# History of Rocketry and Astronautics

Proceedings of the Thirty-Sixth History Symposium of the International Academy of Astronautics

Houston, Texas, U.S.A., 2002

Michael L. Ciancone, Volume Editor

Rick W. Sturdevant, Series Editor

## AAS History Series, Volume 33

A Supplement to Advances in the Astronautical Sciences

## IAA History Symposia, Volume 22

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

*First Printing 2010*

ISSN 0730-3564

ISBN 978-0-87703-558-9 (Hard Cover)
ISBN 978-0-87703-559-6 (Soft Cover)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198
Web Site: http://www.univelt.com

Printed and Bound in the U.S.A.

# Chapter 19

# The Apollo Lunar Module: A Retrospective*

**Joseph G. Gavin, Jr.**†

## Abstract

While much has already been written about the Apollo program, the passage of time has sharpened our view of some of the lessons learned. Apollo was the result of a political imperative. The responsibility for the program was given to an open, civilian agency: the National Aeronautics and Space Administration (NASA). The Lunar Orbit Rendezvous (LOR) mission mode was selected after bitter debate.

The Grumman Lunar Module (LM) contract began a year after the effort on the Command/Service Module (C/SM) was started. An incentive fee contract was devised in which the fee would be determined by the contractor's success in meeting vehicle performance, schedule, and cost targets. It became obvious these targets had different priorities: performance came first—LM had to work, schedule came second, and cost came third. Grumman earned little fee until the actual missions began and then did well—the LM performed successfully every mission! A major factor in this success was a novel approach to reliability.

Several challenging "firsts" were faced. LM was the first fly-by-wire, rocket powered Vertical Take-Off and Landing (VTOL) manned vehicle designed to be flown only in space. Some basic truths were revealed: the usually

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* Presented at the Thirty-Sixth History Symposium of the International Academy of Astronautics, 10–19 October 2002, Houston, Texas, U.S.A.

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ignored paradox in any truly novel undertaking, the contractor/agency relationship, the prime contractor/subcontractor relationship, the program/company relationship, and the limitations of human effort. The importance of an unambiguous goal and committed leadership was clearly demonstrated.

## Introduction

I was very fortunate. During the Apollo years, I was the vice president of Grumman Aerospace Corporation responsible for the Lunar Module (LM) contract. Engineering, manufacturing, procurement, and field operations reported to me. I was the Grumman participant in NASA's three-day-before launch meetings that committed the Grumman team with respect to launch readiness. This article is a review of those impressions that have sharpened with the passage of time.

## The Apollo Background

A brief review is necessary to set the stage for what followed. The year 1957 saw U.S. complacency shattered. On 4 October 1957 the Soviet Union orbited *Sputnik*, a technical and propaganda success. On 6 December 1957 Vanguard[1] failed at lift-off and the United States was humiliated and frustrated. It was not until April 1958 that a bill establishing NASA, a remaking of the National Advisory Committee for Aeronautics (NACA), was sent to Congress. In August 1958 President Dwight Eisenhower assigned manned spaceflight to this new civilian agency. Despite continued opposition by the U.S. Air Force, his successors maintained this decision. By November 1959 NASA's Space Task Group had started a study of a circumlunar spacecraft carrying three men.

On 25 May 1961, more than a month after Yuri Gagarin had orbited Earth in Vostok, President John Kennedy committed the United States to a manned lunar venture: "before this decade is out...." It was not until July 1962 that the Lunar Orbit Rendezvous (LOR) mode for the mission was selected over the earlier assumed Earth Orbit Rendezvous (EOR) mode. In hindsight, there were three significant decisions:

1. President Eisenhower gave the manned spaceflight mission to NASA, a civilian, open-to-the-public agency. Later contrast with the closed, classified program of the Soviet Union proved this to be a political and propagandistic master stroke.

2. John Houbolt[2] risked his career to promote LOR. Robert Seamans listened and made sure this idea was seriously evaluated. NASA Administrator James Webb stood firm in the LOR decision.
3. President Kennedy made an extraordinarily bold, long-term commitment in the face of inadequate information and a number of influential naysayers.

## The Lunar Module Background

In November 1962, when Grumman was selected as prime contractor for the Lunar Module, not only were there unknowns, but the state of the technical art was primitive by today's (2002) standards. The surface of the Moon was unknown. One well-regarded expert postulated a layer of impalpable dust, 10 meters thick! The demonstrated reliability of airborne electronic devices was unacceptable. The art of integrated circuits was new and troubled. There seemed to be no way to flight test a Lunar Module before its mission in the conventional aircraft manner. Thus every mission would be the first flight for the Lunar Module involved. But Grumman was committed to building a fly-by-wire, rocket-powered, VTOL machine that had a gross weight that would vary by a factor of 10 during the mission, and that could operate only in space and only in the Moon's gravitational field. This was also the era of engineering computation on IBM mainframes, a situation hard to visualize today.

## Program Management

The technical development of the Lunar Module has been covered to a large extent in References 1, 2, and 3. From the management perspective, the most difficult technical problem that was pervasive throughout the program was weight growth. A staggering number of engineering hours had to be invested to contain this growth to the extent that was accomplished.

Grumman had an excellent reputation for building aircraft. It had made an impressive showing but did not win the Mercury spacecraft contract. It had also gained experience as a team member of the unsuccessful General Electric bid to win the Apollo Command and Service Module (CM/SM) contract. Grumman had gained further experience in working with NASA Goddard Space Flight Center in developing and building the Orbiting Astronomical Observatory (OAO), notable for its demanding attitude control and pointing accuracy.

The Lunar Module contract required a large share of Grumman's resources. The novel requirements for the Lunar Module were acknowledged to be demanding even if underestimated. The estimate of the requirements for the ground service and test equipment was grossly inadequate. The program management team and structure were established with more autonomy than prior Grumman experience. In all fairness, the Lunar Module program did create a rift in the company. There were plenty of "volunteers," even though many of the conservative aircraft traditionalists considered the program risks too great. In launching a new, demanding project, there is always a competition for talent in both numbers and quality. There were also needs for new facilities. Fortunately, the senior management backed the Lunar Module program well. A more detailed account in Reference 3 describes situations in which corporate support was, at times, either too little or too much. But the team that was assembled was built around a cadre of experienced people well known to one another. And the motivation was intense.

Working with the NASA Manned Spacecraft Center (MSC) in Houston (later the Johnson Space Center) proved quite different from working with Grumman's major customer, the U.S. Navy. With the Navy, Grumman's long experience had developed well-defined relationships. MSC was a new center, and a novel form of contract was desired. The selected cost-plus-incentive fee contract was intended to give MSC the control inherent in cost contract while, at the same time, providing incentive for contractor performance. The incentive arrangement was designed to provide the contractor with some margin for tradeoff between performance, schedule, and cost. This became complicated, first, by the fact that the contract did not purchase a defined design,[3] and, second, by the extensive interaction among contractor engineers and NASA engineers. All this led to many vigorous debates that eventually led to a superior design. In the long run this developed into a remarkable collaboration. However, it did become clear, in short order, that the tradeoffs permitted by the contract had disappeared. Performance (and crew safety) had to come first; the second priority was the schedule; and cost came third. The result was that, from 1963 to 1967, little fee was earned; the program was always behind the desired schedule and over cost. Once the missions began, the fee situation improved; the Lunar Module "worked" every time.

One feature of working with MSC deserves special mention; the Apollo astronauts visited Grumman frequently and consistently so that they became known to all hands. The Lunar Modules were built for acquaintances to fly, not for unknown pilots.

The subcontracting tasks for the Lunar Module were, in aggregate, a major undertaking; about half of the program dollars went to subcontractors. In many ways the demands on the subcontractors were greater than previous industry experience. The technical requirements were often novel. For example, the rocket engine for the descent state required a wide throttling range. After development was well underway, both the descent stage engine and the ascent stage engine (a derivative from Agena) were faced with proving combustion stability. This doubled the development time.

Grumman designed and built aircraft during the 1950s that featured complex electronic systems. All of this equipment depended on air cooling. For the Lunar Module, there was a much higher premium on equipment weight, and heat had to be removed by cold rail conduction. As mentioned earlier, new levels of reliability were required. The procedures for managing the subcontractors became at once more formal and more intimate. As the mission years approached, Grumman's president involved subcontractor presidents in periodic schedule review meetings. While the subcontractors were Grumman's contractual responsibility, NASA demanded and was given complete visibility into contractor operations without infringing on the formal line of contractual direction. Despite initial misgivings, this worked effectively.

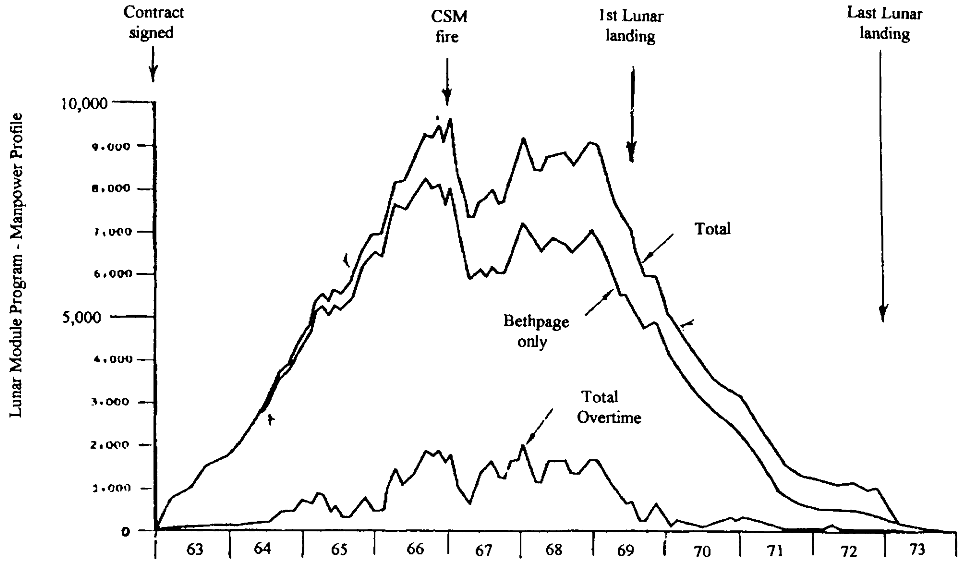



**Figure 1**

Figure 1 summarizes the Grumman staffing for the Lunar Module program. At the peak, there were about 7,500 people involved; slightly more than half were engineers. The valley near the peak resulted from the campaign to review, modify, and test to eliminate sources of combustion in the cabin, a result of the tragic fire in the Command Module at Cape Kennedy. In this program delay, certain fixed costs continued; every effort was made to control the variable costs.

This chart shows, during program buildup, some interesting manpower acquisition rates, which, in hindsight, appear to be practical maximums. In adding manpower Grumman was dealing with people, not a commodity, trying to add talent at the right place at the right time. Adding 250 people per month was the best the contractor could do. Figure 1 shows the manpower at the program central site, Bethpage, New York, as distinguished from the other locations—Cape Kennedy (Florida), Houston (Texas), and White Sands (New Mexico). This chart also shows program overtime. Grumman was often under criticism for the amount of overtime work. But from my personal experience, I think we had it just about optimized. What the overtime plot does not reveal is the extraordinary overtime and effort invested by leaders and supervisors. Understanding and support by their families were critical and remained critical for years.

The program organization chart, Figure 2, is a "snapshot" from 1966. The purpose in showing it is not to point out its merit or to identify individuals. The real point is that the chart does not and never did explain how the organization worked. The Grumman Lunar Module program organization operated with little "vertical" distance among the leaders and doers; communication routinely crossed all chart boundaries, vertically, horizontally, and diagonally. And the organization evolved with time to meet the demands of the program. The practice that proved to be effective in achieving coordinated activity was the daily morning stand-up meeting, from 7:30 to 8:00 a.m., of 20 to 30 key people. This had to be coordinated with telephone conferences with the field sites, Cape Kennedy, Houston, and White Sands.

## Results and Lessons Learned

The most important result was that the Lunar Module operated successfully every mission. A major contribution to this was that subcontractors could and did accomplish a number of challenging firsts: the solid state rendezvous radar, the throttleable descent stage rocket engine, and the strap-down guidance system that provided backup for the primary navigation/guidance system procured by NASA from the Massachusetts Institute of Technology Draper Laboratory.

The most important lesson learned was that high reliability can be attained. The basic assumption was that: *there is no such thing as a random failure.* If there is a failure, it should be possible to find the cause and fix the problem. The Lunar Module could not be flight tested in the conventional fashion. Grumman, therefore, relied on an extensive, evolving ground test program. Testing occurred at many levels: brass-board, prototypes, qualification, delivery acceptance, components, subsystems, systems, and complete vehicles. Complete vehicles were tested before delivery from Bethpage, New York, and completely retested after delivery by a Grumman workforce at the launch site.

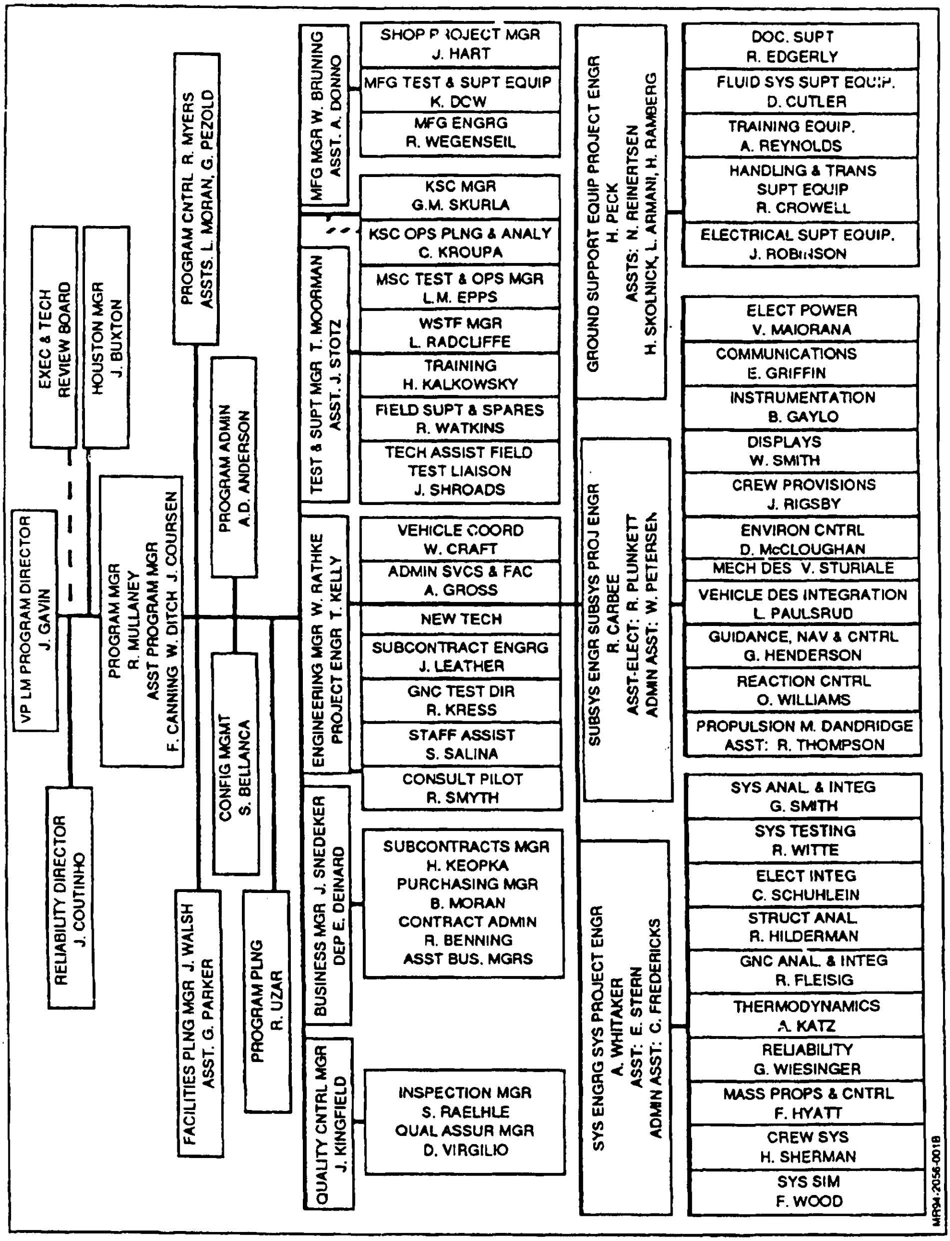


Fig. 1 Grumman LM Program Organization Chart, January 1966

**Figure 2**

A second lesson learned was that Grumman had its priorities right: first, performance and safety; second, schedule; and third, cost.

A third lesson appears to be a basic truth: *In a truly novel undertaking, it is impossible to predict accurately the schedule or the cost.* NASA Administrator James Webb deserves great credit for telling congressional committees at the outset of the program that his estimated cost could well increase three-fold.

A fourth lesson was that Apollo demonstrated the advantages deriving from bold leadership (President Kennedy), long-term vision and commitment, and an easily understood, unambiguous goal. The competition with the Soviet Union seemed real, even to those not privy to classified intelligence.

A fifth lesson was simply to *take nothing for granted.* A junior engineer uncovered a significant fault in the standard miniature toggle switch used for years in scores of aircraft.

In closing, it is noticeable that I have mentioned few people by name. There are so many who deserve recognition. But, if I start an extensive list, where do I fairly stop? The Lunar Module was a team effort: NASA, Grumman, and its subcontractors. None of us will forget being members of that team.

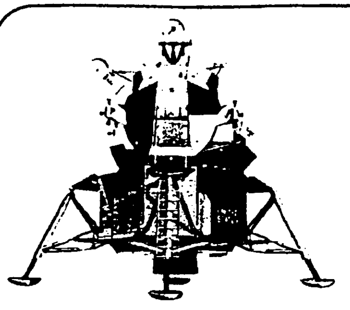
Figure 3 is provided for the information of those whose memory has dimmed and for those who are too young to remember.

Figures 1, 2, and 3 are adapted from Apollo memorabilia in the possession of the author.

**An Abbreviated Time Line**

| Year | Date | Event |
|---|---|---|
| 1957 | 4 Oct | *Sputnik* orbited. |
| | 6 Dec | *Vanguard* failed liftoff. |
| 1958 | 31 Jan | *Explorer* orbited. Van Allen Belt detected. |
| | 26 Mar | Killian and the President's Science Advisory Council consider plans for space. |
| | 2 Apr | A bill to create NASA was sent to Congress. |
| | Jun | AF starts F-1 development at Rocketdyne |
| | 28 Jul | Eisenhower signs NASA act. |
| | Aug | Eisenhower assigns manned space to NASA. |
| | Oct | Stever committee outlines space plans. |
| | Nov | Space Task Group (STG) formed by NASA. |
| | Dec | Jet Propulsion Laboratory transferred to NASA. |
| 1959 | Jan | House Select Committee on Astronautics hears Wernher von Braun predict missions to Moon and landing on Moon. |
| | Mar | First firing of F-1 engine. |
| | May | Goett committee recommends lunar landing (two years before Kennedy approval). |

| | | |
|---|---|---|
| | Oct | Army Ballistic Missile Agency transferred to NASA. |
| | Nov | Gilruth (STG) starts study of three-man circumlunar spacecraft. |
| 1960 | Jan | Top priority given to Saturn booster. |
| | Feb | NASA 10-year plan given to Congress—included circumlunar mission and space station |
| | May | NASA Langley Research Center/STG conference on rendezvous and docking. |
| | Jul | House committee tells NASA to speed up. |
| | 28–29 Jul | Apollo industry meeting. |
| | 13 Sep | Request for proposals—six-month studies based on STG guidelines. |
| 1961 | Jan | Space Exploration Program Council reviews status—STG studies LOR, EOR, and direct modes. |
| | Feb | MIT picked for six-month study of navigation and guidance. |
| | 12 Apr | *Vostok 1* and Yuri Gagarin orbit Earth. |
| | May | Contractors submit six-month study results (see 13 Sep 1960). |
| | 5 May | Shepard rides Redstone rocket on suborbital flight. |
| | 25 May | Kennedy commits U.S. to sending men to the moon "before this decade is out." |
| | Jul | Twelve companies invited to bid Apollo (still based on direct or EOR). |
| | Sep | Houston selected as site for Manned Space Center (MSC). |
| | Oct | John Houbolt submits LOR study. |
| | Nov | North American Aviation (later Rockwell) selected to build CM and SM Modules |
| 1962 | 20 Feb | Glenn makes three orbits in *Mercury-Atlas 6* |
| | Feb–Jun | NASA review of EOR, LOR, and direct modes. Von Braun agrees to LOR on 7 Jun. |
| | Jul | LOR selected officially—11 firms invited to bid. |
| | Nov | Grumman selected to design and build LM. |
| 1963 | Jan | LM contract signed. |
| | May | Last Mercury mission. |
| | Sep | George E. Mueller named Associate Administrator of NASA for manned spaceflight. |
| 1965 | Mar | First Gemini mission. |
| 1966 | Mar | Gemini demonstrates rendezvous and docking with Agena. |

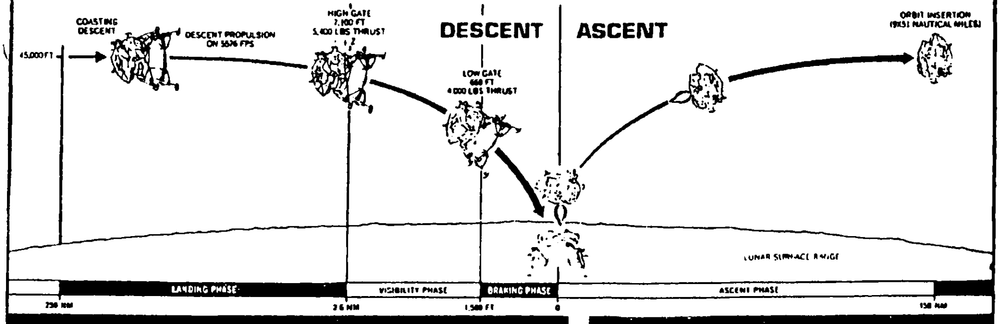


# APOLLO LUNAR MODULE

**PRIMARY OBJECTIVES:**
Manned lunar landing and return within the decade (1960's); scientific exploration of the moon.

**PROGRAM MANAGEMENT:**
National Aeronautics and Space Administration/ Johnson Space Center

**PRIME CONTRACTOR:**
Grumman Aerospace Corporation, Bethpage, N.Y.




## MISSION SUMMARY

| APOLLO | LM | LAUNCH (E.S.T.) | LUNAR TOUCH-DOWN | LUNAR STAYTIME (HRS:MIN) | SURFACE EVA'S (HRS:MIN) | COMMANDER CSM PILOT LM PILOT | PURPOSE |
|---|---|---|---|---|---|---|---|
| 4 | LTA-10R | 9 NOV 67 07:00:01 | — | — | — | UNMANNED | LM TEST ARTICLE, LAUNCH & BOOST ENVIRONMENT |
| 5 | LM-1 | 22 JAN 68 17:48:08 | — | — | — | UNMANNED | UNMANNED PRO-PULSION SYSTEM VERIFICATION |
| 6 | LTA-2R | 4 APR 68 07:00:00 | — | — | — | UNMANNED | LM TEST ARTICLE, LAUNCH & BOOST ENVIRONMENT |
| 9 | LM-3 "SPIDER" | 3 MAR 69 11:00:00 | — | — | — | JAMES A. McDIVITT DAVID R. SCOTT RUSSELL L. SCHWEIKART | 1ST MANNED LM FLIGHT, EARTH ORBIT |
| 10 | LM-4 "SNOOPY" | 18 MAY 69 11:49:00 | — | — | — | THOMAS P. STAFFORD JOHN W. YOUNG EUGENE A. CERNAN | MANNED, LUNAR ORBIT, LOW PASS OVER LUNAR SURFACE |
| 11 | LM-5 EAGLE | 16 JUL 69 08:32:00 | 20 JUL 69 15:17:40 1ST LUNAR STEP 21:56:15 | 21:36 | 2:31 | NEIL A. ARMSTRONG MICHAEL COLLINS EDWIN E. ALDRIN | 1ST LUNAR LANDING |
| 12 | LM-6 INTREPID | 14 NOV 69 11:22:00 | 20 NOV 69 01:54:36 | 31:31 | 3:56 3:49 | CHARLES CONRAD, JR. RICHARD F. GORDON ALAN L. BEAN | 2ND LUNAR LANDING Surveyor |
| 13 | LM-7 AQUARIUS | 11 APR 70 14:13:00 | — | — | — | JAMES A. LOVELL JOHN L. SWIGERT FRED W. HAISE, JR. | ABORTED IN TRANS-LUNAR COAST DUE TO LOSS OF SERV-ICE MODULE CRYO-GENIC OXYGEN |
| 14 | LM-8 ANTARES | 31 JAN 71 16:03:02 | 5 FEB 71 04:18:11 | 33:31 | 4:48 4:35 | ALAN SHEPARD, JR. STUART A. ROOSA EDGAR D. MITCHELL | 3RD LUNAR LANDING |
| 15 | LM-10 FALCON | 26 JUL 71 09:34:00 | 30 JUL 71 15:16:29 | 66:55 | 6:33 7:12 4:50 | DAVID R. SCOTT ALFRED J. WORDEN JAMES B. IRWIN | 4TH LUNAR LANDING |
| 16 | LM-11 ORION | 16 APR 72 12:54:00 | 20 APR 72 21:36:29 | 71:02 | 7:11 7:23 5:40 | JOHN W. YOUNG THOMAS K. MATTINGLY, II CHARLES M. DUKE, JR. | 5TH LUNAR LANDING |
| 17 | LM-12 CHALLENGER | 7 DEC 72 00:33:00 | 11 DEC 72 14:54:57 | 75:00 | 7:12 7:37 7:15 | EUGENE A. CERNAN RONALD EVANS HARRISON SCHMITT | 6TH LUNAR LANDING |

## LUNAR LANDING SITES

| APOLLO MISSION | SITE | COORDINATES | SAMPLES OBTAINED |
|---|---|---|---|
| 11 | SEA OF TRANQUILITY | 0°41'15"N 23°26'00"E | 48.5 POUNDS |
| 12 | OCEAN OF STORMS | 3°12'S 23°24'W | 74.7 POUNDS (PLUS PARTS FROM SURVEYOR 3) |
| 14 | FRA MAURO | 3°40'24"S 17°27'55"W | 96 POUNDS |
| 15 | RIMA HADLEY | 26°6'4"N 3°39'10"E | 170 POUNDS |
| 16 | DESCARTES | 8°59'29"S 15°30'52"E | 213 POUNDS |
| 17 | TAURUS LITTROW | 20°9'41"N 30°45'26"E | 243 POUNDS |

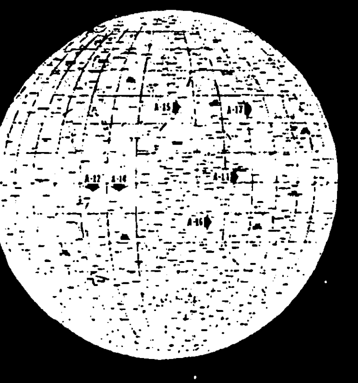
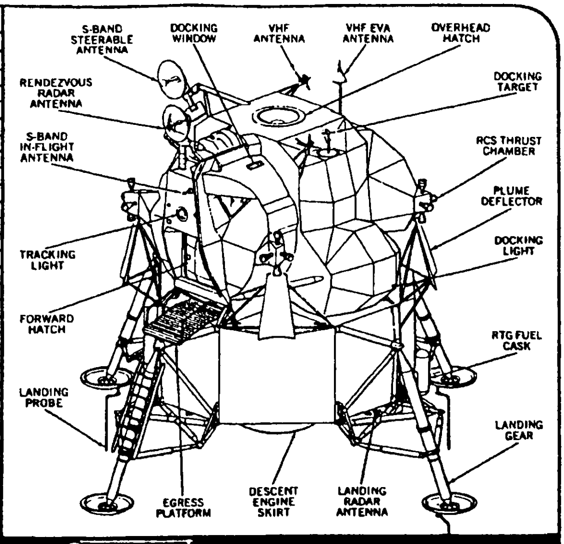
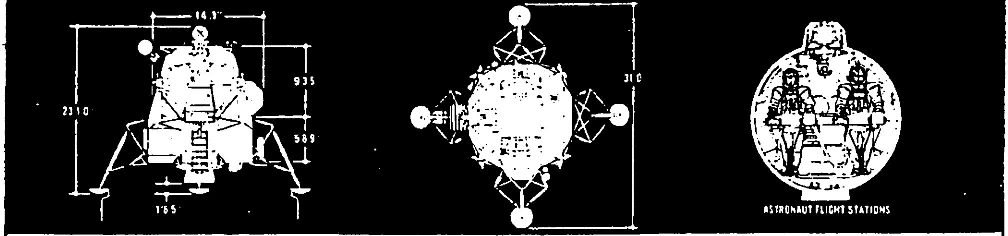



Figure 3

## LUNAR SURFACE EXPERIMENTS & EQUIPMENT

| | APOLLO MISSION | | | | | |
|---|---|---|---|---|---|---|
| | 11 | 12 | 14 | 15 | 16 | 17 |
| PASSIVE SEISMIC | ● | ● | ● | ● | ● | ● |
| ACTIVE SEISMIC | | | ● | | ● | |
| LUNAR SURFACE MAGNETOMETER | | ● | | ● | ● | |
| SOLAR WIND SPECTROMETER | | ● | | ● | | |
| SUPRATHERMAL ION DETECTOR | | ● | ● | ● | | |
| HEAT FLOW | | | | ● | ● | ● |
| CHARGED PARTICLE LUNAR ENVIRONMENT | | | ● | | | |
| COLD CATHODE GAGE | | ● | ● | ● | | |
| LUNAR FIELD GEOLOGY | ● | ● | ● | ● | ● | ● |
| LASER RANGING RETRO REFLECTOR | ● | | ● | ● | | |
| SOLAR WIND COMPOSITION | ● | ● | ● | ● | ● | |
| COSMIC RAY DETECTOR (SHEETS) | | | | | ● | ● |
| PORTABLE MAGNETOMETER | | | ● | | ● | |
| TRAVERSE GRAVIMETER | | | | | | ● |
| LUNAR SOIL MECHANICS | ● | ● | ● | ● | ● | ● |
| FAR ULTRAVIOLET CAMERA/SPECTROSCOPE | | | | | ● | |
| LUNAR EJECT AND METEORITES | | | | | | ● |
| LUNAR SEISMIC PROFILING | | | | | | ● |
| SURFACE ELECTRICAL PROPERTIES | | | | | | ● |
| LUNAR ATMOSPHERIC COMPOSITION | | | | | | ● |
| LUNAR SURFACE GRAVIMETER | | | | | | ● |
| LUNAR NEUTRON PROBE | | | | | | ● |
| LUNAR DUST DETECTOR | | ● | ● | | | |
| RADIOISOTOPE THERMOELECTRIC GENERATOR | ● | ● | ● | ● | ● | ● |
| B&W TV | ● | | | | | |
| COLOR TV | | ● | ● | ● | ● | ● |
| PHOTOGRAPHIC CAMERAS | ● | ● | ● | ● | ● | ● |
| MOBILE EQUIPMENT TRANSPORTER | | | ● | | | |
| LUNAR ROVING VEHICLE | | | | ● | ● | ● |

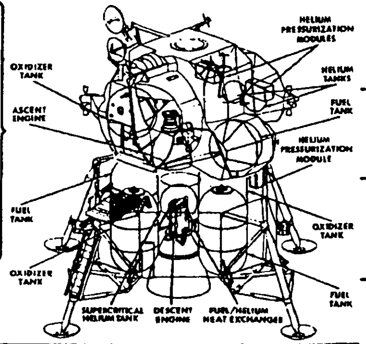



## PROPULSION

DESCENT ENGINE
- RESTARTABLE
- NOMINAL THRUST (FULL THROTTLE)—9900 #
- MINIMUM THRUST (LOW STOP) —1280 #
- PRESSURE FED, HYPERGOLIC, LIQUID PROPELLANT
  - —OXIDIZER $N_2O_4$
  - —FUEL 50/50 MIX $N_2H_4$ AND UDMH
  - —O/F RATIO 1.6:1
- 6° GIMBALLING FOR C.G. TRIMMING
- APPROXIMATE WEIGHT 348 #
- OVERALL LENGTH 95"
- NOZZLE EXIT DIAMETER 63"

ASCENT ENGINE
- RESTARTABLE
- PRESSURE FED, HYPERGOLIC, LIQUID PROPELLANT
  - —OXIDIZER $N_2O_4$
  - —FUEL 50/50 MIX $N_2H_4$ AND UDMH
  - —O/F RATIO 1.6:1
- NO GIMBALLING
- APPROXIMATE WEIGHT 200 #
- OVERALL LENGTH 47"
- NOZZLE EXIT DIAMETER 31"




## INSTRUMENTATION

- MONITOR SUBSYSTEM STATUS
- CAUTION AND WARNING INDICATIONS
- IN-FLIGHT AND LUNAR SURFACE CHECKOUT
- PRECISION TIMING
- VOICE AND DATA STORAGE
- TELEMETRY
  - —277 ANALOG CHANNELS
  - — 77 DIGITAL CHANNELS

## EXPLOSIVE DEVICES

- LANDING GEAR DEPLOYMENT
- PROPELLANT TANK PRESSURIZATION AND VENTING
- INTERSTAGE CONNECTORS
- INTERSTAGE UMBILICAL SEVERANCE
- ELECTRICAL CIRCUIT INTERRUPTION (UMBILICAL)

## LANDING GEAR

- IMPACT ATTENUATION, PRIMARY STRUTS
  - —32" CRUSHABLE HONEYCOMB CARTRIDGE
  - —MAX 10 FPS VERTICALLY; 7 FPS VERTICALLY AND 4 FPS HORIZONTALLY
- DEPLOYED PRIOR TO LM/CSM SEPARATION
- FOOT PADS—37" DIAMETER
- LUNAR CONTACT SENSING PROBES—5 FT. LONG

## REACTION CONTROL SYSTEM

- PROVIDES ATTITUDE AND TRANSLATION CONTROL
- 4 CLUSTERS, 4 ENGINES EACH
- TWO REDUNDANT INDEPENDENT SYSTEMS
- NOMINAL ENGINE THRUST 100 #
- PRESSURE FED FROM POSITIVE EXPULSION BLADDER TANKS
- HYPERGOLIC LIQUID PROPELLANTS
  - —OXIDIZER $N_2O_4$
  - —FUEL 50/50 MIX $N_2H_4$ AND UDMH
  - —O/F RATIO 2:1
- APPROXIMATE ENGINE WEIGHT 5.25 POUNDS
- OVERALL LENGTH 13.5"
- NOZZLE EXIT DIAMETER 5.75"

## COMMUNICATIONS

- LM-EARTH/LM-CSM/LM-EVA
- VOICE
- TELEVISION
- RANGING
- TELEMETRY
- COMPUTER UPLINK COMMAND
- EMERGENCY KEY
- ANTENNAS
  - —S-BAND, STEERABLE 26" PARABOLIC REFLECTOR
  - —S-BAND OMNI (2)
  - —VHF OMNI (2)
  - —VHF OMNI EVA

## TYPICAL WEIGHT (LM-10 THROUGH 12 CONFIGURATION)—POUNDS

| | ASCENT STAGE | DESCENT STAGE | TOTAL |
|---|---|---|---|
| STRUCTURE | 1385 | 1470 | 2855 |
| STABILIZATION AND CONTROL | 79 | 13 | 92 |
| NAVIGATION AND GUIDANCE | 343 | 44 | 387 |
| CREW PROVISIONS | 146 | 234 | 380 |
| ENVIRONMENTAL CONTROL | 297 | 206 | 503 |
| INSTRUMENTATION | 132 | 8 | 140 |
| ELECTRICAL POWER SUPPLY | 737 | 787 | 1524 |
| PROPULSION | 489 | 1069 | 1558 |
| REACTION CONTROL | 242 | 0 | 242 |
| COMMUNICATIONS | 114 | 0 | 114 |
| CONTROLS AND DISPLAYS | 232 | 3 | 235 |
| EXPLOSIVE DEVICES | 29 | 26 | 55 |
| LANDING GEAR | 0 | 406 | 406 |
| LUNAR EXPERIMENTS AND EQUIPMENT | 406 | 1212 | 1618 |
| LIQUIDS & GASES (EXCLUDING PROP) | 136 | 555 | 691 |
| INERT WEIGHT | 4747 | 6133 | 10880 |
| PROPELLANTS | | | |
| MAIN | 5230 | 19507 | 24737 |
| RCS | 605 | 0 | 605 |
| TOTAL WEIGHT—POUNDS | 10582 | 25640 | 36222 |
| —(KILOGRAMS) | (4804) | (11641) | (16448) |

## ELECTRICAL POWER SYSTEM

- BATTERIES PROVIDE PRIMARY POWER
- SILVER ZINC PLATES, 20 CELLS
- POTASSIUM HYDROXIDE ELECTROLYTE
- 2 ASCENT STAGE BATTERIES, 296 A-H EACH
- 4 DESCENT STAGE BATTERIES, 400 A-H EACH (LM-10 TO 12, 5 BATTERIES, 415 A-H EACH)
- NOMINAL VOLTAGE—30V (28V BUS VOLTAGE)
- TWO SOLID STATE INVERTERS, 115V, 400 Hz, SINGLE PHASE

## GUIDANCE, NAVIGATION AND CONTROL

- INERTIAL GUIDANCE, OPTICAL AND RADAR NAVIGATION
- PRIMARY GUIDANCE COMPUTER
  - —FIXED AND ERASABLE MEMORY (36,864 WORDS, 2,048 WORDS)
- ABORT GUIDANCE COMPUTER
  - —FIXED AND ERASABLE MEMORY (2,048 WORDS EACH)
- LANDING RADAR
  - —VELOCITY, FROM ALTITUDE OF 24,000'
  - —ALTITUDE, 10 TO 40,000'
- RENDEZVOUS RADAR
  - —LM/CSM RANGE AND RANGE RATE
  - —80 FEET TO 400 N.MI.; ±4900 FPS

## ENVIRONMENTAL CONTROL SYSTEM

- CONTROLLED ENVIRONMENT FOR SHIRT SLEEVE OR PRESSURE SUIT OPERATION
- ATMOSPHERE—100% OXYGEN, 4.8 PSIA, 75°F
- PRESSURIZED VOLUME 235 FT³
- WATER FOR DRINKING, FOOD PREP, WASTE HEAT REJECTION SUBLIMATORS, FIRE EXTINGUISHING
- ELECTRONIC EQUIPMENT THERMAL CONTROL
- COOLANT—35% ETHYLENE GLYCOL, 65% WATER
- RECHARGE PORTABLE LIFE SUPPORT SYSTEM WITH OXYGEN AND WATER

Figure 3

# References

## Notes

[1] *Vanguard* was the first attempt by the United States to put a satellite into orbit. It failed.

[2] John Houbolt was an analyst at NASA Langley Research Center. He recognized that use of a separate spacecraft to descend to the lunar surface and return to lunar orbit would save carrying the weight of the Apollo spacecraft, and its fuel, for returning to Earth, to the lunar surface and back to lunar orbit. This mode, called LOR, made possible a reduction in Earth launch gross weight.

[3] The NASA request for bid tested the bidder's knowledge and understanding. It did not intend to produce a design of the spacecraft.

## Articles and Books


[1] Joseph G. Gavin, Jr., "Engineering Development of the Apollo Lunar Module," IAA-90-633, in *History of Rocketry and Astronautics*, J. D. Hunley, Editor, (San Diego: Published for the American Astronautical Society by Univelt, Inc., 1997), AAS History Series, Vol. 19, 1997, pp. 225–236 (paper presented at the 41st International Astronautical Congress, Dresden, Germany, October, 1990).

[2] Ross Fleisig, "The First Manned Lunar Landing Spacecraft—Its Design, Manufacture, Ground Test, and Mission," International Space Development Conference, 1996.

[3] Thomas J. Kelley, *Moon Lander* (Washington, DC: Smithsonian Institution Press, 2001).

[4] Roger E. Bilstein, *Orders of Magnitude—A History of the NACA and NASA 1915–1990,* NASA SP-4406, chapters 3 and 4, 1989.

[5] Walter A. McDougall, *...The Heavens and the Earth—A Political History of the Space Age* (Baltimore: John Hopkins University Press, 1986), pp. 302–304.

[6] John M. Logsdon, *The Decision to Go to the Moon—Project Apollo and the National Interest* (Boston: MIT Press, 1970), chapters 1 and 2.

[7] Courtney G. Brooks. James M. Grimwood and Loyd S. Swenson, Jr., *Chariots for Apollo—A History of Manned Lunar Spacecraft,* NASA SP-4205, 1979.

[8] Michael Collins, *Liftoff—Story of America's Adventure in Space* (New York: Grove Press, 1988).

[9] Marsha Freeman, *How We Got to the Moon—The Story of the German Space Pioneers* (Washington, D.C., 21st Century, 1993), pp. 254–255.

[10] William D. Compton, *Where No Man Has Gone Before—A History of the Apollo Lunar Exploration Missions,* NASA SP-4214, 1989.

[11] Wernher von Braun, *First Men to the Moon* [derived from *This Week* magazine serial] (New York: Holt, Rinehart, and Winston, 1958).

[12] Mike Gray, *Angle of Attack—Harrison Storms and the Race to the Moon* (New York: Norton, 1992), pp. 124–130.