The Road to the Moon Went Through Western New York

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The Apollo program was made possible by many contractors and government agencies throughout the United States. There were significant concentrations of effort in many regions, one of which was Western New York between Buffalo, Niagara Falls, and Rochester. Steering of all three stages of the Saturn V was provided by Moog thrust vector actuation. Contributions by Bell Aerosystems were especially notable, from the Lunar Landing Training Vehicle that gave the astronauts the training required to land on the Moon to the Lunar Module ascent engine that returned them to orbit afterwards. The ascent engine was one of the most critical items in the entire Apollo stack as it had to work – there was no backup. Once back in Lunar orbit the astronauts knew they could rendezvous and dock with the Command Module because it was proven during Project Gemini with the Gemini Agena Target Vehicle powered by Bell primary and secondary propulsion systems.

I. Introduction

The history of aerospace achievement in Western New York is well-known and dates back to the earliest days of flight, when Glenn Curtiss won the Scientific American Cup for a pre-announced, publicly-observed flight of over one kilometer in Hammondsport on July 4th, 1908. It continued through World War I, when the Curtiss Aeroplane and Motor Company in Buffalo was the largest aircraft manufacturer in the world, and World War II when the Curtiss-Wright P-40 and Bell P-39 constituted over half of the Army Air Force fighter aircraft overseas until well into 1943. Fewer are aware, however, of the contributions made by Western New York to the early space program, particularly Apollo, but also the Mercury and Gemini programs leading up to it. This paper reviews those contributions in the context of the first five Apollo missions, culminating in "landing a man on the Moon and returning him safely to the Earth" on Apollo 11.

II. Apollo 7 and 8

After a delay to correct deficiencies and make improvements after the tragic Apollo 1 fire, Apollo 7 launched on a Saturn IB booster on October 11, 1968. Wally Schirra, Donn Eisele and Walt Cunningham were to verify the performance and endurance of the Command and Service Module (CSM) required for a lunar landing mission as well as its suitability for a crew. Perhaps most critical was the performance of the Service Propulsion System, or SPS, the large axial engine on the service module that on lunar missions would brake the CSM into lunar orbit and, more importantly, propel it back to earth. The SPS fired eight times, from a maximum duration of 66.95 seconds to two short duration firings of 0.48 and 0.50 seconds to demonstrate its minimum impulse capability.[1] Apollo 7 splashed down 11 days later in the Atlantic Ocean off the coast of Bermuda at 11:11 GMT on October 22.[2]

Apollo 8 was originally intended to be an earth orbital mission to exercise the Lunar Module (LM) and demonstrate rendezvous and docking. In the summer of 1968, however, when it became apparent the LM was not ready, a lunar mission was considered in its place. Even then, a decision had to be made whether the profile would be circumlunar, with a single loop around the Moon on a free return trajectory, or would it enter lunar orbit, which would entail greater risk and require successful operation of the Service Propulsion System to return to Earth.[3] Lunar orbit was chosen, though not without reservations, and the decision was not unanimous.[4] Launching on December 21st, 1968 with the first manned flight of a Saturn V, Apollo 8 completed ten lunar orbits, offering Frank Borman, Jim Lovell, and Bill

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Anders man’s first personal view of the far side of the Moon. During the fourth orbit, Bill Anders took one of the most famous photographs in history, that of the Earth rising over the lunar horizon.

III. Moog Thrust Vector Control on Saturn IB and Saturn V

A. Saturn IB

Apollo 7 was launched by a two-stage Saturn IB booster derived from components of the previously flown Juno II and Jupiter C rockets. It was also later used to launch several Skylab crews. Saturn IB could lift 11 tons to Low Earth Orbit (LEO) by providing a total of 1,590,000 lbf thrust. It used eight Rocketdyne H-1 engines in the S-I first stage and one Rocketdyne J-2 engine in the S-IVB second stage. Moog Servocontrols produced the hydraulic actuators that would provide pitch and yaw motion control for both stages of the Saturn IB vehicle. Moog actuators were used to gimbal four of the first stage H-1 engine nozzles and the single second stage J-2 engine. Hydraulic fluid was supplied to the actuators by pumps driven by the engine turbopumps.

The S-I first stages used eight Moog Model 17-150 actuators to gimbal four of the H-1 engines. With a piston area of 5 square inches, it produced a stall force of 15,000 lbf at 3,000 psi. Moog servovalves were at the heart of the high-power servo control system required for vehicles such as the Saturn IB Saturn V. The servovalves were a two-stage design and took advantage of a mechanical feedback mechanism developed at Moog in the early 1960s. By replacing the pressure transducers, wiring and electrical connections, and feedback electronics, a simpler and more robust design provided improvements in mass, assembly time, and most importantly, reliability.[5] The S-1 first stage burned for 150 seconds after ignition.

Actuation for the S-IV second stage was originally provided by the prime contractor for the stage, Douglas Aircraft. The Douglas actuators exhibited unacceptable instabilities, however, and the work was subcontracted to Moog.[6] The final S-IV design that flew used one pair of Moog Model 17-189 actuators to gimbal the J-2 nozzle. This actuator had a piston area of 11.8 square inches and produced a velocity of 3.4 in/sec at 3,500 psi. The servovalves were a two-stage design with mechanical feedback. The S-IV second stage burned for 470 seconds after separation. With minor changes the S-IV stage evolved into the S-IVB third stage of the Saturn V Vehicle.

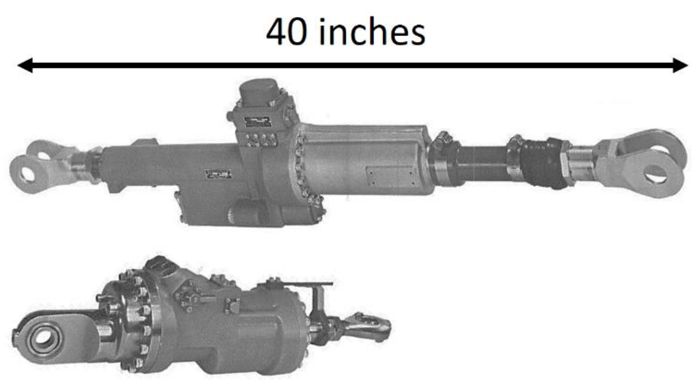

Figure 1. Saturn IB first and second stage actuators. Moog Inc.

B. Saturn V

To place its intended payload into the required translunar trajectory, the Saturn V booster was a massive 3-stage vehicle weighing 6.2 million pounds. The S-IC first stage, manufactured by the Boeing Co., used five Rocketdyne F-1 engines each producing 1.5 million lbf of thrust. The North American Rockwell S-II second stage housed five Rocketdyne J-2 engines, each capable of 230,000 lbf. Following the merger of McDonnell Aircraft and Douglas Aircraft in 1967 the now McDonnell Douglas S-IVB third stage used one J-2 engine. Moog produced hydraulic actuators to provide pitch and yaw motion control for all 3 stages of the Saturn V vehicle. Four of five F-1 first stage engines and four of five J-2 second stage engines were gimballed, as was the single J-2 third stage engine. Some Apollo missions used actuators manufactured by the Hydraulic Research Company as an alternative to the Moog actuators on the S-IC first stage.

The Saturn S-IC first stage Actuators (Model 17-200) were some of the largest made by Moog up until that time. The actuators provided an output of 114,000 lbf. At five feet long, 330 pounds, with a 57 square inch piston area, these actuators required a newly designed 3-stage servovalve operating at 2,000 psi in order to meet the large flow and fast frequency response required. The Guidance and Navigation System computers output commands at very high rate but with very little electrical power. The servovalves take signals of only 50 milliamps to move the small magnetic torque motor and generate a pressure differential that causes a tightly-toleranced spool to slide inside a bushing. When moved, the spool allows the high pressure hydraulic fluid to flow through a set of slots and out through ports to pressurize and move the large actuator piston with the significant forces required. In the case of the S-IC servovalves, a smaller spool is used to pressurize an additional larger spool with a flow area large enough to operate the 50 square inch piston at the response rates required.[7] Unlike the other Saturn V stages, the servovalves and actuators on the first stage were "fueldraulic," using RP-1 kerosene fuel supplied directly from the engine pumps as the hydraulic fluid. The Apollo missions required the first stage engines to fire for 157 seconds.[8] During this time the Moog actuators were responsible for vectoring the engine nozzles to provide pitch, yaw, and roll steering control for the rocket.

The Saturn S-II second stage actuators (Model 17-192) were derived from the previously flown Saturn IB second stage actuators as that stage also used the J-2 engine. Operated at 3500 psi, they had a slightly upsized piston area of 13 square inches with a low flow piston bypass for system damping. These actuators also used a two-stage servovalve design with mechanical feedback. Hydraulic fluid was supplied by pumps run off the engine turbopumps. The second stage J-2 Engines were fired for 367 seconds after first stage separation.[9] The Moog actuators again provided pitch, yaw, and roll steering control to the vehicle.

The Saturn S-IVB third stage was derived directly from the Saturn IB second stage and used one pair of Moog Model 17-189 actuators. With a piston area of 11.8 square inches it produced a no-load velocity of 3.4 in/sec at 3,500 psi. The servovalves were a two-stage design with mechanical feedback. The S-IVB third stage was required to provide two separate burns. The initial burn of 156 seconds placed the vehicle in LEO and the second burn of 336 seconds took the vehicle out of LEO and provided the critical injection into trajectory to the Moon.[10] Restarting the engines and hydraulic systems in space was a new endeavor for the Apollo program.

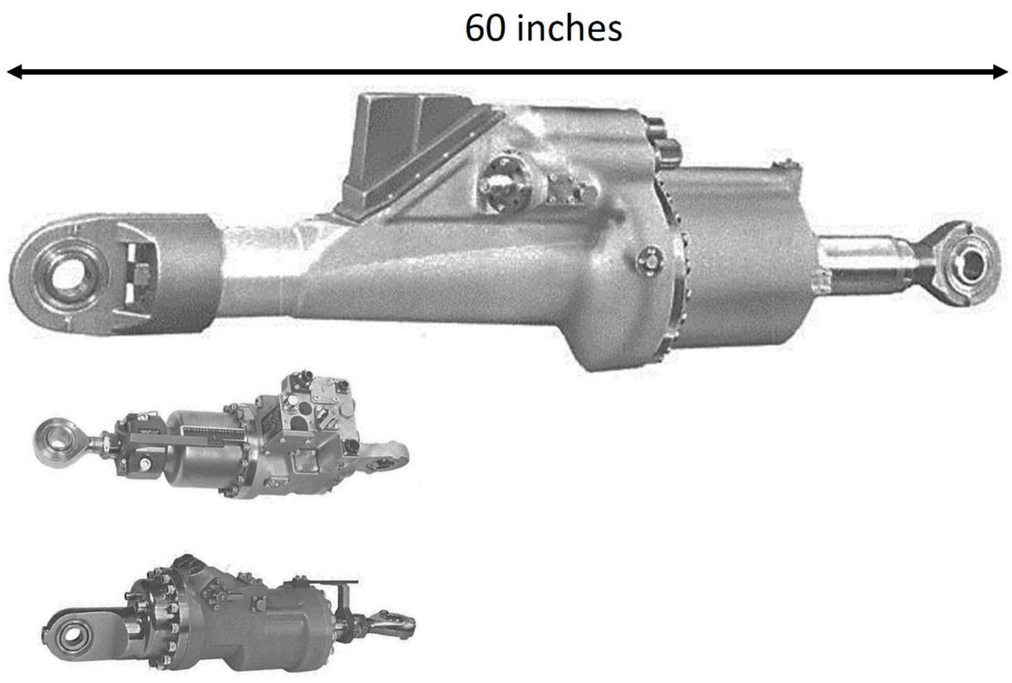

Figure 2. Saturn V first, second and third stage actuators. Moog Inc.

IV. Apollo 9 and 10

The first manned Apollo mission with a Lunar Module, Apollo 9 launched on March 3rd, 1969. Though the LM first flew on the unmanned Apollo 5 launched almost a year earlier, it was primarily to verify the operation of systems and engines in space. 73 hours into launch LM pilot Rusty Schweickart completed a 47 minute extravehicular activity during which time he was sustained solely by the Portable Life Support System to be used by the astronauts on the surface of the Moon.[11] 92 hours after launch Jim McDivitt and Rusty Schweickart flew their Lunar Module "Spider" up to 114 miles from the Command Module "Gumdrop," using the descent engine to achieve separation and the ascent engine for rendezvous and docking after separation from the descent stage.[12] During their time in the Lunar Module it was the first time man was in space in a vehicle not capable of reentering the earth's atmosphere. If they had not been able to execute a successful rendezvous the astronauts would have been lost, and if rendezvous had succeeded but docking had failed they would have had to reenter the Command Module through an extra-vehicular activity (EVA).

A full dress rehearsal for landing on the Moon, Apollo 10 launched on May 18th, 1969, essentially combining the journey to lunar orbit of Apollo 8 with the Lunar Module and Command Module operations of Apollo 9. 95 hours into the mission on May 22nd, Tom Stafford and Gene Cernan flew the Lunar Module to 47,000 feet altitude above the lunar surface before firing the ascent engine to return to orbit to rendezvous and dock with John Young in the Command Module.[13, 14] This was the first time the LM landing radar was exercised in the environment it would be used to land on the Moon.[15]

V. Bell Agena Primary and Secondary Propulsion Systems

Once NASA committed to lunar orbit rendezvous for Apollo, in which a separate craft descended to the lunar surface and then had to rendezvous and dock with an earth-return craft remaining in lunar orbit, the demonstration of routine, repeatable rendezvous became critical to the success of the program. If the lunar module was able to successfully land and then leave the lunar surface but not reach the command/service module, the men who had just walked on the moon would be lost. Rendezvous and docking therefore became a mandatory goal of Apollo's predecessor, Project Gemini, and NASA chose a purpose built, remotely operated spacecraft, the Gemini Agena Target Vehicle (GATV) to be the orbital target for the Gemini spacecraft.

The GATV was derived from the existing Lockheed Agena upper stage, powered by the latest version of the Model 8096 Agena rocket engine manufactured by Bell Aerosystems in Niagara Falls, New York. A true workhorse of the early space age, the Lockheed stage and Bell engine combination was already a proven quantity when first considered for Gemini by James Chamberlin, Gemini program manager in August 1961.[16] At that time only three months had passed since Alan Shepard's suborbital chip shot, and John Glenn's first manned orbital flight was still seven months away, yet Agena had already been launched on 33 orbital missions (though not all were successful).[17] By the time the first manned Gemini launch took place on March 23, 1965, Agena had flown 161 times, including propelling the first U.S. spacecraft to the Moon, Venus and Mars, and 109 Corona and Gambit spy satellite missions (the latter not declassified until 1995 and 2002, respectively).[18]

An evolution of Bell's "Hustler" engine developed to propel a planned Powered Disposable Bomb Pod beneath the B-58 Hustler Mach 2 bomber, Agena was a turbine-fed, bipropellant engine burning hypergolic Unsymmetrical Dimethyl Hydrazine (UDMH) fuel and Inhibited Red Fuming Nitric Acid (IRFNA) oxidizer. Vastly simpler than the three combustion chamber Bell Rascal engine that preceded it, even the first version of the smaller, lighter Agena produced 15,000 pounds of thrust against Rascal's 12,000 pounds.

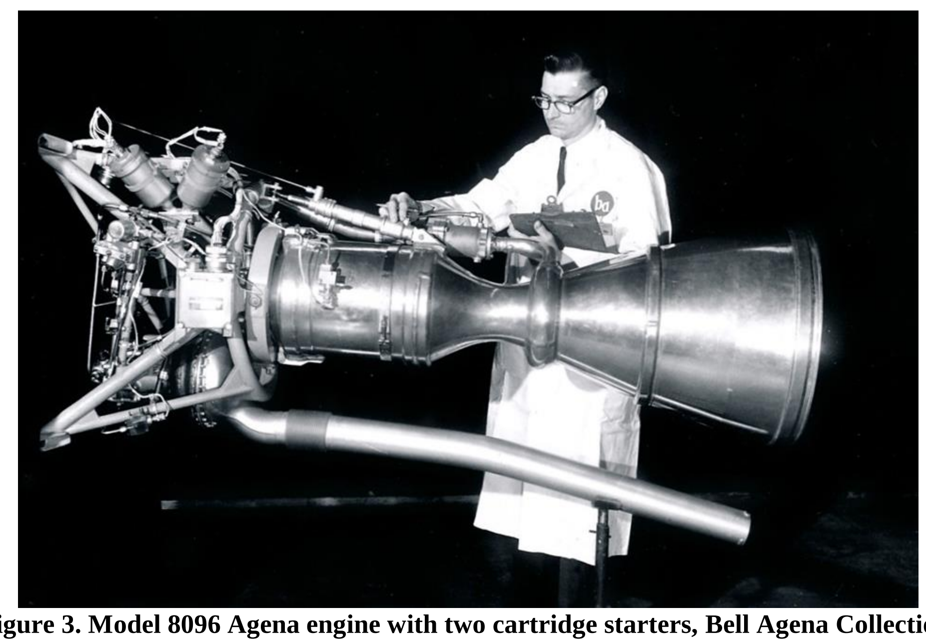

Figure 3. Model 8096 Agena engine with two cartridge starters, Bell Agena Collection. Niagara Aerospace Museum

The most significant change required of the Agena engine for Gemini was the capability to restart in orbit at least five times. This enabled multiple rendezvous on a single mission, as well as restart to propel the combined GATV and Gemini spacecraft as a single vehicle once docked. The existing Bell 8096 engine was capable of a single restart via a second pyrotechnic start cartridge, but that approach was impractical for five or more. For the Model 8247 Agena engine on GATV, Bell engineers added multiple restart capability with rechargeable, positive expulsion propellant tanks, one each for the fuel and oxidizer. When the engine was running the start tanks were recharged by pressure from the same turbopumps feeding propellant to the engine, enabling their use for the next start.[19]

NASA also specified a new Secondary Propulsion System (SPS) for the GATV, designated Bell Model 8250, to perform lesser orbital changes than those requiring the 16,000 pound thrust primary engine, designated as the Primary Propulsion System (PPS). The SPS also performed ullage orientation of the propellant, using the vehicle's acceleration to shift the propellant toward the intake end of the tank prior to the firing of the main engine. The SPS consisted of two self-contained, independent units, I and II, on each side of the spacecraft. Each unit included its own tanks containing UDMH fuel and MON (Mixed Oxides of Nitrogen) oxidizer, and one 200 pound and one 16 pound thruster. The larger engines were used for orbital changes and the smaller for ullage control, and they were always fired in pairs to achieve symmetrical thrust.[20]

The first orbital rendezvous and docking was planned for Gemini VI on October 25th, 1965. GATV-5002 launched atop its Atlas booster at 10:00 AM, but all telemetry with the vehicle ceased 375 seconds later. The countdown for Gemini VI, scheduled to follow the GATV, was cancelled at 10:54 when it was clear the target vehicle did not achieve orbit. GATV launches stood down while the Air Force and NASA both convened review boards to investigate the failure.[21] Three months later, after a bold decision to demonstrate rendezvous between two Gemini spacecraft instead of with a Gemini and GATV, a renamed Gemini VI-A performed the first orbital rendezvous in history with Gemini VII on December 15, 1965. Docking was not possible, however, as the spacecraft were never designed to dock with each other and were not equipped for it.[22]

Meanwhile, investigation determined the likely cause of the loss of the GATV for Gemini VI was a catastrophic start caused by fuel flowing into the combustion chamber before the oxidizer. In previous models of the Agena engine the oxidizer entered first, which made for a smoother start.[23] It wasted oxidizer however, and on a multiple start engine that waste would be magnified, so Bell received Air Force approval for the change. After switching the order back to oxidizer first and subsequent test firings at simulated altitude at Arnold Engineering Development Center, Agena was cleared for flight for Gemini VIII.[24]

GATV-5003 entered orbit shortly before Gemini VIII on March 16th, 1966. Astronauts Neil Armstrong and David Scott performed a successful rendezvous followed by the first docking in space six hours and thirty-three minutes later. A critical milestone for Apollo had been demonstrated for the first time. Unfortunately the mission, including planned spacewalks by Scott, was cut short soon thereafter when a stuck Orbital and Attitude Maneuvering System (OAMS) thruster on the Gemini spacecraft caused the combined vehicles to begin to roll, which only became worse after undocking. Armstrong saved the spacecraft by deactivating the entire OAMS and using the Reentry Control System (RCS) thrusters to stop the roll. Once the RCS was activated, however, the mission had to be terminated as soon as possible. Flight Director John Hodge made the decision to bring them down on their seventh orbit, splashing down in the Pacific less than twelve hours after launch.[25] GATV-5003 was subsequently exercised extensively from the ground, demonstrating many requirements of the new vehicle, including nine restarts of the main engine.[26]

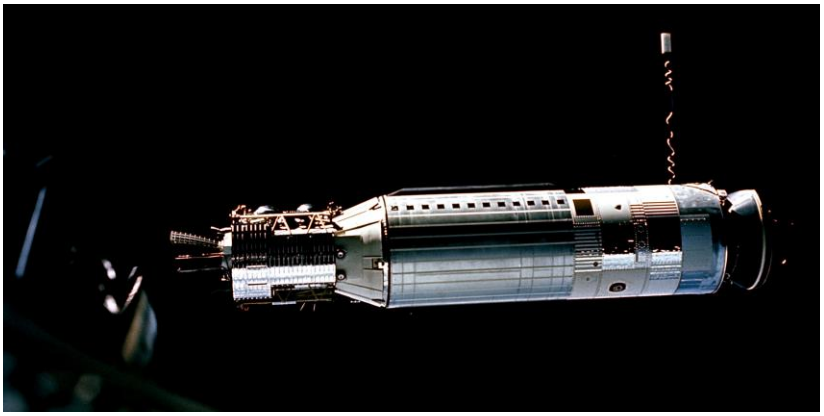

Fig. 4 Gemini-Agena Target Vehicle 5003 prior to docking with Gemini VIII. NASA/David Scott

Gemini IX did not have the opportunity to rendezvous with an Agena when GATV-5004 was destroyed by the failure of its Atlas booster two minutes after launch. The rescheduled Gemini IX-A was able to perform multiple rendezvous with the unpowered McDonnell Augmented Target Docking Adapter (ATDA) created as an Agena backup after the failure of GATV-5003. It could not dock however, as the aerodynamic launch shrouds had not completely separated to uncover the docking adapter. This created the appearance of an open set of jaws on the ADTA and prompted Tom Stafford's notorious "angry alligator" remark.[27]

Gemini X had the most complicated rendezvous and docking profile to date, making use of two Gemini-Agena Target Vehicles. After rendezvous and docking with their GATV-5005, the Agena primary propulsion system was fired for 80 seconds, boosting the combined spacecraft into an elliptical orbit with an apogee of 412 nautical miles, the greatest distance from earth achieved by man. Subsequent firings of the GATV's primary and secondary propulsion systems circularized their orbit nine nautical miles below GATV-5003, still in orbit after its post-Gemini VIII operation but completely without power. After undocking from GATV-5005, John Young used the Gemini spacecraft Orbital and Attitude Maneuvering System to rendezvous with 5003. During the following EVA Michael Collins pushed off from the Gemini and maneuvered to the GATV, retrieving a micrometeorite collection package and bringing it back to John Young in the Gemini hatch.[28]

Gemini XI began with a single-orbit rendezvous with GATV-5006 only 85 minutes after launch, one of the procedures under consideration for Apollo (and achieved on Apollo 14). The Agena then boosted the docked vehicles into an 850 nautical mile apogee orbit that not only exceeded Gemini X, it is an altitude record that still stands today for manned earth orbit. The crew then performed several other burns and exercises, including connecting the two spacecraft together with a tether and rotating the combined vehicles to generate 0.00015 g of artificial gravity.[29] During post-flight debrief, mission commander Pete Conrad remarked that when they undocked from their GATV for the last time, "we made the three foot per second retrograde burn and left the best friend we ever had."[30]

Figure 5. Gemini-Agena Target Vehicle 5005 tethered to Gemini XI. NASA/Dick Gordon

The swan song of the Gemini Agena Target Vehicle on Gemini XII – but not the Agena engine by any means – was limited after the main engine on GATV-5001 (Lockheed's initial test vehicle, prepped and used for flight after the loss of GATV-5004 on Gemini IX) exhibited a six percent drop in combustion chamber pressure during the climb to orbit. Though it recovered immediately and Jim Lovell and Buzz Aldrin were able to rendezvous and dock as planned, mission control made the conservative decision not to fire the big engine again.[31] The SPS was exercised, however, conserving OAMS propellant in the Gemini, and several undockings and dockings were performed. Buzz Aldrin made a highly successful EVA to the GATV, performing exercises and experiments with much greater ease than on previous missions. While known primarily for his PhD in orbital rendezvous at MIT and being the second man to walk on the Moon, Buzz Aldrin's work on EVA prior to and on Gemini XII broke the code on successfully working outside the spacecraft.[32]

Figure 6. Buzz Aldrin performing dexterity exercises on Gemini-Agena Target Vehicle 5001 during Gemini XII. NASA/Jim Lovell

VI. Apollo 11

On July 21st, 1969 at 2:56 AM Universal Standard Time, Neil Armstrong set his left foot on the lunar surface from the ladder of the Lunar Module Columbia.[33] Eighteen minutes later he was joined by Buzz Aldrin, and the two men completed a two and a half hour EVA collecting rocks and performing several experiments.[34] After returning to the LM they took a seven hour sleep period before firing the ascent engine to return to lunar orbit and rendezvous with Michael Collins in the command module, having spent 21 hours 36 minutes on the Moon.[35] This was the most critical mission to date for performance of the ascent engine, as it had to work or Armstrong and Aldrin would be stranded.

VII. Bell Lunar Landing Research and Training Vehicles

The lunar approach and landing maneuver was unlike any piloting task ever performed: taking place in 1/6 Earth gravity, with no aerodynamic lift or drag. So as early as 1961, before the design of the lunar lander itself was determined, a need was recognized for a pilot training vehicle. Conventional fixed-based visual simulators, helicopters, and a giant cable-suspended trainer at NASA Langley partially filled this requirement, but ultimately a free-flying vehicle was deemed necessary to provide sufficient fidelity in the piloting experience.

Thus were the Lunar Landing Research Vehicle (LLRV), and its close successor, the Lunar Landing Training Vehicle (LLTV) conceived by Bell Aerosystems of Niagara Falls, NY in coordination with NASA Flight Research Center (FRC). The odd-looking open-framed vehicles earned the nickname the “flying bedstead” (Figure 7). The central feature was a vertically-mounted General Electric CF700 jet engine on a dual-axis gimbal, which could be rotated to keep the thrust vector vertical as the rest of the vehicle rotated around it. 3,000 psi hydraulic actuators were used to rotate the engine in its gimbal.

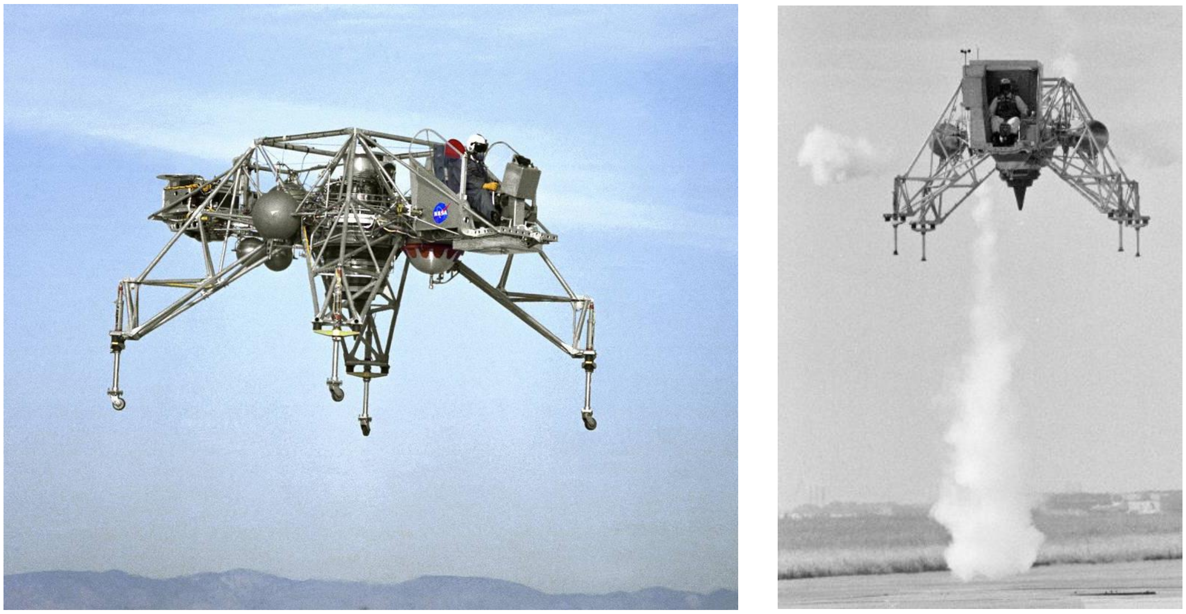

Figure 7. LLRV#1 in flight and Pete Conrad training for Apollo 12 in an LLTV. NASA

During a landing simulation, the vertical thrust of the jet engine was used to cancel 5/6 of the LLRV's weight, approximating lunar gravity. The thrust-to-mass and control torque-to-moment-of-inertia ratios also were tuned to match the LM, and the control system automatically compensated for changing vehicle mass due to fuel depletion, as well as aerodynamic drag and wind. The result, from the pilot's point of view, was a convincing duplication of flight conditions near the lunar surface.

The vehicle's attitude control system consisted of two independent sets of hydrogen peroxide monopropellant thrusters derived from the X-15 program. There were a total of 16 of these in four quad clusters on the corners of the vehicle. They operated in a pulsed on-off fashion, with dramatic puffs of steam ejected as the hydrogen peroxide was decomposed by the internal catalyst screens (Figure 7, right image). Their thrust level could be adjusted from 18 to 90 lbf and a large variety of control modes could be selected, allowing exploration of optimal strategies for piloting the vehicle. Additionally, there were eight 500 lbf lift rockets, fed from the same hydrogen peroxide supply, used primarily to simulate the descent engine in final hover and landing.

The LLRV's control system was completely analog-based fly-by-wire, the first such complete system implemented on an unstable air vehicle.[36] The three later LLTVs had the actual lunar module control joystick installed as well.[37]

Early versions of the design placed the pilot in a centralized cockpit above the jet engine. Obvious practical considerations quickly moved the pilot to the front of the vehicle, which more closely resembled the LM configuration anyway. The electronics boxes were moved to a pallet extending out the rear of the vehicle to balance the weight.

A pilot ejection seat was included and (correctly, as it turned out) considered a critical safety feature. A custom seat cushion had to be tailored for each pilot's weight and cg.[38] Early on, a controversial whole-vehicle parachute system was installed but was never used and later removed to save weight.[39]

The vehicle could also be flown with the jet engine gimbal fixed in place, called VTOL mode. During a landing simulation test, the vehicle would be flown in VTOL mode up to around 150 m altitude and 550 m downrange, pitched nose down and aimed toward the intended landing site with a forward velocity of 14 m/s, and then transitioned to lunar simulation mode.[40] Average flight times were in the seven-to-eight minute range.[41]

The first LLRV was shipped, in pieces, from Bell to Edwards AFB in spring of 1964. As a cost-saving measure, it was assembled and tested on-site by technicians at FRC with the aid of Bell engineers onsite.[42] After testing and validation at Edwards, the first vehicle was shipped to the Manned Spaceflight Center in Houston for training the Apollo crewmembers in December 1966.[43]

Changes from the LLRV to LLTV comprised mostly incremental improvements in electronics, packaging, engine and thruster performance, as well as pilot controls and instrumentation, to reduce weight and make the vehicle more closely resemble the evolving LM.[44] It also had a sidestick versus a center column, and a more enclosed cockpit, which had to be modified following aerodynamic problems. Two LLRVs and three LLTVs were built.

LLRV #1 was flown 21 times by Neil Armstrong, including ejecting safely from a crash that destroyed the vehicle (an event now familiar to popular audiences, having been dramatized in the 2018 motion picture *First Man*[45]).The cause was inadvertent depletion of helium in the attitude thruster propellant pressurization system, which led to loss of control of the vehicle. It had been flown an additional 25 times by various other astronauts. LLRV #2 was flown six times at FRC but never at MSC due to the LLTVs becoming available.[46]

Two of the three LLTVs also crashed after many successful flights, the pilots also ejecting safely in both cases. LLTV #1 crashed on its 15th flight at MSC due to a wind shear condition. LLTV #2, which was also used to train Neil Armstrong for Apollo 11, crashed on its 207th flight due to an electrical failure. LLTV #3 flew a total of 286 flights, the last by astronaut Gene Cernan prior to Apollo 17. The two surviving vehicles, LLRV #2 and LLTV #3 are on display at Edwards Air Force Base and Johnson Space Center respectively.

The LLRV/LLTV program built crucial pilot confidence in the lunar landing task. All of the Apollo primary and backup commanders trained on the vehicles (Due to scheduling limitations, the LM pilots, who did not fly the landings, did not.[47]) The LLRV and LLTV enabled all six Apollo landings to be flown manually, and influenced the decision to not to execute the touchdown phase in fully automatic mode. After Apollo 11 and 12, Commanders Neil Armstrong and Pete Conrad campaigned enthusiastically for continuation of the program in NASA reviews in spite of some inclination on the part of NASA management to cancel the program due to the danger involved.[48]

In Armstrong's words:

> "Six crews landed their Lunar Modules on the moon. They landed on the dusty sands of the Sea of Tranquility and the Ocean of Storms. They landed in the lunar highlands at Fra Mauro and on the Cayley Plains. They landed near the Apennine and Taurus Mountains. Each landing, in widely different topography, was performed safely under the manual piloting of the flight commander. During no flight did pilots come close to sticking a landing pad in a crater or tipping the craft over. That success is due, in no small measure, to the experience and confidence gained in the defining research studies and in the pilot experience and training provided by the LLRV and LLTV."[49]

Or in John Young's words, just over a minute after landing on the Moon in the Apollo 16 Lunar Module Orion, "Just like flying the LLTV. Piece of cake."[50]

An in-flight simulator also carried training rewards commensurate with the risks, as acknowledged by Apollo Commanders David Scott: "I guess I can't say enough about that (LLTV) training. That puts you in a situation in which you appreciate propellant margins and controllability (because the vehicle could fail and crash)"[51] and Gene Cernan: "In the LLTV you had your butt strapped to a machine that you had to land safely or you didn't make it."[52]

VIII. Bell Lunar Module Ascent Engine

In July 1962, NASA's director James Webb made the ground-breaking decision to approve the lunar orbit rendezvous (LOR) path forward for America's mission to the moon.[53] This decision set the stage for the three propulsive elements in the Apollo vehicle: the Service Module Main Engine, the Lunar Module Descent Engine, and the Lunar Module Ascent Engine.

In July 1962, NASA issued the RFP to 11 firms for the Apollo Lunar Module (LM), and in September 1962, Grumman Aircraft Engineering Corporation submitted their proposal. Two months later Grumman was named the winner, and two months after that primary subcontracts for the major vehicle systems would be placed. On January 14, 1963, NASA finally authorized Grumman to begin work on Lunar Module. Three of the four major subcontracts on the LM would be for propulsion system engines: Rocketdyne for the descent engine, Bell Aerosystems for the ascent engine, and Marquardt for the reaction control engines. Having identified rocket engines as the most critical subsystem, Grumman started their development first, and on January 30, 1963 Grumman contracted with Bell Aerosystems to produce the LM Ascent Engine.[54]

The LM was to be equipped with three propulsion systems: descent propulsion system (DPS) with one 10,500 lbf engine, ascent propulsion system (APS) with one 3,500 lbf engine, and the reaction control system (RCS) with sixteen 100 lbf engines.[55] Of the three propulsion engines on the LM, only the ascent engine had no back-up if it failed to operate, and failure to operate meant stranding two astronauts on the moon, which was not an option. "It would not have looked good for NASA. It wouldn't have looked good for the country. There was a letter written that President Richard Nixon would read if the astronauts got stuck on the moon, expressing how sorry we were and so forth. It was a scary letter, really. The ascent engine was an engine that had to work."[56]

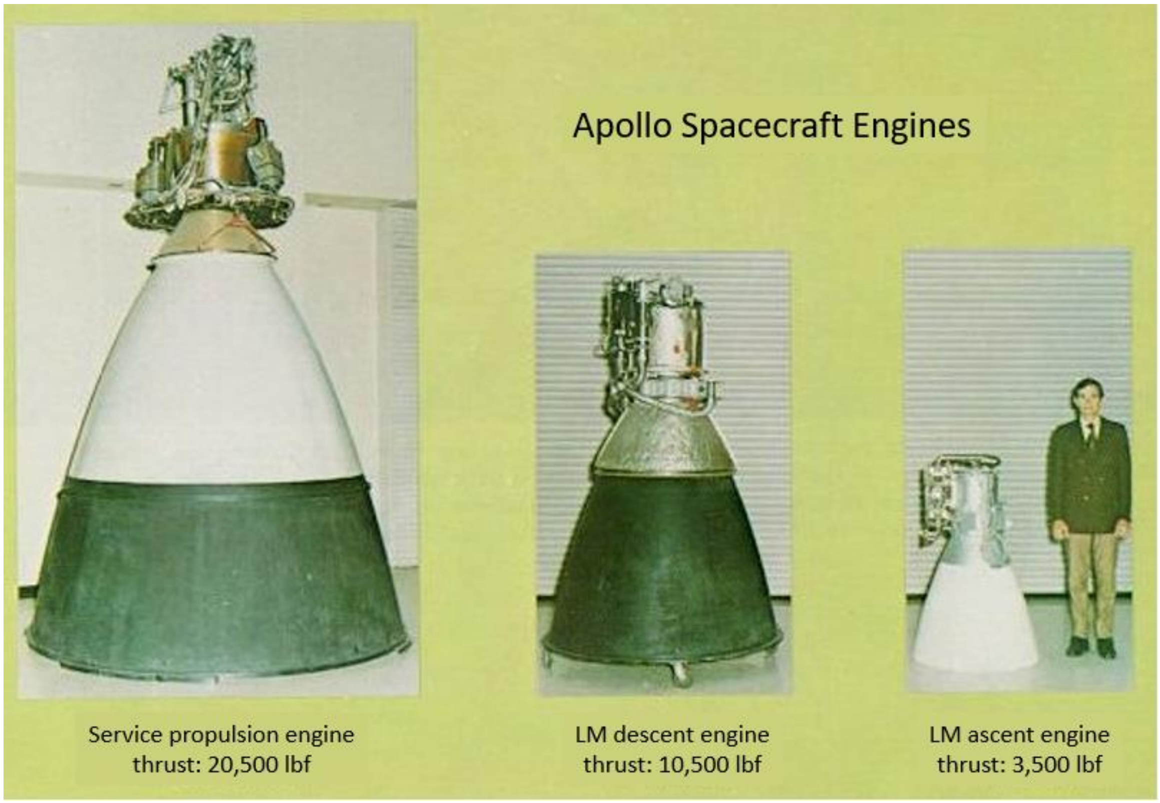

Figure 8. Apollo Spacecraft Engines. NASA

Grumman had high confidence that Bell's extremely successful Agena engine would provide the heritage platform upon which to build the most reliable engine for the LM. Employing a pressure-fed system using hypergolic (self-igniting) propellants, the ascent engine was fixed-thrust and non-gimbaled, capable of lifting the ascent stage off the moon or aborting a mission should a landing not be feasible.[57] Grumman placed a heavy emphasis on reliability for the engine, and this led to a simple design, even for a pressure-fed, storable bipropellant engine. Simplicity and reliability would take precedence over weight and cost, which would derive from a "straightforward design and rugged construction."[58]

Figure 9. Lunar Module Ascent Engine. NASA

The ascent engine was designed to achieve a nominal thrust of 3,500 lbf (15.5 kN) and specific impulse of 310 seconds from a 1.6:1 oxidizer to fuel mixture of Nitrogen Tetroxide and Aerozine-50.[59] As with the LM descent engine, the propellants were fed to the engine from tanks pressurized with helium, and controlled through a system of components (isolation valves, pressure regulators, and relief valves) that managed the redundancy of the entire ascent propulsion system. This feed system delivered the propellants to the Bell Aerosystems-designed engine valve manifold that used pilot-operated valves driven by fuel pressure to control the operation of the main fuel and oxidizer valves that fed the combustion chamber. The engine was the epitome of simplicity, having neither pumps, igniters, gimbals, nor a regeneratively-cooled nozzle bell. Yet despite its simplicity, the ascent engine proved to be one of the greatest threats to the Apollo program schedule.[60]

Figure 10. LMAE Control Valve Manifold. Niagara Aerospace Museum

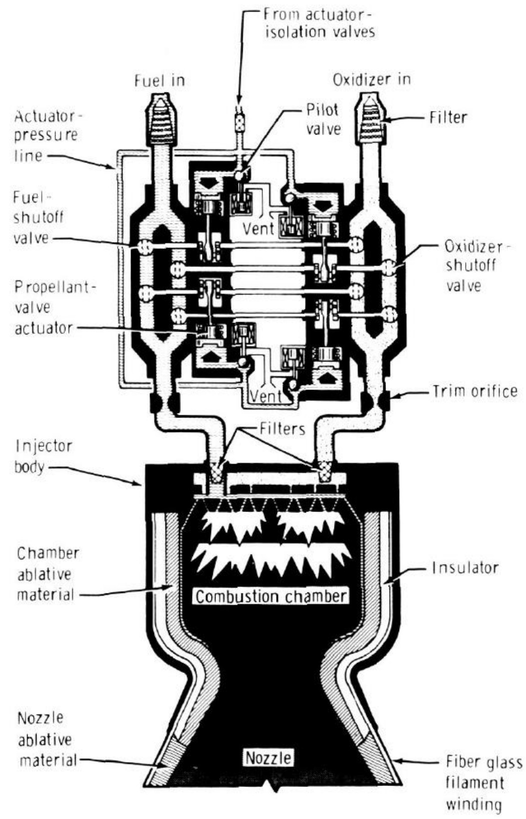

Figure 11. LMAE Schematic. NASA

As with any new rocket engine, there are certain critical aspects of the design that present the greatest challenges, including combustion instability, thermal management, and manufacturing processes. The ascent engine was challenged primarily with achieving combustion stability, along with managing the longevity of the ablative throat and nozzle used in this simple design.

A. Combustion Stability Challenge

The Saturn program with its F-1 engine was already underway when the Apollo program contract for the Lunar Module was awarded. The F-1 was not exempt from combustion instability problems, and became a poster child for the difficulties associated with this problem. It took several years to slay this dragon, in part due to the unpredictable nature of instability events. In the process, NASA and Rocketdyne developed a reliable method of inducing instability by "exploding a small bomb (like a blasting cap) inside the chamber of a firing engine and observing how quickly the pressure oscillations triggered by the bomb damped out."[61] Engine stability was arbitrarily determined to be achieved if these oscillations damped out within 400 milliseconds.

The Bell ascent engine development initially proceeded under the assumption that the engine, being of small size and simple injector, would be immune to the instability problem. With a design evolution leveraged from the Agena engine (and its unmanned rated nature), no bomb test for combustion stability was imposed. Early testing was conducted without the bomb test, and the design seemed to be on a path to success. However, when NASA discovered the absence of the test, they notified Grumman and Bell that the testing was mandatory.[62] Early testing in 1964 with the bomb produced pressure oscillations that did not damp out, although they did not diverge either. This phenomenon did not occur consistently, and it never seemed to cause damage to the engine. However, its existence could not be tolerated for a manned space vehicle, so Bell engineers worked to discover the cause and fix it. This struggle lasted more than two years, with efforts focusing on the injector design, and testing numerous design iterations involving spray pattern variations and the introduction of baffles. A number of failures were initially blamed on mechanical problems prior to the onset of the induced instability event, so design evolution continued. Since the combustion instability problem was too complex to yield to an analytical solution, the design iterations were driven by the ability to quickly build and test multiple variations, which did not advance rapidly due to the time involved in building the complex hardware. In order to meet the overall program timeline for ascent engine qualification and integration into the LM, Grumman and Bell decided to release a production design that had yet to be hot-fire tested.[63]

By this point NASA had grown greatly concerned that a timely solution would be found, and they directed the development of a parallel-path solution for the ascent engine injector. In August 1967, NASA awarded a contract to Rocketdyne, who worked to design a new injector assembly that could be used in place of the Bell-engineered injector.[64] The rapid evolution of the Rocketdyne injector design (less than a year) allowed it to be integrated with Bell's engine components (valve manifold and combustion chamber and nozzle assembly) and tested at Rocketdyne's facility in Canoga Park, CA. Testing at Rocketdyne continued quickly, as they had access to significant testing facilities which facilitated the pace of their development efforts.[65] Their injector was the solution to the ascent engine combustion instability problem, and the assembly was able to move forward into qualification.

At the time Rocketdyne was developing the injector that would solve the ascent engine instability problem, they were also developing a competing design for the ascent engine. As the need to close on a solution for the LM ascent engine accelerated, NASA and Grumman had to decide on which to select, Bell's or Rocketdyne's. George M. Low (Manager of the Apollo Spacecraft Program Office) made the final decision: the LM ascent engine would be made up of a Bell engine with a Rocketdyne injector, with integration and test to be accomplished at Rocketdyne.[66]

B. Ablative Challenges for the Combustion Chamber & Nozzle Assembly

The original requirement for the engine called for an ablative-cooled thrust chamber with a radiation-cooled nozzle. Given the location of ascent engine buried within the LM, and the fact that it would have to perform fire-in-the-hole starts using the descent stage as a launch platform, the radiation-cooled concept was abandoned in favor of an ablative-cooled approach. Bell had originally developed a laminated matrix of materials to create the ablative surface inside the combustion chamber, extending from the injector face through the throat, and out the nozzle to an expansion ratio of 4.6. Development testing of the engine at Bell showed acceptable performance of this design for the ablative protection.

In the fall of 1964, at the same time NASA imposed the bomb test for engine stability, the specification for the engine had changed, requiring a continuous burn time increase to 460 seconds. This increase to the continuous burn time ultimately drove issues tied to the longevity of the ablative lining in the engine. As the combustion stability problems were dealt with by incorporating the Rocketdyne injector, the problem of ablative lining erosion was also being addressed. In the midst of their work creating a suitable injector, Rocketdyne also experienced erosion of the ablative liner during continuous burn times. Although first appearing to be random, over numerous test firings the erosion was found to occur in the same region. Believed to be associated with the film cooling layer injected along the thrust chamber wall, the decision was made to eliminate film cooling in those areas where the erosion occurred. This solved the problem, and the engine was successfully able to survive the continuous burn time requirement.

C. Mission Success

Qualification testing of the ascent engine was completed in July 1968.[67] On Sept 25, 1968, MSC designated the LM ascent engine qualified for LM-3 and subsequent missions, and further identified that it would use the Bell valve system, combustion chamber and nozzle with the Rocketdyne injector. All assembly and test of the finished engine was to be performed at Rocketdyne.[68] The final success of the engine was the culmination of a well-executed team effort between Grumman, Bell, and Rocketdyne.

In his March 7, 1969 report to the Administrator, the Associate Administrator for Manned Space Flight, George Mueller, summed up the feeling of accomplishment as well as the problem of the space program:

> "The phenomenal precision and practically flawless performance of the Apollo 9 lunar module descent and ascent engines on March 7 were major milestones in the progress toward

our first manned landing on the moon, and tributes to the intensive contractor and government effort that brought these two complex systems to the point of safe and reliable manned space flight.

"The inevitable developmental problems that plagued the LM propulsion system were recurring items in our management reporting, and the fact that essentially all major test objectives were met during last Friday's flight operations is an outstanding achievement. The earth orbital simulations of the lunar descent, ascent, rendezvous, and docking maneuvers, taking Astronauts McDivitt and Schweickart 114 miles (183.4 km) away from the CSM piloted by Dave Scott and safely back, were a measure of the skill of the Apollo 9 crew and the quality of the hardware they were flying."[69]

Figure 12. Apollo 9 Lunar Module Ascent Stage. NASA

IX. Other Western New York Contributions

Western New York companies made many other contributions to Apollo which surely warrant their own paper, if not several. Bell Aerosystems contributed 31 positive expulsion fuel, oxidizer, and water tanks to the last four "stages" of Apollo, the S-IVB third stage and the Service, Command and Lunar Modules.[70] Carleton Controls in Orchard Park, now Cobham Mission Systems, provided a high-pressure oxygen regulator in the Portable Life Support System (PLSS) used during extravehicular activity on the surface of the Moon. PLSS EVAs were also performed on Apollo 9 in Earth orbit and on Apollo 15, 16, and 17 in cislunar space returning from the Moon.[71,72] In addition to thrust vector control actuators, Moog provided valves used for RP-1 on the Saturn V S-IC first stage and LOX and LH2 on the S-II second stage.[73]

Cornell Aeronautical Laboratory, now Calspan, performed base heating studies of the S-IC stage using a subscale model incorporating five hot-firing rocket engines. The scaled F-1 engines burned gaseous oxygen and a gaseous-equivalent fuel simulating RP-1, producing near exact temperature and combustion products as an actual F-1 engine. The tests were conducted in their Ludwieg tube tunnel, a short-duration, steady-flow, supersonic wind tunnel (P. Marrone, personal communication, 30 Nov 18; R. Drzewiecki, personal communication, 3 Dec 18).

Last but by no means least, Eastman Kodak of Rochester, New York made the photographic system for the Lunar Orbiter spacecraft. Consisting of 610 mm and 80 mm focal length lenses imaging simultaneously on 70 mm film, the Kodak system *developed the film in lunar orbit* before scanning and transmission back to the earth. On five missions in 1966 and 1967, Lunar Orbiter imaged twenty potential Apollo landing sites with resolution as fine as one meter, and 99% of the entire the lunar surface with resolution 60 meters or better.[74] Lunar Orbiter 1 also took the first picture of the Earth rising over the Moon two years before Bill Anders' photo from Apollo 8.

Figure 13. Earthrise image taken by Lunar Orbiter 1, 8/23/1966. NASA

X. Conclusion

With the closure of Bell Aerospace in Niagara Falls in 1995 and the storied aeronautical and astronautical history it represented, Western New Yorkers could be forgiven for thinking the facilities and talent that made the achievements in this paper possible are long gone. They would be mistaken, however. The Bell rocket group lives on, in their original location, as part of the Moog Space and Defense Group, and delivered over 200 rocket engines in 2017. Moog itself has grown to many times its size in the 60s, and went on to provide thrust vector control actuation for the Space Shuttle and Atlas-Centaur and Delta upper stages that essentially replaced Agena. Carleton Controls, now part of Cobham, to this day can still boast "Every U.S. astronaut since John Glenn has breathed through a Cobham regulator." While Eastman Kodak unfortunately is only a shadow of its former self, much of the Research and Engineering group that created Lunar Orbiter and the highly classified earth imaging systems that preceded it remain in Rochester as part of Harris Corporation, soon to be L3 Harris. Cornell Aeronautical Laboratory was divested from the University in 1972 as the for-profit Calspan Corporation, which lives on today, as well as a non-profit spinoff created in 1983 with the University at Buffalo, CUBRC (formerly the Calspan-UB Research Center).

The efforts of the engineers, technicians, and managers at these companies may not get the headlines they did during the space race in the 1960s, but they are all still making key contributions to U.S. efforts in space, and hopefully will soon again have the opportunity to help man boldly go where no man or woman has gone before.

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