as close to vertical as possible (i.e., within the width of a basketball). **The design specifications called for the jacking cylinders to keep the top of the LES Escape Rocket within plus-or-minus 10’ of arc (i.e., within a 12” to 15” circle) as the unit proceeded up the 5 degree incline to the top of the launch pad.**

- Mobile Service Structure (MSS)

- **Only one (1) was built because of its enormous size. Height: 122.5 meters; weight: 4,763 metric tons.**
- **The Mobile Service Structure had five (5) work platforms,** and shielding at its top that protected the Apollo Command and Service Module (CSM) from the weather. It was used for the extensive checkout of the Space Vehicle at the pad during the weeks prior to launch, as well as for the loading of extremely toxic and dangerous hypergolic propellants into the LM and CSM.
- **The MSS was always removed from the launch pad prior to launch,** and taken to its parking area, by the Crawler-Transporter. Unlike the Mobile Launchers, which were always damaged by rocket exhaust (fire) and water during each launch, the MSS did not have to be overhauled following each launch---therefore, only one had to be built.

The Rollout of the Apollo 17 Saturn V Space Vehicle
on the Mobile Launcher: the **Launch Umbilical Tower (LUT)**
Also Sits Atop the Mobile Launcher
(Photo taken from the roof of the Vehicle Assembly Building, or VAB.)



Mobile Launcher/LUT and Saturn V Enroute Pad 39A
On Top of the Crawler-Transporter



**The Crawler-Transporter Moves the Mobile Service Structure
Into Place at Pad 39A**
(Note Saturn V Sitting Atop Its Mobile Launcher Above Flame Trench.)



It took almost 6 months (working 24/7) to assemble, test, and launch an Apollo-Saturn V Space Vehicle at the Kennedy Space Center; at the height of the Apollo Program, almost 24,000 engineers and technicians were employed at KSC; the Apollo Program employed (directly and indirectly) about 400,000 American workers.



The Apollo 8 Mission: *The Single Biggest Risk, and the Biggest Leap*

- **Goal:** Circumnavigate the Moon with a crew of three American astronauts in the newly redesigned Apollo Command Module, and thereby deprive the USSR of another possible “first” in the space race:
 - Two Soviet “Zond” flights, using unmanned Soyuz spacecraft, circumnavigated the Moon in the fall of 1968; **NASA feared that a human circumnavigation by Soviet cosmonauts would allow the USSR to claim “victory” in the Moon race, *without even landing a man on the Moon.***
 - NASA’s Lunar Module was considerably behind in development, and was not ready to fly, so the concept was to send a Command and Service Module (CSM) and its crew to the Moon *without a Lunar Lander; in retrospect, and with 20-20 hindsight following the near disaster of Apollo 13, this appears to have been extremely risky. There would be no “lifeboat” if anything went wrong on the Command and Service Modules.*
 - The plan eventually adopted was not just to circumnavigate the Moon in a “figure eight” loop and immediately return home, *but instead to slow down upon arrival, orbit the Moon ten (10) times, and then return to Earth.*
 - The Apollo 8 mission would take human beings out of Earth orbit for the first time in history, and would test the SPS engine; radio communications via the spacecraft’s high-gain antenna and NASA’s new Deep Space Network; and inertial navigation on the spacecraft---*all for the first time in cislunar space, between two planetary bodies;*
 - And for the first time, human beings would re-enter the Earth’s atmosphere at the higher speeds involved in a return from the Moon (involving subjecting the heat shield on the CM to much higher temperatures than in a return from earth orbit);
 - Although the first unmanned Saturn V launch had gone perfectly in November of 1967, **the second unmanned launch, in April of 1968, had been a near disaster, and had barely reached orbit.** [See next slide for details]
 - While NASA engineers at Marshall Space Flight Center were confident they had corrected the 3 problems on the Saturn V rocket identified in the April 1968 test launch, **NASA made the startling decision to “man-rate” the Saturn V launch vehicle *without another unmanned test flight,* and to not only place a human crew on the behemoth on its very next launch, but to send the crew all the way to the Moon.** Such were the pressures inherent in an international competition for political prestige, based on demonstrated technological superiority, during the Cold War. [Originally, two earth-orbit test launches of both the CSM and the LM had been planned, using the Saturn V launch vehicle, before leaving Earth orbit; but now, the first men to fly a Saturn V would go all the way to the Moon!]
 - NASA demonstrated with this one flight that its redesign of the Command Module was sound; its “deep space” communications (as yet untried) were sound; its recently developed cislunar navigation programs were sound; its inertial navigation equipment and programming onboard the Command Module were sound; and proved that the SPS engine was fully reliable for use in the cislunar environment. **NASA’s management took a carefully considered, calculated risk---and reaped the appropriate rewards with the stunning success of this bold mission.**

Problems with the Saturn V Launch Vehicle

Experienced During Its Second Unmanned Launch in April 1968

(All of these problems had to be corrected prior to the Apollo 8 launch in December)

- **“POGO”** was the name given to the severe longitudinal axis vibrations in the first stage (S-IC) caused by resonance between the five F-1 engines’ vibrations and the booster structure’s natural vibration frequencies. The problem was so severe during this launch that two panels on the SLA were damaged and actually fell off of the rocket during its ascent! It was felt that severe POGO could also threaten the health and safety of the astronauts.
 - **THE FIX:** “POGO” in the first stage of the Saturn V was resolved by introducing gaseous helium into the five LOX prevalues above the F-1 engines, prior to the introduction of LOX into the turbopumps and the LOX dome above each engine; the gaseous helium in the prevalues served as a “shock absorber,” greatly ameliorating the POGO problem.
- **Premature Shutdown of two (2) of the five (5) J-2 Engines in the Second Stage** was caused by a combination of two problems: *first*, the Augmented Spark Igniter line’s bellows cracked due to resonance-induced vibration in the cold vacuum environment of space, eventually causing a “flame out” of engine # 2; *second*, when the I.U. ordered engine # 2 to shut down, *engine # 3 shut down instead*, because engines # 2 and # 3 had been inadvertently cross-wired.
 - **THE FIXES:** (1) The accordion-like bellows in all J-2 engine Augmented Spark Igniter lines were removed, and replaced with graceful bends in the piping; and (2) the wiring to each J-2 engine was henceforth built in different lengths so that a manufacturing error was no longer possible, removing the human propensity for error from the equation.
- **The single J-2 engine in the third stage (the S-IVB) would not restart, as planned, after reaching earth orbit.** [This restart was required for TLI, or trans-lunar injection, in normal lunar mission profiles.] The cause was the same as it had been for J-2 engine # 2 in the second stage: a cracked bellows on the Augmented Spark Igniter line.
 - **THE FIX:** The fragile bellows assemblies were removed from the Augmented Spark Igniter lines for **ALL** J-2 engines in the Saturn V booster: from the five J-2 engines in the second stage, as well as from the single J-2 engine in the third stage. Unlike the F-1 engines in the first stage (which only required a temporary, short-lived ignition source to commence ignition), all of the J-2 cryogenic engines required a continuous ignition source to maintain combustion.

The Competition: The USSR's Moon Landing Program Was Taken Seriously by the CIA and NASA

- In 1964 the USSR had an Earth-Orbit Rendezvous scheme, involving 3 separate N-1 launches to assemble a 200-ton Lunar Spacecraft stack in Earth orbit, followed by a Soyuz launch of the 2-man crew in a standard R-7 launcher; after launch, the Soyuz spacecraft would rendezvous with the Lunar Spacecraft stack in Earth orbit before commencing the voyage to the moon. This was a “do-able” concept, but extremely expensive; its weakness (aside from its high cost) was dependency upon a tight schedule of multiple launches.
- In 1965---emulating the Apollo concept---the USSR reconfigured its Lunar Landing Program into a Lunar Orbit Rendezvous scheme which depended upon only 1 N-1 launch to land on the Moon with a relatively lightweight, one-man lander; the second Cosmonaut would remain in lunar orbit in a Soyuz module.
- In 1968, two “Zond” Missions used a large “Proton” booster to send the new 2-man Soyuz spacecraft on Unmanned Circumnavigations of the Moon (in “figure-8” trajectories, without orbiting):
 - The Zond 5 Mission, from September 15-21, 1968, successfully circumnavigated the Moon at a closest approach of 1,960 kilometers, with biological specimens (2 turtles, fruit fly eggs, and plants) onboard. Due to numerous errors in the stellar guidance systems affecting its trajectory and retrofire, the spacecraft had to land in the secondary landing zone in the Indian Ocean instead of in the USSR. Nevertheless, the two turtles survived the trip and the rough water landing. Two additional unmanned circumnavigations were planned for Nov. and Dec. of 1968, prior to a tentative manned circumnavigation in January of 1969.
 - The Zond 6 Mission, from November 10-17, 1968, successfully circumnavigated the Moon again at a closest approach of 2,420 kilometers. However, on the trip back to Earth, and during re-entry, the spacecraft accidentally depressurized and the biological specimens died. Furthermore, due to premature separation of the parachute at high altitude, the spacecraft then crashed and was destroyed. Following this double failure, the USSR decided not to use a December 9th launch window to try to beat Apollo 8 to the Moon.
- After the American Triumph of Apollo 8 in December of 1968, the USSR Abandoned the Idea of Circumnavigation, and Focused on Beating the United States with a Manned Lunar Landing; But Two N-1 Launches Failed Dramatically in 1969:
 - On February 21, 1969 the first N-1 launch (unmanned) failed when the KORD computer cut off all of the main engines in the first stage prematurely (70 seconds after launch); the huge booster then crashed about 50 kilometers from the launch pad in Kazakhstan.
 - On July 3, 1969 the second N-1 launch (also unmanned), less than two weeks prior to the launch of Apollo 11, was an unqualified disaster of major proportions. The rocket's KORD computer, in response to engineering difficulties immediately after launch, shut down 29 of the 30 rocket engines in the first stage about 10 seconds into the launch at an altitude of less than 200 meters. The fully fueled booster fell back onto the launch pad at the Baikonur Cosmodrome in Kazakhstan, destroying the pad facilities with a massive explosion equivalent to 250 tons of TNT, and damaged another N-1 on the adjacent launch pad which otherwise might have been used in a manned lunar landing attempt:
 - If the Apollo 11 mission had failed, the Soviets had still hoped to beat America to the first Moon landing, until this July 3rd launch ended in disaster.
- Two subsequent failed N-1 launches forever ended Soviet ambitions to land a man on the Moon, and the N-1 program was terminated in 1974. The unused flight hardware for 6 additional N-1 rockets was destroyed.

The Apollo 8 Crew:
Frank Borman, William Anders, James Lovell

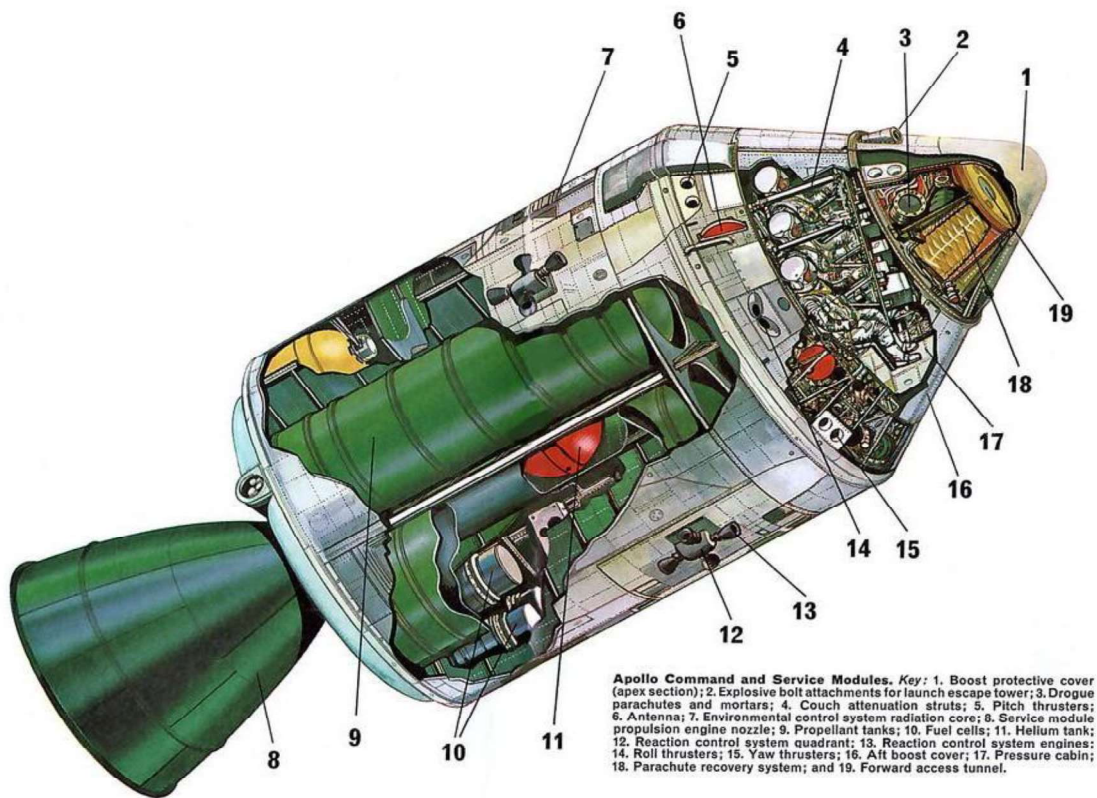


Apollo 8's Liftoff: December 21, 1968



The Apollo 8 Command and Service Module Traveled to the Moon Without a Lunar Module

(Consequently, there was no probe mechanism in the nose of the Command Module)



The Most Famous Apollo Photograph Ever Taken

(Photo credit: "Earthrise," taken by Astronaut Bill Anders, was judged one of the most 100 influential photographs in history, and was credited with energizing the environmental movement.)



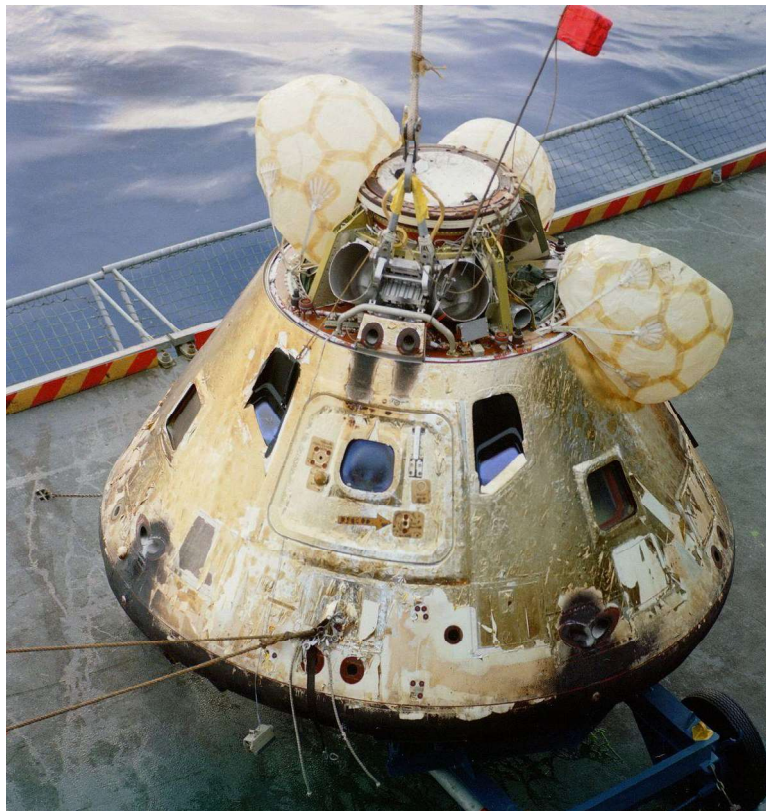
Shipboard Recovery of the Apollo 8 Command Module December 27, 1968

(The flotation collar affixed by the Splashdown Recovery Team will be removed.)



Final Stages of Shipboard Recovery for the Apollo 8 CM

(The Command Module has been placed on a cradle with wheels, so that it can be moved into the aircraft carrier's hangar bay.)



The Apollo 8 Command Module

[Now On Display at Chicago's *Museum of Science and Industry*]



The Lunar Module, or “LEM” [NASM]

[The term “Lunar Excursion Module” (or LEM) was dropped in favor of the designation “Lunar Module” (LM) in the mid-1960s, but many preferred to continue pronouncing the new acronym in the old way.]



Early Design Model of Lunar Excursion Module ("LEM") Versus Final Lunar Module (LM) Design [NASM]

1962 Design



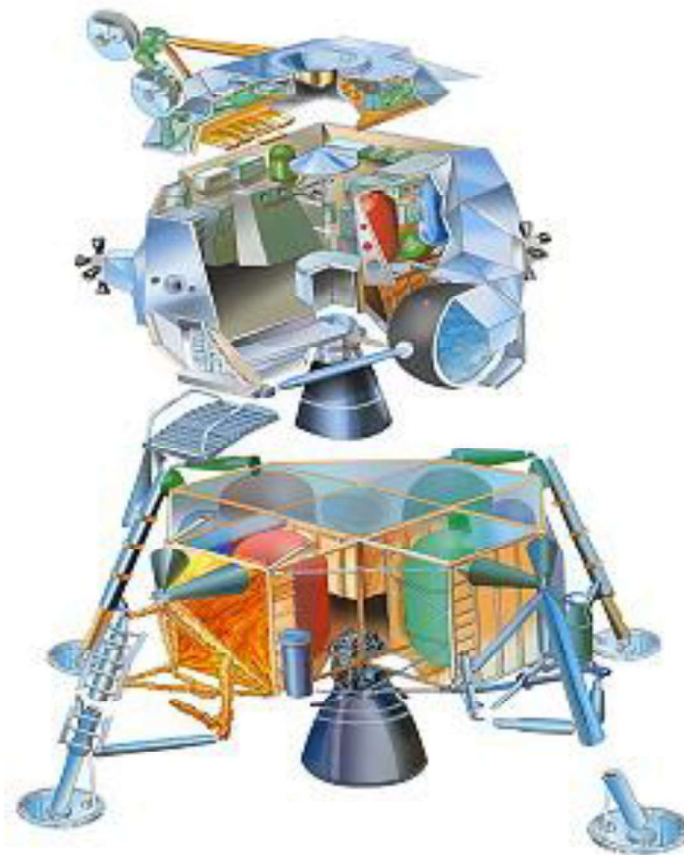
Final Design



The “LEM” in Washington, D.C. at NASM
Is A True Flight Article---The Second LM Manufactured by
Grumman, *But Never Flown* (Due to Schedule Acceleration)
(Displayed With Apollo 11 Markings, Supposedly Identical with LM “Eagle”)



The Lunar Module Was Actually Two Spacecraft:
A Descent Stage and An Ascent Stage,
Flying Together to the Moon, and Separating *Only At Lunar
Liftoff of the Ascent Stage*

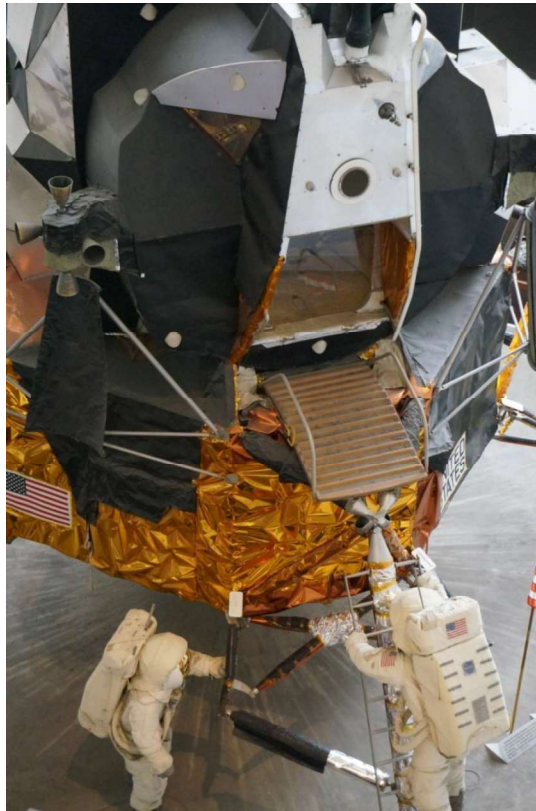


Frontal View of LM Ascent Stage [NASM]

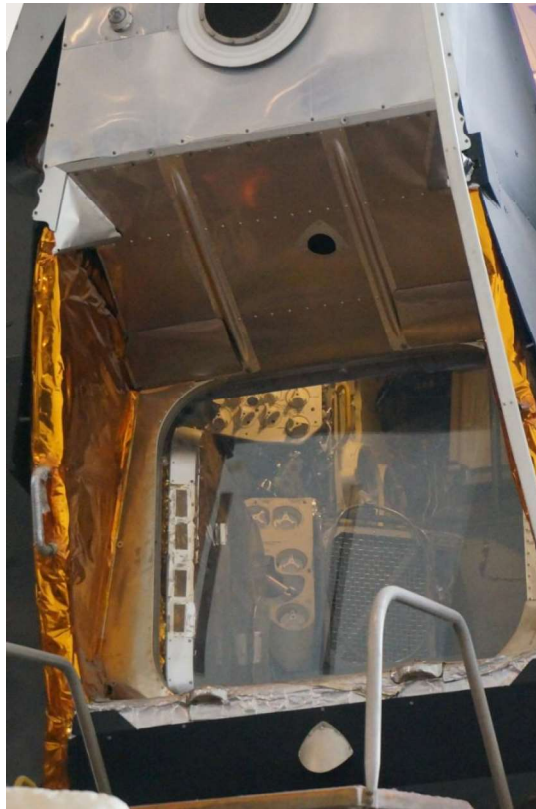


Aerodynamics Not Required in Space! [NASM]

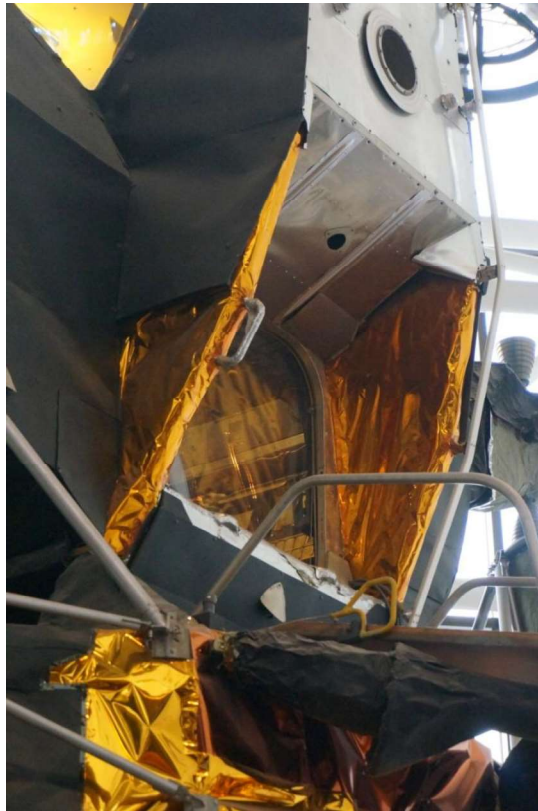
(Note Mylar Thermal Blanketing on Descent Stage,
and the “Front Porch”)



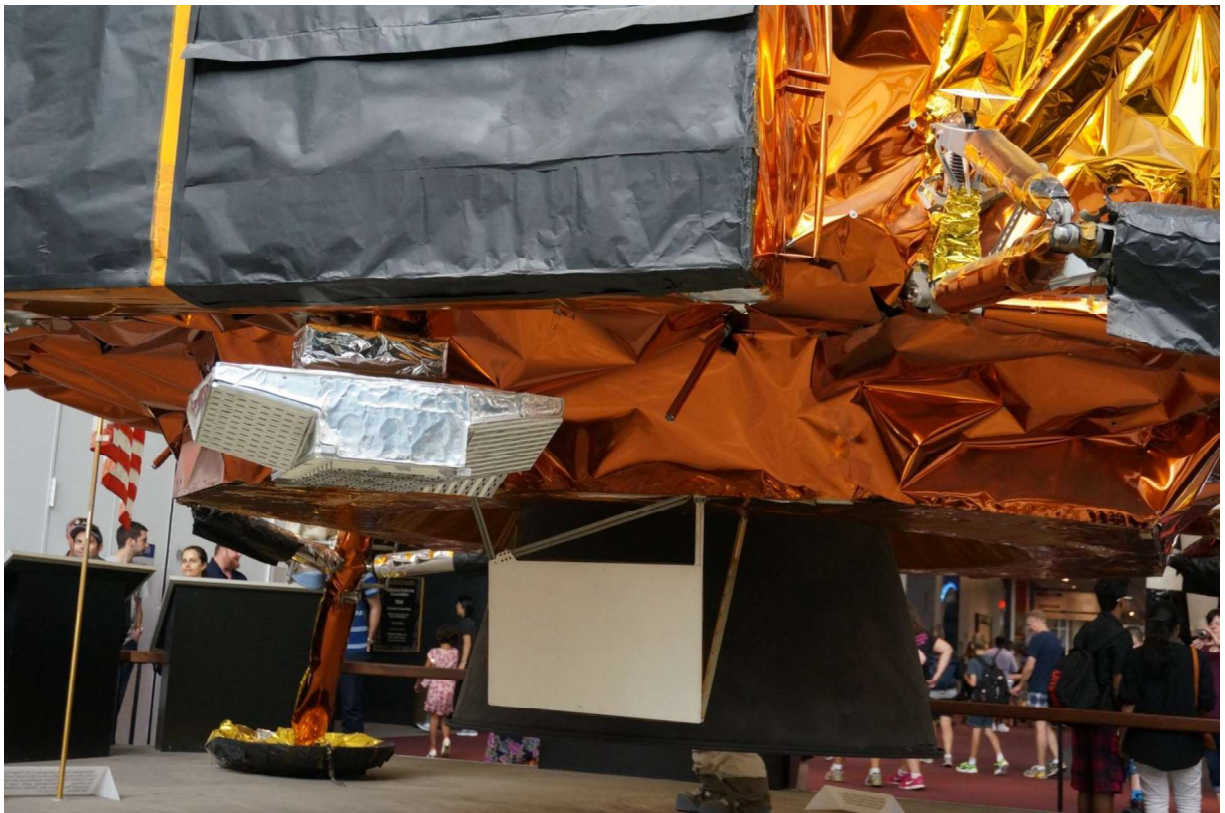
Close-Up of LM Egress/Entry Hatch [NASM]
(The Environmental Control System Is Visible Inside the LM.)



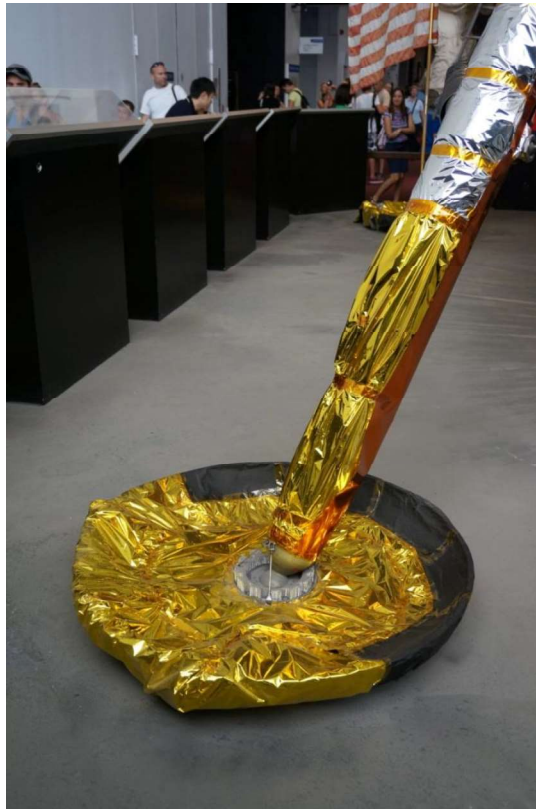
Second Close-Up of LM Egress/Entry Hatch and “Front Porch” [NASM]



LM Landing Radar Visible on Underside of Descent Stage **[NASM]**



Close-Up of Thermal Blanketing on LM Leg and Footpad [NASM]



**“Quad” Thruster Plume Shields Were First Installed On
Apollo 11’s Lunar Module, “Eagle” [NASM]**

(Each “Quad” Rocket Nozzle Produced Only 100 lbs. of Thrust; “Quads” Were Used Solely for Attitude Control; Four (4) “Quad” Assemblies Located on Each Ascent Stage)



LM Descent Stage and Ascent Stage Rocket Engines [NASM]
(10,500 lbs. thrust and 3,500 lbs., respectively)

