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Neil Armstrong: From Lunar Landing to Master of Science Degree

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Abstract

On January 22, 1970, a "distinguished member of a student body" of the School of Engineering of the University of Southern California (USC) gave a one-hour seminar on "techniques and procedures" of lunar landing. He thus completed the requirements for the Master's degree in aerospace engineering which was conferred on him after the lecture. The name of the student was Neil A. Armstrong who had commanded the Apollo 11 lunar mission six months earlier and become the first man to set foot on the surface of Earth's only natural satellite. The article begins with the details of graduate studies of Armstrong at USC and then describes his visit to the campus on that January day in 1970 for the festive dedication of a major science center building and the seminar. A review of the design and operations of the Apollo missions and its lunar modules follows. Finally, the article focuses on Armstrong's lecture on the guidance and control of the Lunar Module *Eagle* during its historic landing in the Sea of Tranquility (Mare Tranquillitatis) on the moon and concludes with the degree award to the astronaut.

Keywords: Neil Armstrong; Apollo 11; Apollo program; Lunar Module; lunar landing; University of Southern California

Acronyms/Abbreviations

AFB	Air Force Base
AIAA	American Institute of Aeronautics and Astronautics
CM	Command Module
CSM	Command and Service Module
DOI	Descent Orbit Insertion
FRC	Flight Research Center
HSFS	High Speed Flight Station
IL	Instrumentation Laboratory
IU	Instrument Unit
LLRV	Lunar Lander Research Vehicle
LLTV	Lunar Lander Training Vehicle
LM	Lunar Module
LMDE	Lunar Module Descent Engine
LOI	Lunar Orbit Insertion
LOR	Lunar Orbit Rendezvous
MIT	Massachusetts Institute of Technology
M.S.	Master of Science
NACA	National Advisory Committee for Aeronautics
NTO	nitrogen tetroxide
PDI	Powered Descent Initiation
SEB	Source Evaluation Board
SLA	Spacecraft – Lunar Module Adapter
SM	Service Module
SPS	Service Propulsion System
TLI	Translunar Injection
TD&E	Transposition, Docking and Ejection
UDMH	unsymmetrical dimethylhydrazine
USC	University of Southern California
VSOE	Viterbi School of Engineering

1. Introduction

On January 22, 1970, the School of Engineering of the University of Southern California (USC) conferred a degree of Master of Science (M.S.) in Aerospace Engineering on a student. The press release of the USC News Bureau stated on the occasion,

> A distinguished "member of a student body" of the University of Southern California today completed the academic requirements for his master's degree with the delivery of a scientific lecture on "Lunar Landing: Techniques and Procedures."
>
> His name -- Neil Armstrong [1].

Neil A. Armstrong, 1930-2012, was among the most renowned USC graduates. He got his Bachelor of Science degree in aeronautical engineering from Purdue University in January 1955 on the Holloway Plan scholarship that included flying combat missions as a naval aviator in the Korean War. In September 1955, he began graduate studies part-time at the University of Southern California while being stationed as a research test pilot at the NACA High Speed Flight Station (HSFS) located at the Edwards Air Force Base (AFB) in California [2-7]. The USC campus near the downtown of Los Angeles is about 80 miles [130 km] away from the Edwards AFB.

On October 1, 1958, the newly formed NASA absorbed 8000 scientists, engineers, and technicians in several centers of the 43-year-old National Advisory Committee for Aeronautics, or NACA, spread across the country [8]. Its HSFS research unit at Edwards became the NASA Flight Research Center (FRC) in 1959 and then the Hugh L. Dryden Flight Research Center in 1973. Today, it is the Armstrong Flight Research Center named after Neil A. Armstrong.

Armstrong had completed all graduate coursework except the thesis required for his Master's degree when he transferred to Houston, Tex., in the fall of 1962 after selection to the second group of NASA astronauts. Thus "one small step" toward the degree remained to be made.

In July 1969, astronaut Neil Armstrong commanded NASA's Apollo 11 mission to the moon. After entering lunar orbit, Armstrong and astronaut Edwin E. "Buzz" Aldrin Jr. in the Lunar Module with the callsign *Eagle* separated from the Command Module *Columbia* piloted by astronaut Michael Collins. On July 20, Armstrong and Aldrin landed in the Sea of Tranquility on the moon, while Collins remained in lunar orbit waiting for their return. Armstrong descended from the Lunar Module and became the first human to make that famous "one small step for [a] man, one giant leap for mankind." Aldrin followed. The Apollo 11 crew successfully returned to Earth and splashed down in the Pacific Ocean on July 24, 1969.

Neil Armstrong came back to USC on January 22, 1970, and gave an hour-long seminar on the technical aspects of the historic landing on the moon. This completed the requirements for the Master's degree which was conferred on him at the conclusion of his lecture [1,5].

The article begins with Armstrong's graduate studies at USC and then describes his visit to the campus on that January day in 1970 for the festive dedication of a major science center building in the morning. A review of the design and operations of the Apollo missions and its lunar modules follows. Then, the historic landing of Apollo 11 in the Sea of Tranquility (Mare Tranquillitatis) on the moon is recounted. Finally, the article focuses on Armstrong's afternoon lecture on the guidance and control of the Lunar Module *Eagle* and concludes with the degree award to the astronaut.

2. Studies at USC and return to campus on January 22, 1970

In the 1950s, the USC School of Engineering offered courses at a few off-campus locations, including the Edwards Air Force Base. At that time, the school was expanding its graduate programs to working professionals at leading aerospace and defense companies in the Greater Los Angeles area. This outreach had provided the basis for establishing a distance education program by the early 1970s, initially relying on televised classes [5,9]. The school was renamed the Viterbi School of Engineering, VSOE, after Dr. Andrew Viterbi in 2004. Today, VSOE's distance education network, DEN@Viterbi, is among the highly-ranked large online programs offered by engineering schools in the United States [9,10].

After receiving his Bachelor's degree in January 1955 and a brief 5-month stint at the NACA center in Cleveland, Ohio, civil servant Neil Armstrong transferred as an aeronautical research scientist (pilot) to the NACA High Speed Flight Station, the future NASA FRC, at the Edwards Air Force Base [7]. He began part-time graduate studies in aeronautical engineering leading to a Master of Science degree at USC in September 1955. Armstrong scored 580/690/600 on his Graduate Record Examinations, or GRE, on August 9, 1956 [11].

Robert E. Vivian served as the USC Dean of Engineering from 1942 to 1958. He described that in the early 1950s, the "Mechanical Engineering Department [at USC] had absorbed the former curriculum of aeronautical engineering inherited from the Santa Maria campus. It offered two curricula: mechanical engineering, as before, and mechanical engineering with an aeronautical sequence [of courses]" [5]. Following the national trend [12-14], the aeronautical option was renamed aerospace engineering in 1962. Two years later in 1964, the School of Engineering established a separate Aerospace Engineering Department.

Armstrong's active involvement in the hypersonic rocket-powered X-15 vehicle research program [15-17] at the High Speed Flight Station and then the X-20 Dyna-Soar [18,19] space plane made part-time studies difficult. The future astronaut pointed out in an internal HSFS memorandum in August 1959 that

> [t]he duties of a research pilot require frequent and extended trips away from the HSFS obviating the possibility of completing part-time extension courses on a regularly scheduled basis. In eight consecutive semesters [since 1955], it has been possible to complete only four courses [20].

He then noted that two courses of interest "are presented at Edwards AFB during the fall [1959] semester. If the schedule permits, these courses may be taken at Edwards minimizing travel requirements."

The student records from December 1959 show that Armstrong successfully completed three graduate courses (*Aircraft Dynamics* AE 516a, *Mechanics of Compressible Fluids* AE 518a, and *Advanced Heat Transfer* ME 530a) during that fall semester of 1959 [21]. With his earlier coursework of *Advanced Calculus* Ma 424 in Fall 1955, *Introduction to Complex Variables* Ma 475 (Spring 1957), *Aircraft Jet Propulsion* ME 459 (Fall 1957), and *Orbital Mechanics* AE 580 (Spring 1959), he thus completed the course requirements for a Master's degree with thesis. Armstrong's cumulative grade point average was 3.25, weighed down by not stellar performance in his very first course in the program in 1955.

To receive the degree, Neil Armstrong had to write a Master's thesis (4 units of credit) and perform 3-units of research work. The thesis effort had to be split into two semesters, ME 594a and ME 594b, two units of credit each. The records show that, as of November 17, 1959, one-half of his thesis work (2 units, ME 594a) and research (1 unit, ME 590) were "in progress," or IP [22]. Most likely these in-progress units had been completed by the end of the semester in the middle of December 1959. After considering a few topics for the thesis and associated research [23-25], Armstrong finally selected "a research area of aerodynamic-entry energy management" [26]. The thesis committee consisted of mechanical/aeronautical engineering faculty Associate Professor James Vernon (committee chairman) and Professor C. Roger Freiberg (department chairman) as well as mechanical engineering instructor Clarke Howatt [11].

In early 1960, the NASA FRC granted Armstrong a partial "training leave" to attend the University of Southern California in February-June 1960. Armstrong planned to take one additional graduate course *Advanced Heat Transfer* ME 530b and finish the remaining research and thesis (ME 594b) [27].

Apparently, this leave for studies never took place and the thesis could not be completed. As Neil Armstrong wrote, "[a]t that time, I was selected as senior NASA member of the Dyna-Soar Pilot Consultant Group, necessitating spending every second month at the Boeing Company in Seattle or traveling in conjunction with this project" [26]. The Air Force selected Boeing as the prime contractor for the X-20 Dyna-Soar boost-glide space plane, which was a highly challenging endeavor originating in the WWII German *Silbervogel* (silver bird) concept [28] and the winged extension of the A-4 (V-2) rocket. Then, in the summer of 1961, Armstrong's two-year-old daughter was diagnosed with a malignant tumor. She died in January 1962 [7].

Later that year, in September 1962, NASA announced the selection of the second group of nine astronauts including Neil Armstrong. The press would call them the "New Nine." Following his civil service orders, Armstrong reported to NASA's Manned Spacecraft Center (today's Lyndon B. Johnson Space Center) in Houston, Tex., in mid-October [7]. The professional and personal circumstances thus took his effort and attention away from the degree, with all coursework taken and only the Master's thesis requiring the final push.

In one more attempt to finish the studies, Armstrong sent a letter to USC's Professor (mechanical engineering) E. Kent Springer in April 1963. Springer had reviewed Armstrong's standing in the USC academic program during a counseling trip to the FRC in the fall of 1962. Armstrong noted in the letter to Springer that for his Master's degree, "[o]nly a thesis completion and the associated engineering research were required" and added that "[i]t appears that completion of the academic program as earlier conceived would be extremely difficult [during intense astronaut training for the Gemini and Apollo programs]." He wrote, "Although our schedule is very busy, and I would be unable to compromise our NASA program in any way, I am most interested in investigating any possibility of completing the MS [degree] requirements" [26].

It is not clear whether USC had responded to the letter, and, apparently, no immediate solution had been found until January 22, 1970. On that day, half a year after landing on the moon, Neil Armstrong returned to the University of Southern California for a day filled with events, beginning with the opening of the Frank R. Seaver Science Center. The new building included "a three-story centralized science-engineering library with facilities for more than 90,000 volumes, and a seven-story laboratory complex for interdisciplinary research and teaching in the solid-state sciences" [5]. The Los Angeles Times described this $4.8 million (in current dollars) science center as "the largest and most modern of its kind in the West" [3]. Long-time USC trustee Mrs. Blanche Seaver gave a gift of $2.6 million in honor of her late husband Frank Seaver who had died in 1964. The National Science Foundation provided the remaining funds.

On the morning of that January day, USC President (1958-1970) Norman Topping presided over the dedication ceremony of the new science center featuring the donor Mrs. Seavers and astronaut Armstrong (Fig. 1). Vice President for Research and Graduate Affairs Dr. Milton Kloetzel introduced Neil Armstrong to the gathered guests as "a hero to the nation and the world. We cannot follow in his footsteps," said Kloetzel, "but we admire and envy the path that they [astronauts] have taken" [1]. Then, Armstrong spoke at the event (Fig. 2) and was "joined with officers, faculty, and students of the University to honor Mrs. Seaver" [5].

The Seaver Science Center houses the science and engineering library to this day. It lost much of its space to other units, however, when the university moved many of its library holdings to an off-campus location. The new generations of faculty and students increasingly rely on digital publications instead of paper books and journals, venerated by scholars for centuries.

Later in the afternoon of the same day, Apollo 11 Commander Armstrong gave a one-hour seminar (Section 6 below) on the technical aspects of landing on the moon. Finally, an annual Archimedes Circle black-tie dinner in the International Ballroom of the Beverly Hilton Hotel capped the day of celebrations, with California Governor Ronald Reagan as the principal speaker. One hundred charter members established the Archimedes Circle in early 1962. This group was instrumental in winning the financial support of alumni of the School of Engineering and its friends [5].

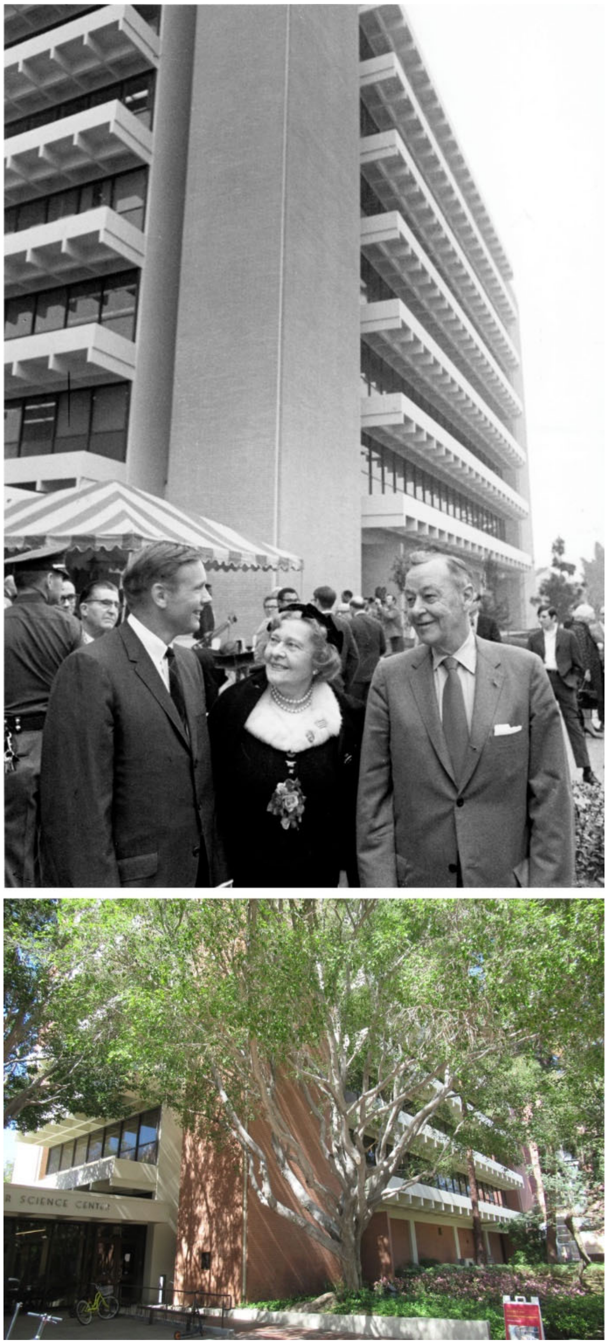


Fig. 1. Top: astronaut Neil Armstrong (left), donor Mrs. Blanche Seaver, and USC President Dr. Norman Topping at the dedication of the Frank R. Seaver Science Center on the USC campus on January 22, 1970. The seven-story laboratory complex wing is behind.

Bottom: view of the building from approximately the same spot in 2023. Its library section (not seen) is to the left of the entrance.

Photographs courtesy of Special Collections, USC Library (top) and Mike Gruntman (bottom).

Fig. 2. Neal Armstrong speaks at the dedication of the Seaver Science Center on January 22, 1970. Photograph courtesy of Special Collections, USC Library.

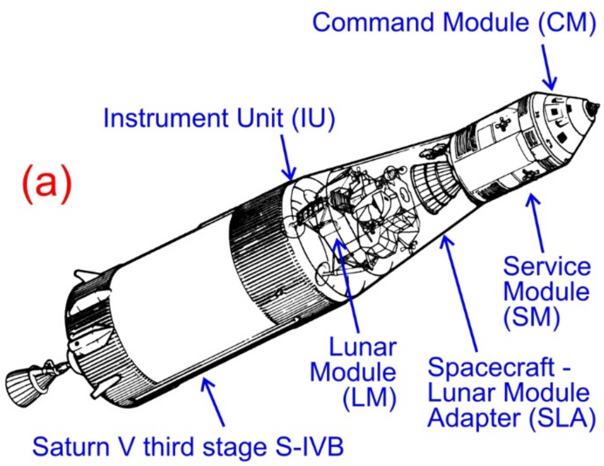
Governor Reagan began his dinner remarks by acknowledging “the genius, the work, the thrift, and the unselfishness of a wonderful man, … Frank Seaver” and the donor, “Blanche Seaver, Frank’s beloved wife and helpmate.” He then concentrated on “the importance of higher education and science and technology and engineering” and their impact on society. As many would appreciate it today, Reagan presciently warned about “real dangers to freedom of the individual in the technological society” and emphasized the importance of “protect[ing] our freedom and our well-being at the same time that we advance our technological and scientific expertise.” The governor also praised the consequential contribution of the Archimedes Circle that had “done so much for the USC School of Engineering” [29].

3. Apollo Missions and Spacecraft

In the afternoon lecture at USC, Neil Armstrong focused on lunar landing techniques during his historic Apollo 11 mission, one of the most challenging and complex accomplishments of the space program and engineering in general. Numerous publications describe various aspects of the Apollo program (e.g., [30-36]), including the Apollo 11 mission (e.g., [37-40]).

Briefly, on July 16, 1969, the mighty three-stage Saturn V rocket (serial number AS-506) launched into low Earth parking orbit Apollo 11’s spacecraft consisting of a Command Module (CM, serial number 107), Service Module (SM, serial number 107), and Lunar Module

(LM, serial number 5) attached to Saturn's third stage S-IVB (Fig. 3a). A three-foot high cylindrical ring between the third stage and the LM bottom, the Instrument Unit (IU), carried the "brains" of the launch vehicle, providing telemetry, tracking, communications, and control functions. The unit took almost 1350 measurements of various Saturn V parameters during the flight. The NASA Marshall Space Flight Center developed the IU in-house, and IBM's Federal Systems Division in Huntsville, Ala., built the flight units [41].



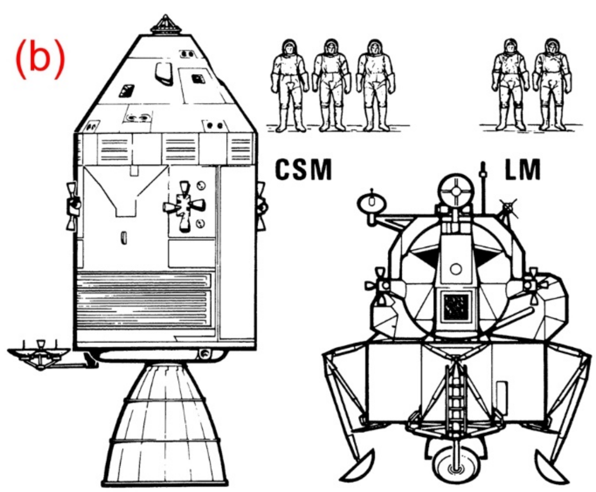


Fig. 3. (a) Saturn V's third stage S-IVB with the attached Apollo spacecraft, including the Command Module with the crew, in low Earth parking orbit. Following the injection into the translunar trajectory, the astronauts rearranged this cluster of vehicles in the Transposition, Docking and Ejection maneuver.

(b) Left: combined Command and Service Module, CSM, with the protruding nozzle of the Service Propulsion System. Right: Lunar Module, LM.

Figures from [38]; callouts in (a) by Mike Gruntman.

The aerodynamically smooth Spacecraft – Lunar Module Adapter (SLA) protected the Lunar Module during its ascent through the atmosphere (Fig. 3a). It also structurally supported the Apollo spacecraft with the launch escape system on top during the launch. The SLA was a "truncated cone 28 feet [8.5 m] long tapering from 260 inches [6.60 m] diameter at the base [on top of the IU] to 154 inches [3.91 m] at the forward end at the service module mating line" [38].

The combined but separable CM and SM operated as a joint unit throughout most of the mission and were designated the CSM, or the Command and Service Module (Fig. 3b, left). The CM and SM separated on the way back to Earth from the moon only shortly before the atmospheric reentry of the Command Module with the crew.

George M. Low managed the Apollo spacecraft development program at NASA from 1967-1969 and served as NASA Deputy Administrator from 1969-1978. He described the CSM and LM as "two machines, 17 tons of aluminum, steel, copper, titanium, and synthetic materials; 33 tons of propellant; 4 million parts, 40 miles of wire, 100,000 drawings, 26 subsystems, 678 switches, 410 circuit breakers" [42]. In 1969, NASA restored the privilege for astronauts to name their spaceships, the callsigns used in communications, which had been suspended in 1965. Apollo 11 crew "went patriotic with their spacecraft names. The CSM was *Columbia*. The lunar module was *Eagle*" [35].

The Douglas Aircraft Company won the contract and built Saturn V's third-stage S-IVB. (The company merged with McDonnell Aircraft in 1967, forming McDonnell Douglas Astronautics Company, today's part of Boeing.) The Rocketdyne Division of the North American Rockwell Corporation at Canoga Park, Calif., developed an advanced hydrogen-oxygen rocket engine, J-2, for the S-IVB. Five of these J-2 engines also powered Saturn V's second stage S-II which was built by North American Aviation (part of North American Rockwell from 1967). Wernher von Braun noted that "[t]o develop and manufacture the large S-II and S-IVB stages, the two West Coast contractors required special facilities. A new Government plant was built in Seal Beach where North American [Aviation] was to build the S-II. S-IVB development and manufacture was moved into a new Douglas center at Huntington Beach" [41].

The 21.7-ft [6.6 m] in diameter and 58.3-ft [17.8 m] tall S-IVB carried 235,000 pounds (approximately 107,000 kg or 107 metric tons) of propellant. During the Apollo 11 launch, the third stage's J-2 engine first fired for 147.1 seconds and consumed 30% of the propellant [37] to reach the low Earth orbit with the attached spacecraft (Fig. 3a). Here and thereafter, the key orbital parameters and velocity increments are given as compiled by [34,39,40].

After one-and-a-half revolutions around the Earth, S-IVB's engine restarted for the second burn of 346.8 seconds executing the Translunar Injection (TLI) maneuver which increased the speed of the vehicle by 10,441.0 ft/sec [3182.4 m/s] and injected it into a free-return trajectory toward the moon. This circumlunar trajectory would have allowed the space vehicle to fly around the moon and return to Earth without the engine firing, thus enabling a mission abort in case of emergency. Half an hour after the TLI, the astronauts rearranged the cluster of the vehicles shown in Fig. 3a.

The cone-shaped Command Module housed a crew on the way to the moon and back to Earth, including atmospheric reentry and splash down in an ocean. It accommodated three astronauts (Fig. 3b, left). This pressure vessel with heat shields was 11 ft 5 in. [3.5 m] high with a base diameter of 12 ft 10 in. [3.9 m]. A cylindrical Service Module, the SM, with a diameter of 12 ft 10 in. [3.9 m] and height (including the nozzle) of 24 ft 7 in. [7.5 m] was attached to the CM, forming the CSM (Fig. 3b, left). The SM carried a Service Propulsion System (SPS) with a large protruding nozzle of its rocket engine. In addition, the Service Module housed hydrogen-oxygen fuel cells supplying electric power to the spacecraft, silver-zinc batteries, and consumables such as oxygen. The fuel cells provided drinking water to the astronauts as a by-product of their operations.

During the mission, the SPS rocket engine injected the spacecraft into the lunar orbit and subsequently provided the velocity increment for sending it back home with the astronauts on the return trajectory to Earth. The Aerojet-General Corp. at El Monte, Calif., built the restartable AJ10-137 engine of the Service Propulsion System [43]. It used Aerozine 50 as fuel and nitrogen tetroxide (NTO) as oxidizer.

Aerojet-General had developed Aerozine 50, a 50%-50% mixture by weight of unsymmetrical dimethylhydrazine (commonly referred to as its abbreviation UDMH) and hydrazine, several years earlier for the Titan-II intercontinental ballistic missile program. Aerozine 50 forms a hypergolic combination with NTO, igniting on contact and thus not relying on spark plugs for engine firing. This important feature contributed to the high reliability of the SPS in multiple restarts. The engines of the Lunar Module used the same hypergolic propellant combination.

Several industrial teams proposed to design and build Apollo's Command and Service Module. The Source Evaluation Board (SEB) assigned the highest score to the proposal by The Martin Company. NASA's leadership overruled the SEB and announced on November 28, 1961, the selection of a division of North American Aviation, Inc., in Downey, Calif., as the principal contractor for the CSM [31,44]. North American Aviation would also build the Spacecraft – Lunar Module Adapter [31,36].

Merges and acquisitions have been continuously changing the aerospace field and industrial "namescape" in the United States [8], including the Apollo contractors. In September 1967, Rockwell Manufacturing Company acquired North American Aviation, forming North American Rockwell, renamed Rockwell International in 1973. The latter then sold its aerospace business in Downey and Seal Beach, Calif., to Boeing. The Downey unit would win the contract for the Space Shuttle Orbiter in 1972.

The Instrumentation Laboratory (IL) under Charles S. Draper at the Massachusetts Institute of Technology in Cambridge, Mass., developed an advanced guidance and navigation system for Apollo's CSM and LM [42]. Actually, "NASA awarded its first hardware contract for Apollo" to Draper's IL "on 9 August [1961] to develop the guidance and navigation system" [31]. Since the 1950s, the Laboratory excelled in advancing inertial guidance systems for long-range ballistic missiles. Its heavy involvement in defense programs of the free world caught the attention of the disapproving American political left in 1969, a critical time for the Apollo program. During the heat of the Cold War, the unrelenting pressure and demonstrations of the leftists finally forced the separation (the divestiture) of the Instrumentation Laboratory from MIT in 1973 [8]. These years of turmoil did not boost the morale of scientists and engineers working on the Apollo guidance and navigation.

Twenty-five minutes after the translunar injection, the Apollo 11 astronauts began the Transposition, Docking and Ejection (TD&E) maneuver to form a combined space vehicle consisting of the CSM and LM, the CSM/LM, for translunar coast and then the Lunar Orbit Insertion (LOI). They first separated the CSM module away from Saturn V's third stage S-IVB (Fig. 3a) and jettisoned the side panels of the SLA adapter. Following the separation, "the CSM … translate[ed] 50 feet [15 m] [away], pitch[ed] 180 degrees, roll[ed] 60 degrees and move[ed] to docking interface of the lunar module" [37].

After docking, the now combined CSM/LM vehicle (shown in Fig. 4a) separated from the third stage S-IVB and fired its SPS engine, acquiring an additional velocity of 19.7 ft/sec [6.0 m/s] in an "evasive maneuver" to get away from the large S-IVB. The latter then dumped the remaining propellants through its J-2 engine, which reduced the stage velocity by 115 ft/sec [35 m/s] and perturbed its trajectory, sending the S-IVB into a heliocentric orbit by the "slingshot" flyby of the moon [37]. The stage circles the Sun to this day with a 342-day orbital period, orbit eccentricity of 0.061, and inclination of 0.38 degrees. The empty S-IVB stages on the subsequent missions, beginning with Apollo 13, would crash onto the moon to study its interior with seismometers deployed on previous landings.

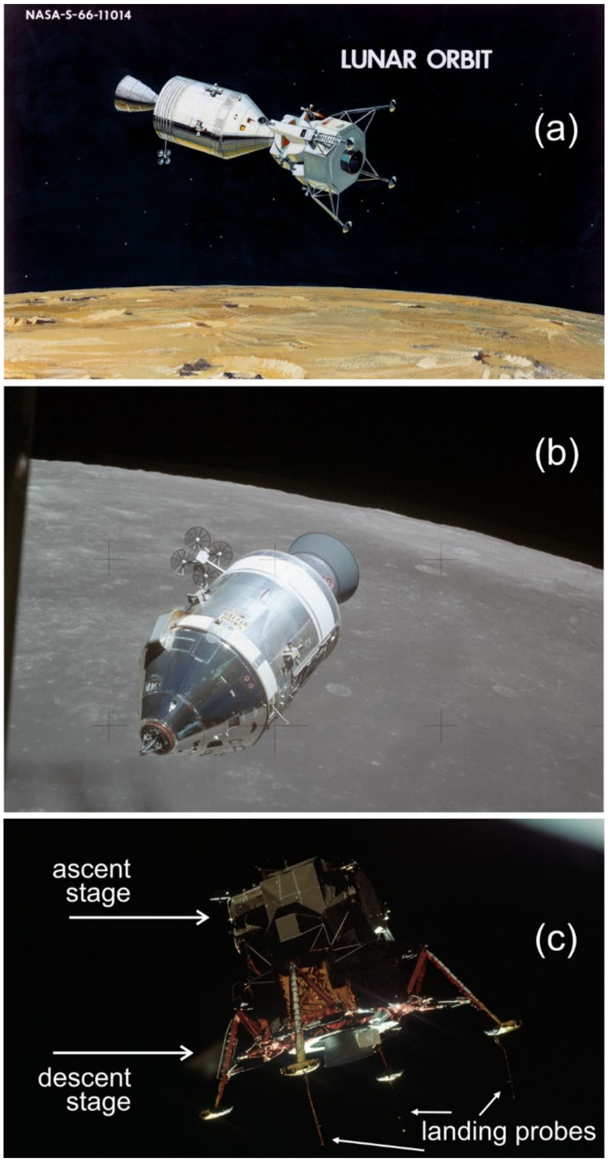


Fig. 4. (a) Artist's concept of the joint CSM/LM vehicle orbiting the Moon after translunar coast and lunar orbit injection. Then, the modules separate. One astronaut remains in the CSM (b), while the LM (c) with two astronauts descends and lands on the moon. The LM ascent stage launches from the moon and brings them back to the lunar orbit where it docks the CSM. Two astronauts transfer to the CSM, jettison the LM, and the crew starts its journey back to Earth.

(b) Apollo 15's CSM in lunar orbit photographed from the Lunar Module on August 2, 1971.

(c) Apollo 11's LM *Eagle* with descent and ascent stages before landing, photographed in lunar orbit from CSM *Columbia* on July 20, 1969. One can see landing probes (5.6-ft [1.7 m] long) attached to the footpads for positive indication of surface contact.

Images courtesy of NASA. Callouts in (c) by Mike Gruntman.

A docking hatch connected the linked CM and LM, allowing astronauts to move between the modules. After the translunar injection and transposition, docking, and ejection, the CSM/LM vehicle executed only one midcourse correction (four options were initially planned) on the way to the moon. Its SPS engine fired for 3.1 seconds which changed the velocity by 20.9 ft/s [6.4 m/s]. From now on, the spacecraft was no longer on the free-return trajectory. The joint CSM/LM vehicle with three astronauts on board thus set on the translunar coast to its destination, the moon, and then lunar orbit insertion. Figure 4a shows an artist's concept of the combined CSM/LM in lunar orbit. Subsequently, the CSM (Fig. 4b) and LM (Fig. 4c) modules would separate and operate independently during the landing phase of the mission.

For all three Apollo 11 astronauts (Fig. 5), 38-year-old mission commander Neil A. Armstrong, Lunar Module pilot Edwin E. "Buzz" Aldrin Jr., 39, and Command Module pilot Michael Collins, 38, this was their second space flight. They were experienced aircraft pilots with 4000, 4000, and 3500 hours of flying time, respectively. NASA Astronaut Armstrong served as a

Fig. 5. Apollo 11 astronauts in front of a lunar module mockup during training on June 19, 1969. From left Command Module pilot Michael Collins, mission commander Neil A. Armstrong, and Lunar Module pilot Edwin E. "Buzz" Aldrin Jr. Photograph courtesy of NASA.

naval aviator from 1949 to 1952. He joined NACA, subsumed later by NASA, as a research pilot in 1955. NASA Astronauts Aldrin and Collins were colonel and lieutenant colonel in the United States Air Force. Armstrong and Aldrin served in Korea and flew 78 and 66 combat missions, respectively. In 1969, Armstrong's civil servant rank was GS-16 Step 7, and he earned $30,054 per annum while "the annual pay and allowances of an Air Force lieutenant colonel with Collins' time in service totals $17,147.36" [38].

On July 19, 1969, the joint CSM/LM vehicle approached the moon. At about 76 hours after the Apollo 11 launch, the SPS engine AJ10-137 fired for 357.5 seconds, or nearly 6 minutes, slowing the vehicle down by 2917.5 ft/sec [889.3 m/s] and inserting it into an initial elliptical lunar-centric orbit with the pericynthion altitude 60.0 n.mi. [111.1 km] and the apocynthion altitude 169.7 n.mi. [314.3 km]. (1 n.mi. = 1852.0 m (exact) is one nautical mile.) During this first 6-minute Lunar Orbit Insertion (LOI-1) maneuver, the spacecraft flew at altitudes from 86.7 n.mi. [160.7 km] to 60.1 n.mi. [111.3 km] above the surface.

At that time, NASA's scientific and engineering documents described the apsides of elliptical lunar orbits (periapsis and apoapsis, or the closest and farthest orbital points, respectively, from the central body) as pericynthion and apocynthion "after the Roman goddess of Moon" [38]. Today, the commonly used terms are perilune and apolune or periselene and aposelene.

After four hours and two lunar orbits, the SPS engine fired again for 16.8 seconds in the LOI-2 maneuver, reducing the vehicle velocity by 158.8 ft/sec [48.4 m/s], lowering its orbit and making it nearly circular with the apside altitudes 66.1 n.mi. [122.4 km] and 54.5 n.mi. [100.9 km]. The Apollo 11 crew conducted these two lunar orbit insertions, LOI-1 and LOI-2, when their CSM/LM space vehicle was behind the moon. The astronauts executed and monitored the orbit insertion maneuvers without contact with and direct support by the ground control.

Precise navigation in the lunar environment required well-developed capabilities for predicting the evolution of orbital parameters in time. The moon, like other celestial bodies including our home planet Earth, is not perfectly spherical and its density is not uniform. At the time of the first Apollo missions, the uncertainties due to the insufficiently accurate knowledge of the lunar mass distribution and resulting gravitational field posed serious challenges for navigation. In addition, determining the exact coordinates and velocities of vehicles, known as state vectors, also presented problems as well as accounting for adding up multiple small changes in vehicle velocities due to attitude maneuvers, station-keeping activities, undocking impulses, and even cabin and tunnel venting [40].

4. Apollo Lunar Module

Until 1967, Apollo's Lunar Module, LM, was called the Lunar Excursion Module, or LEM. NASA's George Low explained that "LM, pronounced LEM, which had actually been its [earlier] designation—for lunar excursion module—until someone decided that the word 'excursion' might lend a frivolous note to Apollo" [42]. The Lunar Module was essential to the design of Apollo missions which became known as the Lunar Orbit Rendezvous (LOR). It relied on rendezvous and docking of manned space vehicles in lunar orbit [36,42]. In a bold decision, NASA adopted the LOR concept in 1962, only several months after the first orbital flight of John Glenn who had completed a mere three revolutions around the Earth. No rendezvous and docking had been demonstrated even in low Earth orbit at that time.

All operations of a Lunar Module took place in a vacuum. Therefore, its shape and structure (Fig. 6) lacked the aerodynamic qualities of machines flying in an atmosphere. The module consisted of two stages (Fig. 4c), a lower (descent) stage and an upper (ascent) stage [36,42,45-47]. The LM separated from the Command and Service Module after the insertion of the combined CSM/LM (Fig. 4a) into lunar orbit. Then, operating independently (Fig. 4c), the Lunar Module descended and landed on the surface of the moon with two astronauts, while the third crew member remained in the Command Module (Fig. 4b) of the CSM in lunar orbit.

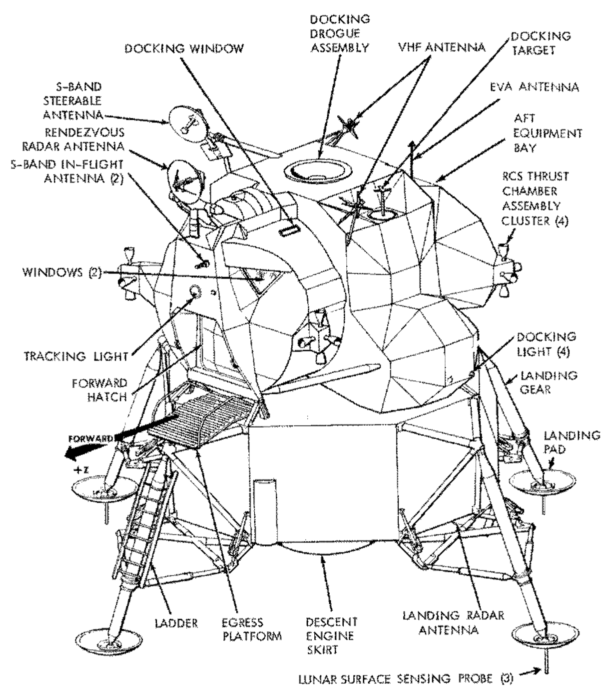


Fig. 6. Standing nearly 23 ft. [7 m] high, Apollo's Lunar Module was designed for operations in a vacuum of space. Figure from [38].

After completing the on-surface mission, the lower, descent stage of the LM remained on the moon and served as a pad from which the ascent stage with two astronauts launched into lunar orbit. Then, it docked the CSM. Finally, the ascent stage of the Lunar Module was jettisoned, and the CSM headed back to Earth.

On November 7, 1962, NASA selected the Grumman Aircraft Engineering Corp. in Bethpage, N.Y., as the principal contractor for the development and building of the Lunar Module. (The company changed its name to the Grumman Aerospace Corporation in 1969; it merged with Northrop Corporation in 1994 to form today's Northrop Grumman.) Intense negotiations between NASA and Grumman followed, with the cost-plus-fee contract finalized and the work authorized in January 1963 [31,36].

The minimization of the mass of Lunar Modules was indispensable for the success of Apollo. Thomas Kelly led Grumman's technical proposal to NASA and subsequently directed the LM engineering development. He later wrote that the module "was a delicate structure in the earth environment: for example, the chemically milled wall of the pressurized cabin was only 0.012 in. [0.3 mm] thick, and was protected from damage by the crew by the interior flooring and by the display and control consoles" [45]. The total weight of the Lunar Module of Apollo 11 was about 33,000 lb [15,000 kg]. The weight of the modules increased to 36,000 lb [16,300 kg] on the final three Apollo missions as the performance of the Saturn V launch vehicles improved [45].

Building Lunar Modules required the advancement of diverse technologies. The list included developing large throttleable rocket engines, replacing conventional threaded fittings with brazed systems to prevent leaks of propellants, understanding and eliminating contaminations in nickel-cadmium batteries, and strict temperature control of high-energy-density silver-zinc batteries [46,47].

Propulsion systems enabled the success of Apollo missions in important ways. NASA's George Low noted that "the guidance system only told us where the spacecraft was and how to correct its course. It provided the brain, while the propulsion system provided the brawn in the form of rocket engines, propellant tanks, valves, and plumbing" [42]. There were 16 thrusters of the 100-lbf [445 N] class for attitude control on the Lunar Module alone.

The main engines of LM's ascent and descent stages differed in size significantly (Fig. 7). The Rocketdyne Division of the North American Rockwell Corp. at Canoga Park, Calif., built the rocket engine of the ascent stage [48] with thrust 3450 lbf [15.35 kN] and specific impulse 309 sec [40]. As a single-point failure element of the Apollo lunar missions, the engine emphasized simplicity to achieve critically important reliability. Its failure would have prevented the astronauts from getting back to Earth. The Aerojet-built AJ10-137 engine of the Apollo Service Module was also in the same category. In contrast, a failure of the descent engine "would not be as critical, because the ascent engine might be used to save the crew members" [42] in aborted descent.

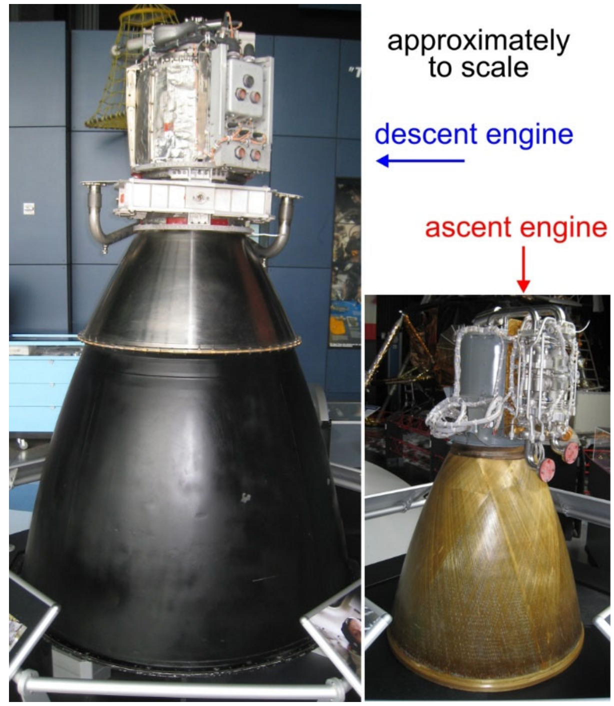


Fig. 7. Descent (left) and ascent (right) rocket engines (approximately to scale) of Lunar Modules on display at the U.S. Space and Rocket Center in Huntsville, Ala. The development of the throttleable descent engine represented a challenging task for the Apollo program. The ascent engine emphasized reliability through the simplicity of its design and operations. Photographs (August 15, 2013) by Mike Gruntman.

Initially in 1963, Bell Aerospace (part of Bell Aircraft Corporation, bought by Textron in 1960) at Buffalo, N.Y., received a contract to develop the Lunar Module's ascent stage engine. They ran into problems with "catastrophic" instabilities. In the summer of 1967, NASA brought Rocketdyne to develop a backup engine, in competition with Bell. Rocketdyne became the prime contractor the next year, with Bell contributing some engine parts and both companies working "in concert" [42,48]. The inherently simple design of the ascent stage engine relied on a hypergolic propellant combination of Aerozine 50 and nitrogen tetroxide, constant (fixed) thrust, and a gas-pressure propellant feed system.

The development of the Lunar Module Descent Engine (LMDE) faced major challenges, in particular the requirement to operate at a variable thrust with a 10:1 throttling capability. At first, highly experienced Rocketdyne received the contract to build the LMDE in

1962. NASA had concerns, however, about achieving the desired throttling and initiated a backup engine development program. A team from the Space Technology Laboratory (STL) in Redondo Beach, Calif., under Gerard "Jerry" W. Elverum won this latter contract, competing against Aerojet and Reaction Motors Inc., and started work in July 1963 [49]. At that time, the rapidly growing defense contractor STL was a subsidiary of TRW and focused on ballistic missiles and space systems. STL continued to expand despite loss of many of its scientists and engineers to the Aerospace Corporation formed in 1960 [8]. After "a year and one-half of very intense competition with Rocketdyne," NASA chose the STL/TRW team to be "the decent engine contractor" [49], replacing Rocketdyne.

The LM's descent engine also used the hypergolic propellants Aerozine 50 and NTO. It controlled their flows at different rates and with a constant mixture ratio by variable area cavitating venturi valves. The engine thrust ranged from 1000 lbf [4.45 kN] to 10,000 lbf [44.5 kN] at full thrust, with the corresponding specific impulse changing from 292 sec to 304 sec, respectively [50,51]. The nozzle extension, the skirt, was crushable at landing on a rock. Its wall was made of a Columbium (known as Niobium today) alloy and was "structurally designed to collapse a distance of 28 inches [71 cm] on lunar impact" [50]. Near its exit, the nozzle was only 0.007 in. [0.18 mm] thick.

The initial uncertainty of the nature of the lunar surface material and the thickness of the dust layer led to the installation of large landing footpads, 37 in. [0.94 m] in diameter [52], on the Lunar Modules (Figs. 4c, 6). Despite verifications of the surface strength by the earlier Surveyor lunar landings, some scientists persisted in arguing for the possibility of a thick layer of dust. "One of the most important lessons," as the first NASA flight director and later director of the Johnson Space Center in Houston, Tex., Chris Kraft noted, "was that any apocalyptic prediction by a scientist would almost certainly be wrong. … The fright-monger scientists … proved that fear is more powerful than common sense, but by then the money [for mitigating raised problems] was spent and the public's attention was elsewhere" [35].

Grumman's Thomas Kelly pointed out that only at some landing locations (Apollo 12 and 15) on the moon "there was sufficient surface dust blown up by the descent engine exhaust plume to obscure the crews' vision out the windows during the final 50 ft [15 m] or so prior to touchdown. The possibility had been anticipated in the LM design, which provided the pilot with instruments to permit zero visibility landing" [45]. Kelly also observed that "the LM landing gear proved to be greatly overdesigned, thanks to the skills of the astronaut pilots" [47].

Such an expert astronaut flying unusual vehicles in a low-gravity environment of the moon was a truly remarkable achievement, a result of extensive training on specially-built fixed-based and free-flight simulators. In the early 1960s, the NASA Flight Research Center and Bell Aerospace Systems had initiated a development program of an experimental free-flight Lunar Landing Research Vehicle (LLRV) even before NASA adopted the design of Apollo's lunar modules [53,54].

Figure 8a shows the first LLRV-1 which was "a skeleton framework of tubing supporting a control station, fitted in the center with a downward thrusting jet engine to offset five-sixths of its weight" to simulate lunar gravity [32]. Sixteen small monopropellant hydrogen peroxide thrusters with thrust varying from 16 to 90 lbf [80-400 N] each controlled attitude. Two throttleable rocket engines with a maximum thrust of 500 lbf [2200 N] enabled descent, hover, and translation [53].

Bell Aerospace delivered two LLRVs to the FRC at the Edwards AFB in 1964 for testing. After two hundred flights, NASA transferred the vehicles to Ellington Air Force Base in Houston. Neil Armstrong began flying the Lunar Landing Research Vehicle in March 1967. During his flight on May 6, 1968, the LLRV control failed, and, with the vehicle "rolling into a 30-degree bank" [6], Armstrong "ejected (Fig. 8b), when the craft was about 200 feet [60 m] above ground and beginning to nose up and roll over" [54]. He parachuted safely (Fig. 8c) "with only superficial injuries."

Bell Aerospace built three more vehicles optimized for astronaut training, the Lunar Landing Training Vehicles, or LLTVs. Figure 8d shows Neil Armstrong flying an LLTV on June 16, 1969, one month before the launch of Apollo 11. In addition to free-flight LLTVs, the astronauts also trained at NASA's lunar module mission simulator, LLTV fixed-base simulator, and lunar landing research facility [53].

Grumman's Thomas Kelly emphasized the importance of "a high degree of functional redundancy" in the design of the Lunar Module and Apollo missions in general [47]. Consequently, the Lunar Module would play a critical role of a lifeboat, "a triumph of systems engineering … foreseen six years earlier," in the dramatic rescue of Apollo 13 in April 1970. During the first year of the LM development, it was realized that it could provide such an astronaut-saving function and make Apollo missions safer "if a little more water and oxygen than required for its normal mission were placed aboard the LM … This was easily done in the early stage of the program when LM existed only on paper" [46].

An oxygen tank in the Service Module of Apollo 13's CSM/LM exploded when the space vehicle was two-thirds of its way to the moon. An earlier midcourse correction had changed the initial spacecraft's free-return circumlunar trajectory to the one optimized for lunar orbit insertion. It was the LM's descent engine that provided then the necessary velocity increments to bring Apollo 13 back to Earth (Section 5 of the article).

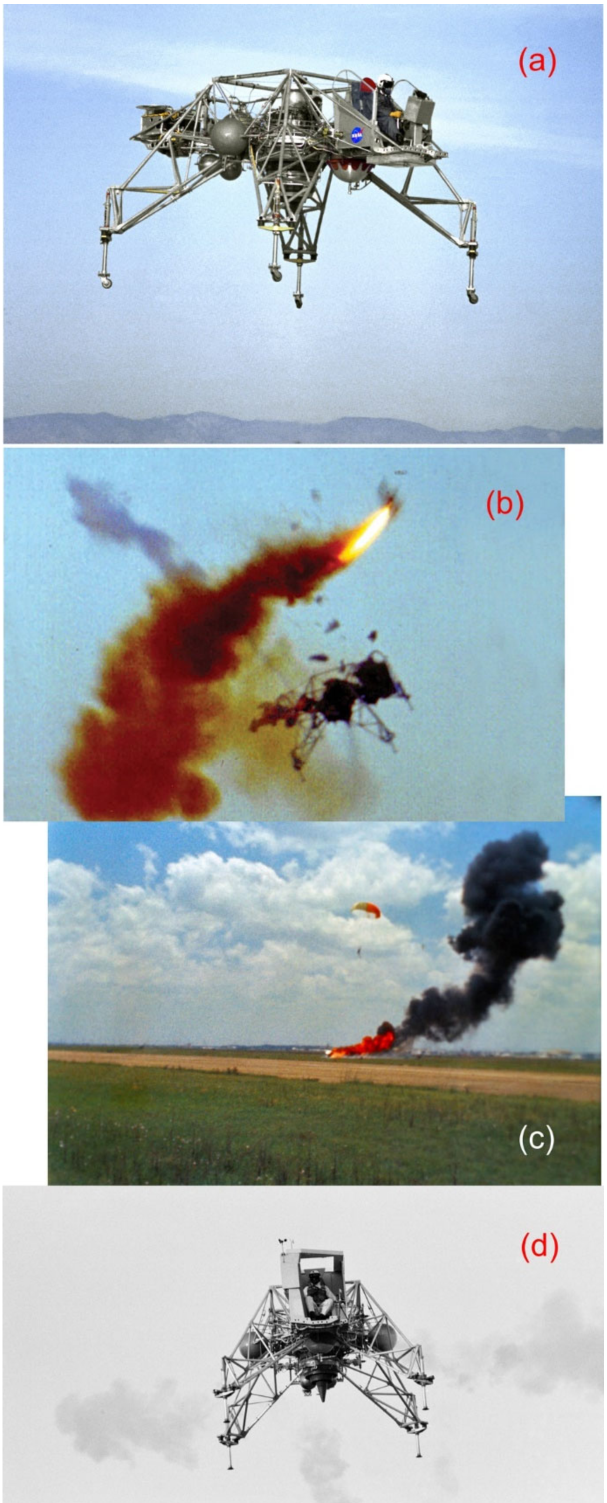


Fig. 8. (a) Lunar Landing Research Vehicle LLRV-1 in flight on December 9, 1964. (b) and (c) Neil Armstrong on May 6, 1968: ejecting from LLRV-1 seconds before it crashed and parachuting to safety after ejection. (d) Armstrong piloting LLTV on June 16, 1969. Photographs courtesy of NASA.

To survive, Kelly explained, "[t]he three astronauts transferred from the Command Module to the LM, where they lived off the oxygen and water stored there. When they reached a point close to the vicinity of the Earth, they re-entered the Command Module, which still had a small supply of oxygen. The Command Module then re-entered the Earth's atmosphere and returned the astronauts safely" [46].

5. The *Eagle* has landed

Ten Lunar Modules flew on Apollo missions. (Grumman Aerospace built a few more for ground tests and a couple of units were not completed and scrapped, as the program ended.) The first Lunar Module, LM-1, went to space on the unmanned Apollo 5 (AS-204) mission in January 1968. Then, Apollo 9 carried the first full Apollo spacecraft with the operational CSM and LM (LM-3) on a ten-day mission in low Earth orbit in March 1969. The astronauts performed crewed flight of the LM, conducted docking, tested the LM's ascent and descent engines, and demonstrated the use of the descent engine, the LMDE, to propel the combined CSM/LM vehicle in case of emergency [42].

This latter ability would save Apollo 13 one year later. Then, the descent engine of its Lunar Module (LM-7) first performed a burn for 34.2 seconds during its approach to the moon to return the CSM/LM vehicle to a circumlunar free-return trajectory. After emerging from behind the moon, the LMDE fired for 263.8 seconds, providing an 860.5-ft/sec [262.3 m/s] velocity increment, to place the vehicle on a homebound transearth trajectory with the desired splashdown in the Pacific Ocean.

After Apollo 11's second lunar orbit insertion maneuver, LOI-2, its CSM/LM vehicle was in a nearly circular lunar orbit. Astronauts Neil Armstrong and Buzz Aldrin transferred to the Lunar Module *Eagle*, LM-5, and undocked from the CSM. Michael Collins remained in the Command Module *Columbia*. The Lunar Module first fired its descent engine for 30 seconds which reduced the spacecraft velocity by 76.4 ft/sec [23.3 m/s] in the Descent Orbit Insertion (DOI) maneuver which lowered the orbit pericynthion (perilune) altitude down to 7.8 n.mi. [14.4 km].

One hour later at pericynthion, the LM-5 crew fired the LMDE again and started the 12.5-minute-long three-phase powered descent. At this Powered Descent Initiation (PDI) point, the Lunar Module was 260 n.mi. [480 km] from the planned landing site (Fig. 9). During the first phase, called the braking phase, from the PDI to high-gate at 7120 ft [2170 m] above the surface, the spacecraft reduced its speed down to approximately 600 ft/sec [182 m/s] [53]. It had a descent rate of 125 ft/sec [38 m/s] [40]. The second phase, known as the approach or visibility phase, continued "until low gate, a position approximately one-half mile up range of the selected landing site at an altitude of 500 to 1000 feet" [53].

The Apollo program used the aircraft-pilot terminology that described the beginning of the approach to an airport as a "high gate." The "low gate" referred to a point for a pilot to visually assess the landing site and, in the case of the LM descent, to select either automatic or manual control. What was usually called manual control of the Lunar Module would be better described as manually-operated fly-by-wire control.

The final (third) landing phase began at low gate at a 500-ft [152 m] altitude, about 5 n.mi [9 km] uprange from the landing site. Neil Armstrong assumed direct control of the Eagle landing when "it became clear that an automatic descent would terminate in a boulder field surrounding a large sharp-rimmed crater … and the range was extended to avoid the unsatisfactory landing area." This "[m]anual control began at an altitude of approximately 600 ft [180 m]" [40].

The lead designer of the descent engine Jerry Elverum considered the landing of Apollo 11 "most difficult." He recalled that "like everything else, NASA came up with a specification for the rock this [LMDE] engine would have to land and for the way the nozzle would have to crush on it. … Armstrong … found out they were over a boulder field … Armstrong kept looking and looking and looking" in order to "find a NASA specification rock on which to land" [49]. And finally,

> EAGLE: Houston, Tranquility Base here. The *Eagle* has landed!
>
> HOUSTON: Roger, Tranquility…
>
> TRANQUILITY: … That may have seemed like a very long final phase. The auto targeting was taking us right into a football-field-sized crater, with a large number of big boulders and rocks for about one or two crater-diameters around it, and it required flying manually over the rock field to find a reasonably good area.
>
> HOUSTON: Roger, we copy… [55]

The Lunar Module *Eagle* landed in the Sea of Tranquility (Mare Tranquillitatis) approximately 3.75 n.mi. [6.9 km] southwest of the planned point (Fig. 10, left). The astronauts initiated the powered descent at the preplanned PDI time but the LM was 4 n.mi. [7.5 km] farther downrange than anticipated. This difference in the state vector caused the shift of the landing point. During the touchdown, the down velocity of the Lunar Module was about 1 ft/sec [0.3 m/s], and its side velocity was less than 2 ft/sec [0.6 m/s].

The descent engine of Apollo 11's Lunar Module operated with varying thrust for 756.3 seconds or more than 12.5 minutes. The thrusters of the reaction control system used more propellant than predicted because of attitude and translational maneuvering in finding the place for landing [40].

Post-flight analysis showed that at its cutoff, the descent engine of the Lunar Module had propellant left only for 45 seconds of operation [34], slightly more than 30 seconds as believed by the ground control in Houston. They got increasingly concerned at the time of landing and radioed to the *Eagle* after the touchdown,

> HOUSTON: … We copy you [are] on the ground. You've got a bunch of guys [in the control room] about to turn blue. We're breathing a lot [now] [55].

Armstrong's heart rate was also the highest (Fig. 11) during the last three minutes of the descent [39,40].

During the powered descent, five alarms of the Apollo Guidance Computer of the Lunar Module

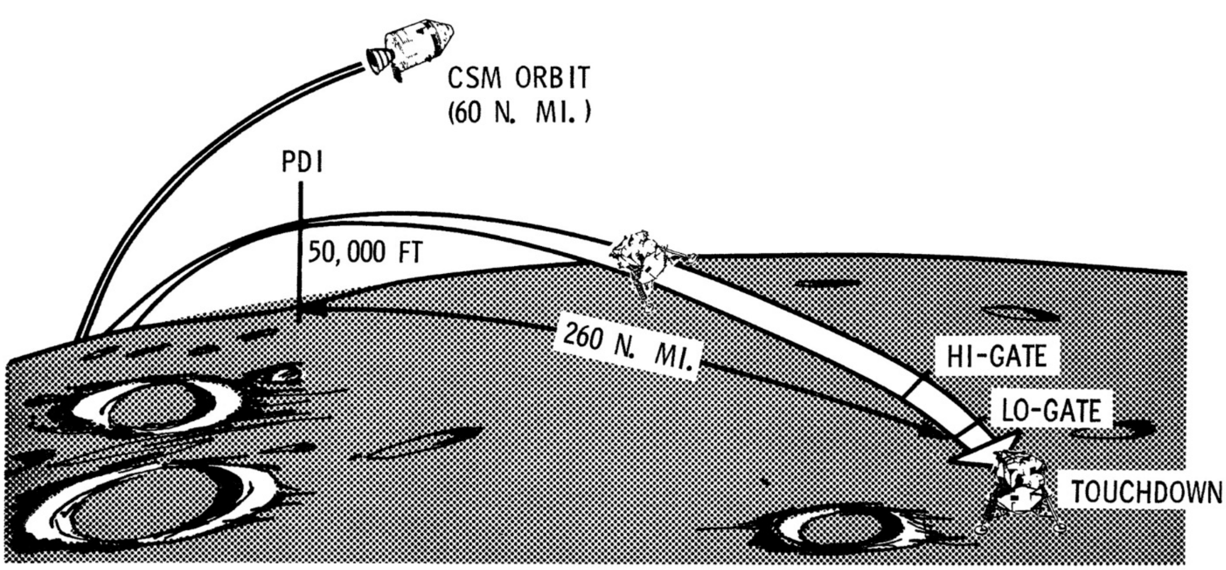


Fig. 9. Three-phase powered descent of Apollo 11. PDI – Powered Descent Initiation point. Figure from [38].

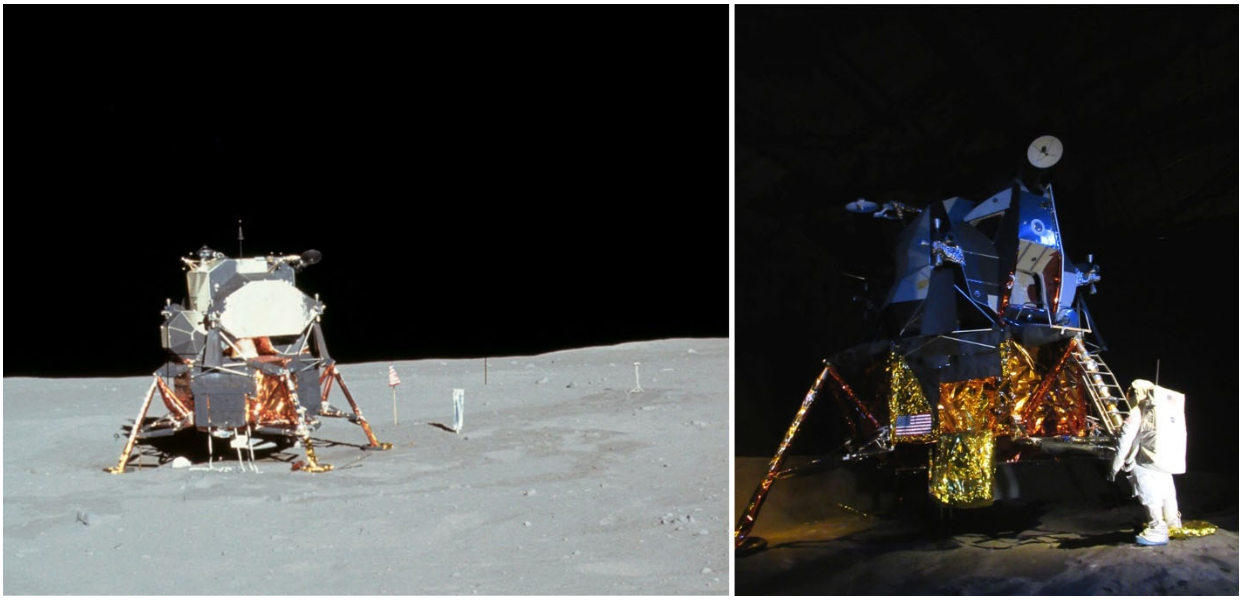


Fig. 10. Left: Lunar Module *Eagle*, LM-5, at Tranquility Base photographed by Neil Armstrong during the Apollo 11 mission (photograph courtesy of NASA). Right: never flown Lunar Module LM-13 (intended for the canceled Apollo 18 or 19) on display at the Cradle of Aviation Museum in Garden City, New York (photograph, June 6, 2019, by Mike Gruntman). Multi-layer gold-colored blankets provide thermal insulation; silver-and-black shields are for micrometeorite protection.

occurred, the last one 72 seconds before the touchdown. The mission report noted that "[a]lthough the alarms did not degrade the performance of any primary guidance and control function, they did interfere with an early assessment of the landing approach of the crew" [40]. The astronauts and ground control determined in real time that computer overloads caused the problems and that "it was safe to continue the landing" [34].

On the moon, as the official history summarized, "The total time spent [by astronauts Armstrong and Aldrin] outside the LM [on the ground] was 2 hours 31 minutes 40 seconds; the total distance traveled was 3,300 feet (1 km); and the collected samples totaled 47.52 pounds (21.55 kg). The farthest point traveled from the LM was 200 feet (60 m), when the commander visited a crater 108 feet in diameter (33 m) near the end of the extravehicular period" [34].

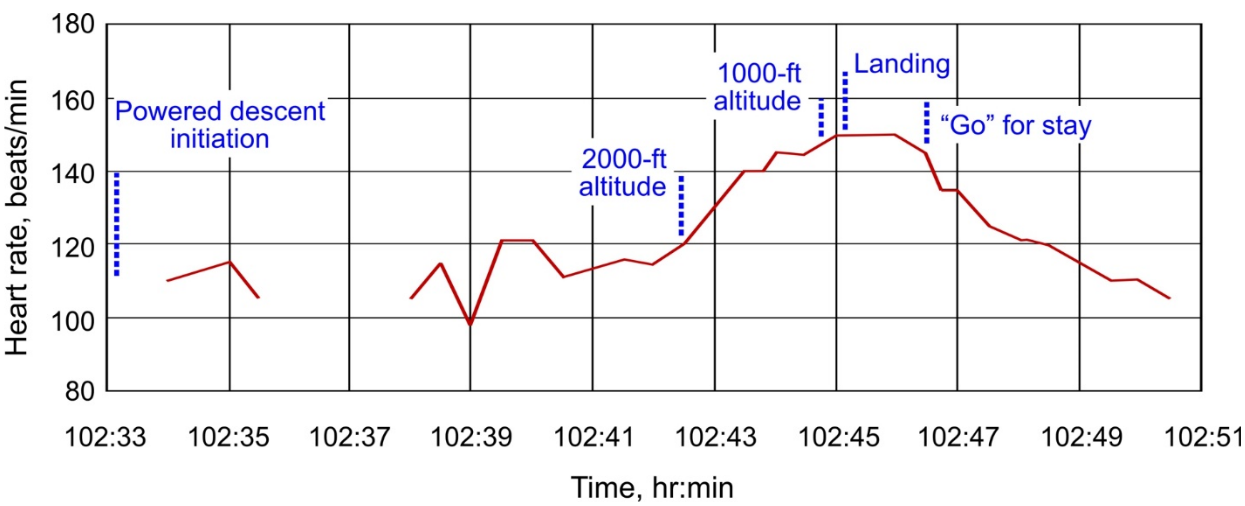


Fig. 11. Heart rate of Apollo 11 Commander Neil Armstrong during lunar descent. (Based on Fig. 12-1 in [39,40], rendering by Mike Gruntman.) The average heart rate of Armstrong during the entire mission was 71. The time in the horizontal axis is "given as elapsed time from range zero (g.e.t.), which is established as the integral second before lift-off." Range zero for the Apollo 11 mission was 13:32:00 GMT, July 16, 1969 [40].

Nearly twenty-two hours after the landing, the Lunar Module astronauts fired the ascent engine for 434.9 seconds (more than 7 minutes) which placed the ascent stage of the LM into an elliptical lunar orbit. Maneuvers followed for the *Columbia* and the *Eagle* to rendezvous and dock. Armstrong and Aldrin joined Collins in CSM's Command Module. Then, the astronauts separated the LM's ascent stage from the CSM. (The discarded ascent stages of Lunar Modules on the subsequent Apollo missions, except Apollo 13 and 16, would be intentionally deorbited to impact the moon at the desired locations [34].)

In five hours, CSM's AJ10-137 engine fired for 151.4 seconds, providing a velocity change of 3279 ft/sec [999.5 m/s] for the vehicle which placed it on the homebound trajectory back to Earth. Almost 60 hours later, the Service Module was jettisoned, and the Command Module with the three astronauts reentered the atmosphere and parachuted down into the Pacific Ocean on July 24, 1969. The USS Hornet (CVS-12) picked up the crew.

As the Apollo program progressed and Saturn V's performance improved, Grumman Aerospace built lunar modules that carried more supplies to support astronauts for longer stays, up to three days, on the surface of the moon and considerably more scientific instruments. They deployed Lunar Roving Vehicles in the last three missions (Apollo 15, 16, 17). Grumman only partially completed the last existing Lunar Module, LM-13, being built for the Apollo 18 or 19 mission when the program was canceled. This last never-flown module was restored, and today, it is on display at the Cradle of Aviation Museum on Long Island, N.Y. (Fig. 10, right).

6. Seminar by Neil Armstrong at USC

In the fall of 1962, Neil Armstrong reported to the Manned Spacecraft Center in Houston, Tex., for astronaut training and could not finish his graduate studies at USC (Section 2 of this article). Only a few credit units of Master's thesis and associated research were needed to graduate. Dean of Engineering Robert Vivian described later that Armstrong "had completed all except seminar requirements for the M.S. degree when he was transferred to NASA-Houston" [5].

It seems – this is my speculation – that the leaders of the USC School of Engineering creatively established, ad hoc, these new "seminar requirements" for astronaut Armstrong to complete his studies and receive the degree. Replacing the Master's thesis with a technical lecture on a topic of tremendous current interest would certainly meet the remaining credit unit and effort requirements toward the degree in spirit if not strict formality. No doubt that the overseeing office of the provost did not object. So, Armstrong justifiably called it "an earned degree" [5] at the receiving the diploma.

Fig. 12. Bovard Administration Building on USC campus, Los Angeles, California. Photograph (2010) courtesy of Mike Gruntman.

Neil Armstrong gave his Master's seminar "Apollo 11 Lunar Landing Mission. Lunar Landing Techniques" at the packed Bovard Auditorium in the afternoon of the day of his return to USC on January 22, 1970. This auditorium in the Bovard Administration Building (Fig. 12) remains to this day the main meeting venue for official and festive occasions on the USC campus. The building also houses the offices of the university president and provost.

The USC records from 1970 show [56] that its Institute of Aviation Safety and the Division of Cinema (today's School of Cinematic Arts) held five-minute videotapes of "the degree presentation" at Bovard. The tape in the Cinema Division was in color and with sound. The USC radio station, KUSC, aired "the entire program" and had the sound tape. None of these recordings can be found today. In addition, the university records indicated that "VOA has [an] audio tape of the whole thing" [56]. Here, VOA likely stood for the Voice of America radio service. It is not clear whether this audio tape is preserved and can be located.

Some time ago, the Moving Image Archive of the USC School of Cinematic Arts received a 5-minute amateur film footage of the degree presentation to Armstrong from one alumnus [57]. This reel seems to be the only existing silent and out-of-focus video of the event at Bovard. It can be accessed on the Vimeo video-sharing platform [58].

The monthly magazine of the School of Engineering, *USC Engineer*, published the notes of the lecture by Armstrong as an article titled "Apollo 11 Lunar Landing Mission. Lunar Landing Techniques" (Fig. 13) in March 1970 [59]. This 5,200-word technical paper included numerous engineering details and insights into piloting the Lunar Module *Eagle* and landing on the moon as well as many figures (Fig. 13, bottom). It described, step by step, powered descent to the surface from a lunar orbit.

The title page of Armstrong's presentation (Fig. 13, top right) was nearly identical to the cover of the 257-page NASA Press Kit for the Apollo 11 mission [38] released on July 6, 1969, ten days before the flight. The differences were only in the removal of the words "Press Kit" and the addition of "Lunar Landing Techniques, by Neil Armstrong, From a Master's Seminar, January 22, 1970" at the bottom. The use of this page as well as several other figures from NASA public documents was a convenient way of avoiding time-consuming effort for clearing new figures for open release.

Neil Armstrong began his seminar talk at the Bovard Auditorium (Fig. 14) by identifying a major technical challenge of the powered descent and lunar landing on a wingless vehicle in an unusual gravity and airless environment:

> There were a number of new things on Apollo 11, but one of the most challenging was the powered descent and the landing. It is that subject to which I address myself. I've had very few opportunities to make presentations to a technical nature in the months since the flight, and I really look forward to an opportunity to talk about the strategy that was employed in that effort.

Here and thereafter, unless indicated otherwise, Armstrong's quotes are from the article in *USC Engineer* [59].

Fig. 13. March 1970 issue of *USC Engineer* [59]. Top (left to right): magazine cover, table of contents, and title page (p. 21) of the lecture of Neil Armstrong. Bottom: Armstrong's entire article on pages 21-32.

After discussing the selection of the landing site at the Sea of Tranquility, the astronaut pointed out the importance of landing near the terminator, the boundary between sun-illuminated and dark parts of the moon. Not only the temperatures were lower there, but also the long shadows revealed local surface roughness and established good depth perception.

He then talked about orbital maneuvering, starting from the Descent Orbit Insertion, DOI, and reaching the moment of Powered Descent Initiation, PDI (Section 5 of this article). Armstrong used the term perilune in his talk rather than pericynthion common in mission-related NASA documents. He described step-by-step the techniques and the rationale for the selected Lunar Module trajectory, maneuvers, and orientation throughout the three phases of the powered descent from the PDI to the high gate and then the low gate (Fig. 9).

The astronaut noted that the Lunar Module "trajectory was vaguely familiar to me. Its speed, 5500 feet per second down to zero; the altitude range, and the distance, about 260 [nautical] miles; and the time which is about 11 minutes are almost exact duplicate of the [rocket-powered experimental vehicle] X-15 trajectories that I had flown ten years earlier [at the NASA FRC at Edwards]." He then explained the navigation techniques during descent and position checks that relied on the Lunar Module's instrumentation and radar and visual observation of landmarks by the astronauts. Armstrong also confirmed that reaction control thrusters had spent more fuel during the landing as "several hundred unexpected firings occurred." He attributed them "primarily due to a reaction to the fuel sloshing in propellant tanks." (Sloshing refers to the uncontrolled motion of liquids in partially filled vessels, affecting vehicle dynamics.)

The astronaut then talked about several control system alarms during descent. He noted that "the computer was overloaded and sounded alarms. That required a good bit of attention inside the cockpit [of the Lunar Module] and prevented our successfully redesignating [by instructing the computer to change the course to a new landing site] inside the desired landing area. Our trajectory was long and we actually landed to the west of our intended landing area."

Fig. 14. Neil Armstrong speaks at Bovard Auditorium on January 22, 1970. Frame from out-of-focus video [58].

Armstrong went into the details of optimizing and controlling the attitude of the Lunar Module. The limits on modulation of the thrust of the LM's descent engine also brought challenges. Switching to manually-operated control in the last phase of landing was not unexpected. He emphasized that "[t]he automatic system was not seriously considered for the first landing, in as much as it would be unable to guarantee a landing in an acceptable spot… We had, from the start, planned to make a manual attitude control coupled with one of the automatic throttle modes."

Finding a good area to land was difficult. The Lunar Module was approaching, as Armstrong described, an area "surrounded by a field of large rocks … We decided to extend the range to the westward and find a suitable landing area. I thought first that there was [sic] several good landing areas, but they turned out to be too rough. Finally, I selected a small area as being the final touchdown spot." It was a "very soft touchdown." Then, he discussed minute details behind the varying spacecraft's attitude and altitude during the final two minutes of flight.

The remaining fuel in the Lunar Module during descent caused concerns, with warnings sounded by the ground control. The pilot could not use all the propellant in the descent stage for landing and had to preserve some for the case of abort. The astronaut explained that "if we are at low altitude and needed to go back to orbit, we would use the descent engine to establish the initial upward acceleration for about twenty seconds; stage and ignite the ascent engine once we had sufficient clearance from the ground."

Neil Armstrong concluded the article (and presumably the lecture in the Bovard Auditorium) with a photograph, taken by him, of an American flag on the moon with the words about his feelings at the moment: "That gave me the opportunity to take this picture, probably one of the greatest thrills any American has ever had."

Then, as the USC News Service reported,

> The degree, that of Master of Science in Aerospace Engineering, was conferred on the NASA astronaut, the first man to set foot on the moon, by Dr. Z.A. Kaprielian, Dean of USC's School of Engineering, at the conclusion of Armstrong's hour-long presentation in USC's Bovard Auditorium [1].

USC Provost (and future, 1970-1980, USC President) John R. Hubbard also took part in the degree award ceremony (Fig. 15).

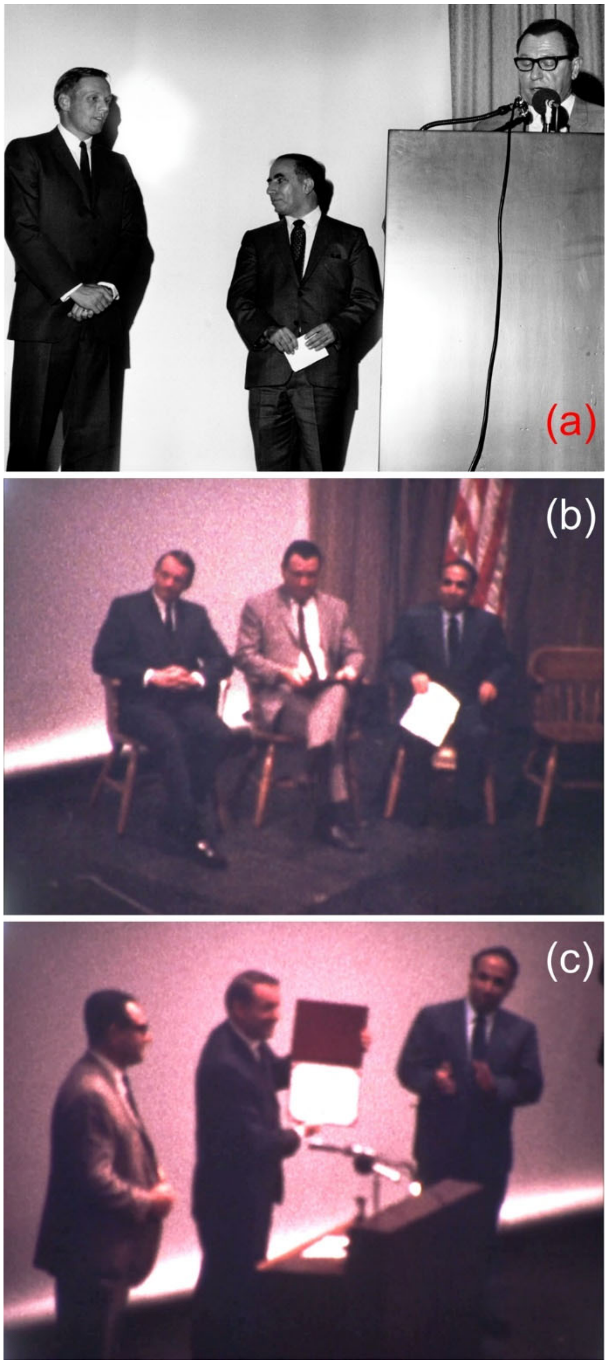


Fig. 15. Presentation of the Master of Science degree at Bovard Auditorium on January 22, 1970.

(a) Left-to-right: Neil A. Armstrong, Dean of Engineering Zohrab A. Kaprielian, Provost (and later USC President, 1970-1980) John R. Hubbard. Photo courtesy of Special Collections, USC Library.

(b) Left-to-right: Neil Armstrong, John Hubbard, Zohrab Kaprielian; (c) Hubbard, Armstrong with his Master's degree diploma, and Kaprielian. Frames (b) and (c) from video [58].

Receiving the diploma, the astronaut "commented that it was 'an earned degree'" [5]. The Associated Press news story, printed in many newspapers across the country, also emphasized that "[i]t wasn't an honorary degree. Armstrong, the first man to set foot on the moon, earned it" (e.g., [60-62]).

Figure 16 shows the diploma of Master of Science in Aerospace Engineering conferred on Neil Alden Armstrong [63]. It is signed by the USC president, chairman of the board of trustees, and the dean of engineering and dated January 28, 1970. The diploma presented at the conclusion of the seminar on January 22 (Fig. 15c) must have been temporary, to be replaced with the signed document a week later.

7. Final note

Neil Armstrong resigned from NASA in 1971 and became a professor in an aerospace engineering department at the University of Cincinnati. Later, his interests turned to corporate life, and he served on boards

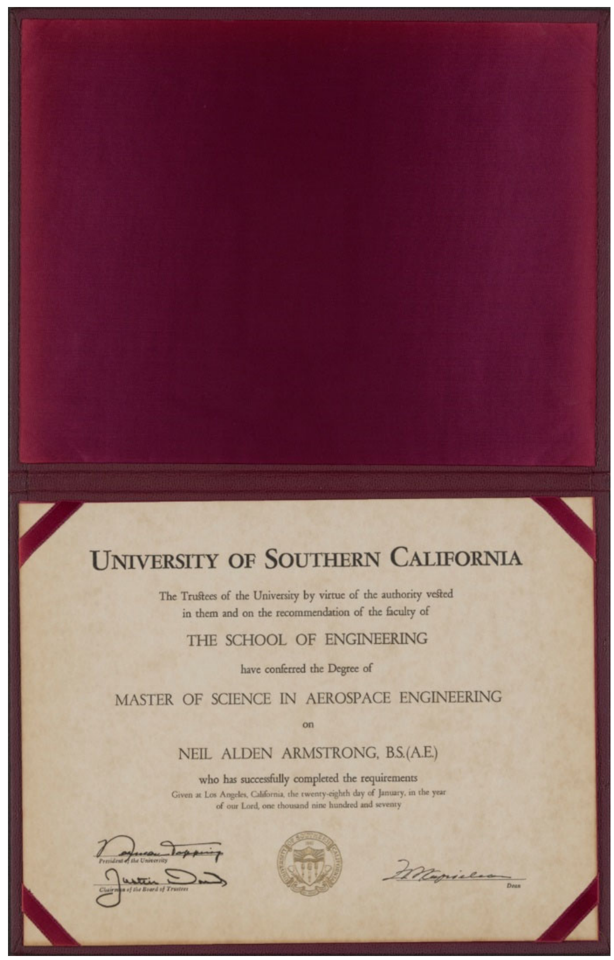


Fig. 16. Diploma of Master of Science in Aerospace Engineering conferred on Neil Alden Armstrong, B.S. (A.E.) [63]. Image courtesy of Purdue University Archives and Special Collections.

of directors of several companies. He was also vice chairman of the commission investigating the tragic loss, in 1986, of the Space Shuttle Challenger [6]. Many years later in 2005, USC proudly honored its Apollo astronaut alumnus with the degree of Doctor of Humane Letters, *honoris causa* [64].

Neil A. Armstrong passed away in 2012. He was 82. Then-president of the American Institute of Aeronautics and Astronautics (AIAA) Mike Griffin summarized that Armstrong "showed us how to be famous with dignity, how to be celebrated without becoming a celebrity, and how to do it with a gracious modesty and the unyielding courage to do [the] right thing as he saw it" [65].

One year later, the university erected a bronze statue of Armstrong (Fig. 17) by sculptor Jon Hair [66] on the Archimedes Plaza, today's Epstein Family Plaza, on the USC campus. The first man to set foot on the moon Neil Armstrong continues to inspire new generations of engineers, especially future rocket scientists in a large space engineering program [9,14,67], at the University of Southern California.

Fig. 17. Bronze statue of Neil Armstrong by sculptor Jon Hair [66] on USC campus. Photograph (2013) by Mike Gruntman.

Ad astra.

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