8

Viking Lander: Building a Complex Spacecraft

The Viking lander represented a careful melding of the demands imposed by the scientific mission and the high degree of reliability required of the spacecraft subsystems. Weight and volume considerations affected the size of each subsystem. After the Voyager program with plans for an 11 500-kilogram spacecraft was abandoned in 1967, a follow-on study concluded that a spacecraft weighing 3700 kilograms could be transported to Mars by a Titan-Centaur-class launch vehicle. The lander and its flight capsule would account for more than a third of this weight (1195 kilograms). At the start of the mission, the orbiter and lander would be housed in a 4.3-meter shroud atop the Titan-Centaur. The landed spacecraft would be 3 meters at its widest point and 2 meters tall from the footpads to the tip of the large disk S-band high-gain antenna. While weight and volume limitations helped to shape the Viking lander, data about Martian atmospheric pressure obtained during the Mariner 69 mission were also influential.

Mariner 69's occultation experiment indicated that the atmospheric pressure at the surface of Mars ranged from 4 to 20 millibars, rather than 80 millibars as estimated earlier. This information had a definite impact on the aerodynamic shape of the Mars entry vehicle being designed, since weight and diameter would influence the craft's braking ability. Langley engineers had determined that aerodynamic braking was the only practical method for slowing down a lander as large as Viking for a soft touchdown. The entry vehicle would have a diameter of 3.5 meters, an acceptable ballistic coefficient that would help ensure Viking's safe landing on Mars.

Since electrical power requirements were thought of in terms of the weight that the power apparatus would add to the spacecraft, the design engineers sought creative means for getting maximum results from a minimum amount of power. Low-power integrated circuits were used extensively both to conserve energy and to keep the package small. In addition, power switching techniques were devised to reduce energy requirements. As John D. Goodlette, deputy project director at Martin Marietta, noted, the design rule was "turn off unneeded consumers."[1] When power had to be used, the equipment was designed with multiple power levels, or states, so that only the minimum power required to achieve the immediate function would be consumed.

Once separated from the orbiter with its 700-watt solar panels, only 70 watts of radioisotope-thermoelectric-generated power would support the long mission on the surface. Because of this limitation on landed power, the radio transmitters could be used only sparingly, a factor that in turn controlled the amount of data that could be sent to Earth.

The Viking lander was a highly automated spacecraft for a number of reasons. Since there was only a 20-minute one-way communications opportunity between Earth and Mars during the landings, control of the lander from Earth from separation to touchdown was not practical. The entire function of navigation—from obtaining an inertial reference to locating a local surface reference—had to be accomplished by the onboard computer. After landing, the spacecraft would be out of direct communication with Earth for about half of each Martian day. And because of electrical power limits, the communications between lander and mission control in California would amount to only a short time each day. The lander, therefore, had to be capable of carrying out its mission unattended by Earth. Mission specialists could send the lander new assignments or modify preprogrammed ones, but for the most part the craft was on its own as it did its day-to-day work.

LANDER MISSION PROFILE

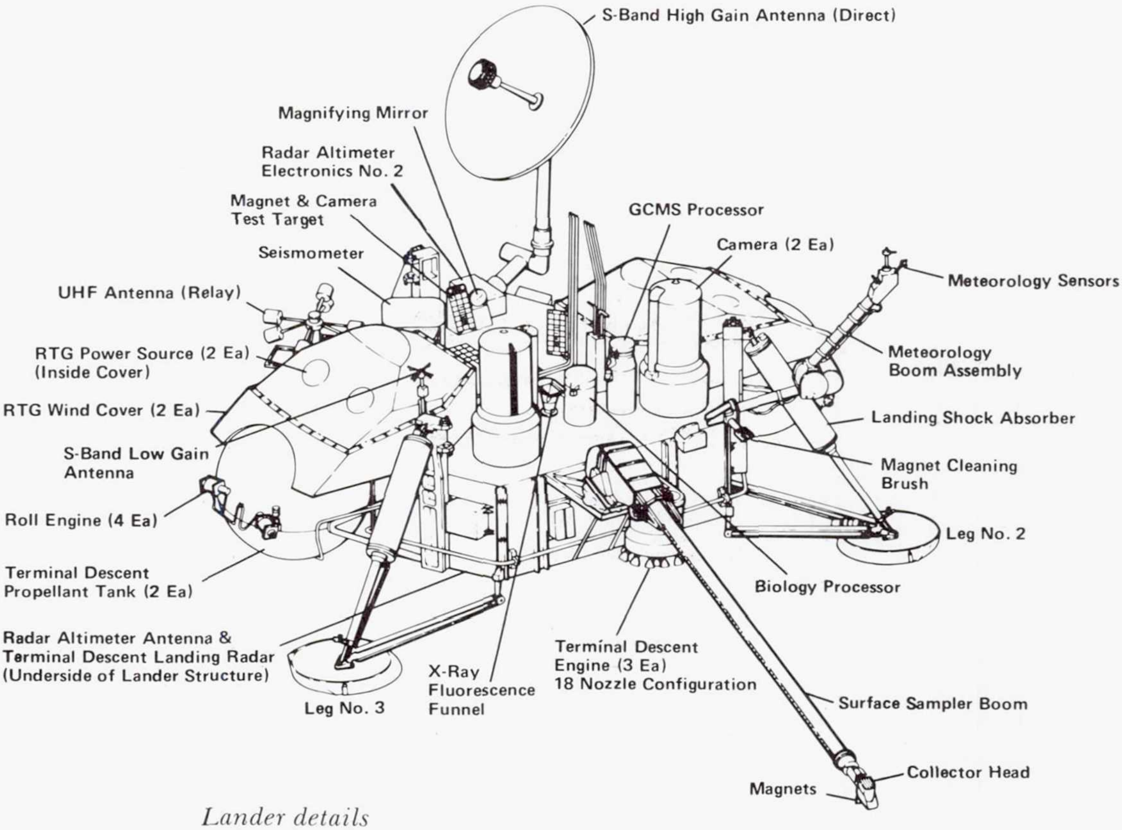
Jim Martin and his colleagues hoped the lander mission would follow the ideal schedule: Final prelaunch activities begin 56 days before launch with the terminal sterilization of the entire lander system within its bioshield. The craft must survive a 40-hour sterilization cycle, during which temperatures will reach a maximum of 112°C. During this preparation period, the lander is functionally passive except for its two mass-spectrometer ion pumps. Following a checkout, the propellants, pressurants, and flight software are loaded, and the lander is mated with the orbiter. After the first prelaunch checkout, initiated by the orbiter under local control of the guidance computer, the spacecraft is encapsulated, transported to the launch pad, and mated with the launch vehicle, followed by the second and final prelaunch checkout. All major communication with the lander before separation is accomplished through the orbiter communications link.

During the launch and boost phases, only the power and pyro controllers, the data acquisition system, and the tape recorder are active. After the spacecraft separates from the launch vehicle, the orbiter commands the lander computer to separate the bioshield cap and begins the lander cruise state. During cruise, the lander is largely passive. Only the data acquisition system, ion pumps, and thermostatically controlled heaters on propulsion equipment, the biology instrument, and the inertial reference unit are powered. The heaters prevent the freezing of propellants and biology nutrients. Heat also controls viscosity of the gyro flotation fluids. The primary housekeeping chore during the cruise phase is monitoring the thermal balance and the equipment when it is powered.

The tape recorder is activated about every 15 days to ensure its later performance. An update to the computer requires the activation of the computer and the command detectors and decoders. The portion of the computer memory used during prelaunch checkout procedures is modified during the cruise so that it can perform other operations during the mission. The gas chromatograph-mass spectrometer requires a venting-and-bakeout sequence to rid the analyzer section of absorbed gases. For bakeout, with its high peak-power demand, the lander batteries are first conditioned and charged using orbiter power; the computer, detectors, and decoders are powered up; and a six-hour bakeout sequence is commanded from Earth, followed by a week-long cooldown period to reestablish the proper thermal equilibrium. About five such cycles in two groups are required, each accompanied by mass-spectrometer readings, which are analyzed to determine the performance and health of the instrument. After each activity, the lander is powered back to cruise state and, after the final bakeout of the gas chromatograph-mass spectrometer, a cruise check is made and the batteries discharged. About 52 days before reaching Mars, the final conditioning and charge cycle is undertaken for the lander batteries.

Before the lander separates from the orbiter, a four-and-one-half-hour checkout verifies the lander systems' health. A group of orbit commands precedes this last check, during which local control is assumed by the lander computer and power is transferred from the orbiter to the lander. At checkout completion, the computer memory is read out, the batteries are recharged on internal power, and the computer reverts to standby. After cruise checkout, power is transferred back to the orbiter, which assumes control. The next events prepare the lander for its release. For eight hours, the radioisotope thermoelectric generators recharge the lander's batteries.

Twelve hours before separation—318 days into the mission—an orbiter commander turns on lander command detectors and decoders, placing the lander under the control of its own computer. Mission control commands update descent information and carry out checkout decisions made by the operations team. The commands are directed to the lander via its S-band receivers. A memory readout follows update, and the lander assumes a standby mode. This sequence is repeated three and one-half hours before separation. About two and one-half hours before separation, direct orbiter command starts the separation sequence. Final preparations begin with warming up the inertial reference unit to its operating temperature. At 37 minutes before separation, a final "go" is uplinked from Earth and received by the lander 15 minutes before separation. At this point, valve-drive amplifiers, pyrotechnic controllers, entry thermal control, and relay communications link are activated. A final check verifies that the inertial reference unit has transferred to the entry condition and that all systems are go. If these checks fail, the lander is powered down and transferred to the update mode. If the checks pass, the telemetry system is



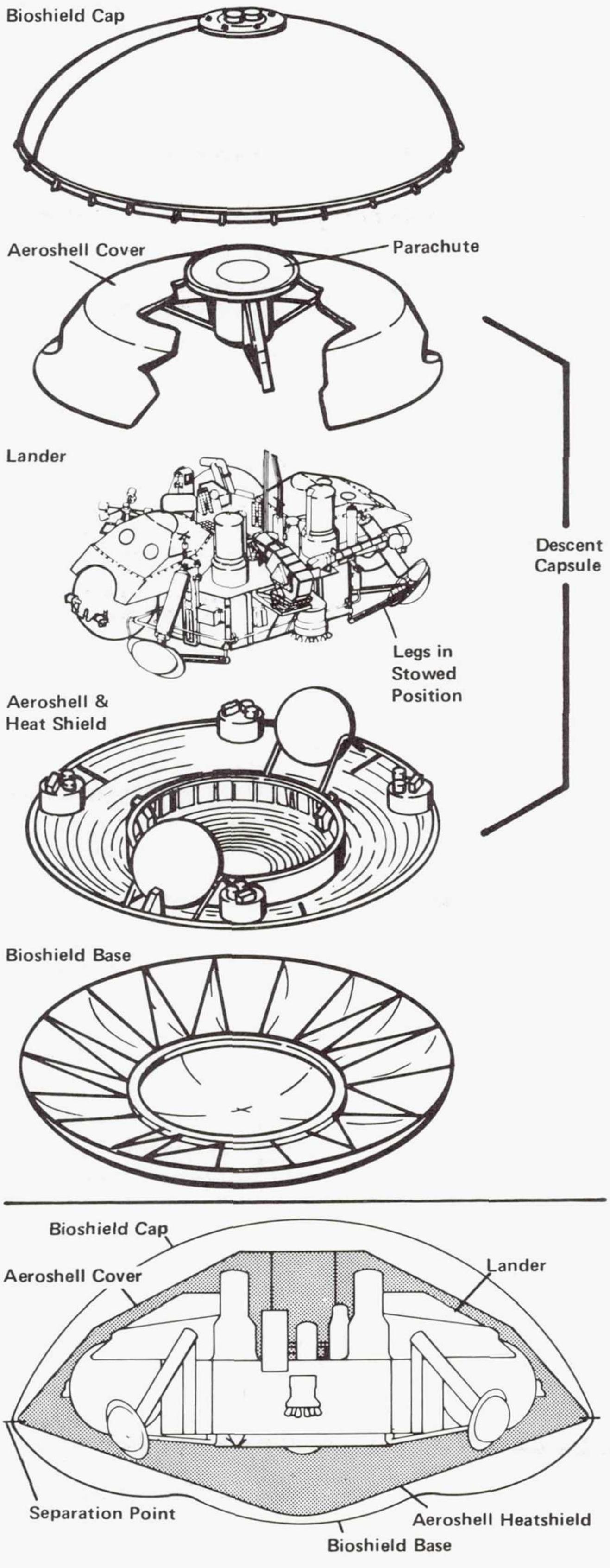
Lander details

switched to an entry mode, the bioshield base connectors between orbiter and lander are separated, and the lander-orbiter separation pyrotechnic devices are fired.

Immediately after separation, attitude control-deorbit propulsion is readied by opening the isolation valves. After inertial reference unit calibration, attitude control is initiated by orienting for the deorbit burn. The burn is delayed until the lander capsule is far enough away from the orbiter that the orbiter's solar panels will not be damaged or contaminated. The pitch-yaw engines supply the deorbit impulse with a 23-minute burn. The control system ensures that the lander is in the proper position for the entry science experiments to function. The retarding-potential analyzer and the upper-atmosphere mass spectrometer collect data during the three-hour descent.

Entry and Landing

After orienting the lander in preparation for entry into the Martian atmosphere, the control system turns on the radar altimeter, which assumes the high-altitude search mode. On sensing 0.05 g with the longitudinal accelerometer, the attitude control system is adjusted, and the computer begins radar-altimeter data processing. Aerodynamic forces quickly trim the entry vehicle to about a -11° angle of attack, corresponding to the lander's



Landing capsule system

offset center of gravity. Instruments collect additional entry science data for pressure and temperature during the remainder of the deceleration period.

At 5.5 kilometers above Mars, the computer begins parachute deployment based on radar range to the surface. Terminal-propulsion valve-drive amplifiers power up, the aeroshell separates from the lander, and the terminal-roll-propulsion isolation valves open within about seven seconds after parachute deployment. Radar-altimeter changes occur with separation of the aeroshell, and a lander body-mounted antenna switches into use. The four-beam doppler terminal-descent and landing radar is also activated to sense velocity relative to the surface. The lander's legs are deployed from their stowed position.

At about 1.5 kilometers above the surface, the computer initiates another radar-altimeter mode change and shortly thereafter opens the terminal-propulsion isolation valves. The parachute–base cover assembly separates from the lander, and the lander descends toward the surface under three-axis attitude control. The control system and engines halt the horizontal velocity acquired while on the parachute by tilting the entire lander upwind. At the same time, residual vertical velocity is stopped. On sensing 610 meters to the surface, the radar altimeter switches to low-altitude mode; the low-altitude mode for the terminal-descent and landing radar begins at 100 meters. At about 50 meters, vertical navigation continues inertially, ignoring radar-altimeter data. At 17 meters, the terminal engine-shutdown switches are armed, and a constant velocity descent is initiated to maintain a speed of 1.5 meters per second until landing-leg touchdown. Velocity steering continues, using the terminal-descent and landing radar. On sensing closure of the terminal-engine-shutdown switches, the computer commands shutdown of the terminal propulsion system by closing a pyro-activated isolation valve, backed up by a software timer.

Landed Operations

The landed mission begins with several housekeeping chores, which include shutting down all descent guidance and control equipment except the computer and the inertial reference unit; the latter operates five more minutes to establish the local vertical altitude and the direction of north. This information is used to compute the direction of Earth so the high-gain antenna can be accurately pointed the following day. Protective devices are armed but not yet activated, the telemetry is set to the highest relay data rate mode of 16 kilobits per second, and the first real-time imaging sequence is begun. A multiple readout of about 25 percent of the computer's memory follows.

After deploying the high-gain antenna and the meteorology boom, opening the camera dust-removal valve, and opening the cover to the biology-processor and distribution assembly, all mission pyrotechnic events are completed. A second real-time imaging sequence begins and continues until the orbiter disappears over the horizon. The relay link fades out about 10 to 12 minutes after landing and, at 15 minutes after, the transmitter is shut off. The meteorology instrument and the seismometry instruments are turned on, and the high-gain antenna is stowed to its normal rest position. Finally, the adaptive mission is begun by activating the mission sequence of events.

Before the Viking landers had the opportunity to perform this complex series of events on Mars, managers, scientists, and engineers faced a multitude of problems on Earth.

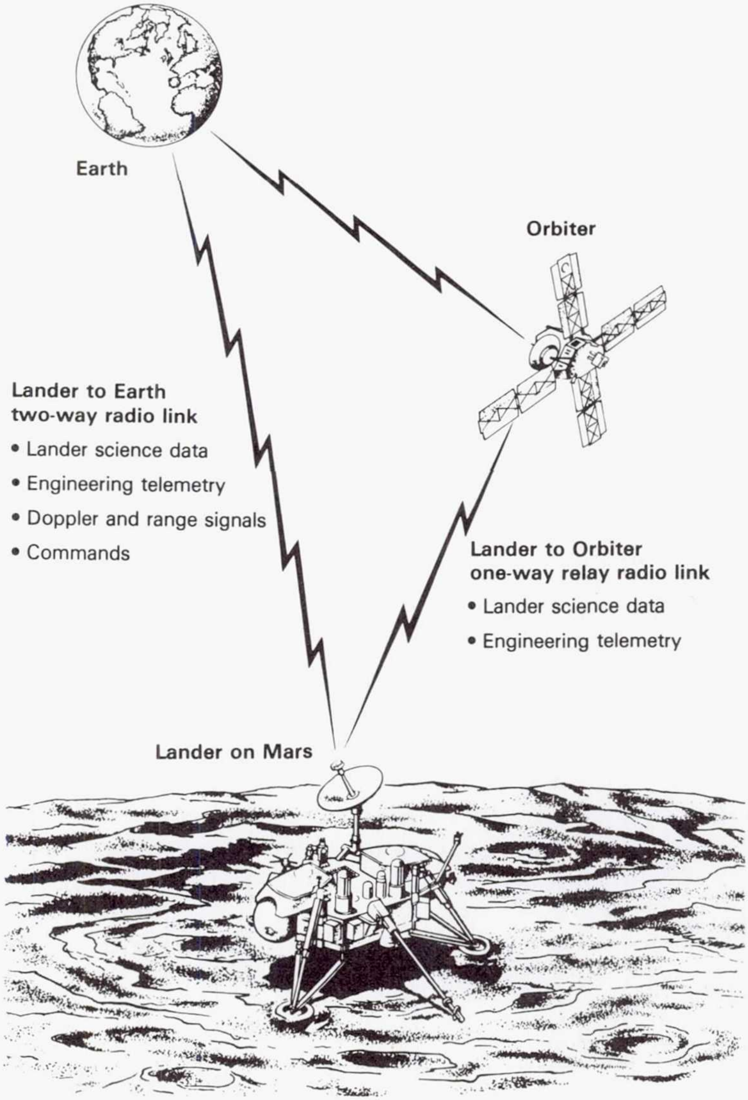
SCIENCE DATA RETURN

The goal of obtaining the greatest amount of scientific information possible from the Martian surface was the major influence on the design and structure of the lander. During 1975 and 1976, Mars and Earth would be at their maximum separation distance, about 380 million kilometers. Since the distance would vary during the mission and since the length of relay opportunities would also vary, several data transmission links were built into the lander equipment for direct communications with Earth (1000, 500, and 250 bits per second were available at a single transmitter output of 20 watts). A second communications link, UHF through the orbiter, was functionally redundant with the direct link. The orbiter relay had three transmitter power levels (1, 10, and 30 watts) and two data rates (4 and 16 kilobits). Since available communication time was severely limited by the power available, typical communication periods would be about 1 hour for the direct link transmitters and 20 minutes for the relay link transmitters. With these link times, data rates, and power output, the rate of scientific data returned to Earth would be about 1 million bits per day for the direct link and 20 million for the relay link. Since the relay link was the more efficient from an energy standpoint, the mission planners would use the orbiter link for the majority of the mission's activities.

Several electronic tricks could be played with the data transmitted (telemetered) to Earth. Because of the short transmission times, "housekeeping" engineering data would be telemetered in real time. Much of the scientific data would be sent on a delayed schedule, having been stored on the tape recorder. Bits of immediate data and delayed data could be electronically interleaved. Although this combination of information cut in half the amount of data that could be returned, it did guarantee the return of important scientific and engineering data during the crucial communication periods. Furthermore, each instrument was constructed to convert its scientific information into a digital code. The imaging system would produce large amounts of digital information, but the biology instrument and the gas chromatograph-mass spectrometer would send much lower volumes of data. With the exception of the imaging system, the lander instruments could automatically communicate with the guidance, control, and sequencing computer when their storage capacities were full. At that time, the data would be dumped into bulk storage. Imaging-data storage or direct transmission, however, had to be preplanned because of the very large amounts of digital information.

Considerable technical sophistication was required to execute the scientific experiments, digitize the information collected, store the data, manipulate it, and transmit it to Earth on cue. This technological complexity and sophistication had a direct dollar equation: developing such a complicated machine in a small package against a specific deadline required a large budget. The world in which NASA operated, however, was full of budget restrictions.

The stringent post-Apollo fiscal scene forced the space agency's managers to work hard and be tough with their personnel and their contractors. Legislators who favored tighter federal budgets argued that such activity was a natural part of NASA's job, but a decade earlier many of these same senators and representatives had willingly appropriated extra dollars when



Apollo managers needed them to solve the problems associated with winning the race to the moon. Post-space race hardware was also expensive, and the Mars landing was a complicated project. The Viking managers were committed to accomplishing their mission in a scientifically valid manner and within a reasonable budget, but more dollars—and the spirit of the Apollo era—would have made it easier. Ingenuity and good management would have to substitute for extra appropriations.

Management's warnings about costs began to sound like a broken record to many of the scientists in the Mars venture; but, like it or not, scientists had to think about money as much as about science. In the fall of 1973, the total project cost had been estimated at $830 million. During the spring and summer of 1974, that figure grew substantially, and despite additional parings the estimated cost at completion reached $930 million by the fall of 1974. That amount, however, did not include the extra dollars the biology instrument ($7 million) and the gas chromatograph-mass spectrometer ($4 million) would demand from fall 1974 to spring 1975. These two instruments long occupied prominent places on Jim Martin's Top Ten Problems list.

Table 43

Cost History of Viking Lander and Selected Subsystems

(in millions)

Date	Estimated Cost at Completion					Total Lander Actual Cost
	Biology	GCMS	Lander Camera	GCSC	Total Lander	
June 1970		17.8			360	19
Sept. 1970	13.7	20.6	9.8	3.4		
Aug. 1971	17.0	25.0	12.9		401	62
Feb. 1972	34.5	35.0	17.4		381	107
July 1972	32.3	35.0	18.1	10.2	420	149
Apr. 1973	29.2	35.4	22.9	10.2	430	286
Mar. 1974	44.2	38.7	23.1	24.1	512	411
July 1974	50.3	39.9	27.4	24.7	543	451
Sept. 1974	55.0		23.5	28.1	559	473
Mar. 1975	59.0	41.0	27.5		545	545
June 1976	59.5[a]	41.2[a]	27.3[a]	28.1		553.2[a]

[a] Actual cost incurred.

GCMS = gas chromatograph-mass spectrometer.
GCSC = guidance, control, and sequencing computer.

TOP TEN PROBLEMS

Martin began the Viking Top Ten Problems list in the spring of 1970 to give visibility to problems that could possibly affect the launch dates. Viking project directive no. 7, issued 4 October 1971, codified the concept:

"It is the policy of the Viking Project Office that major problems will be clearly identified and immediately receive special management attention by the establishment of a Top Ten problems list." To qualify for this dubious distinction, the problem had to be one that seriously affected "the successful attainment of established scientific and/or technical requirements, and/or the meeting of critical project milestones, and/or the compliance with project fiscal constraints." Anyone associated with the Viking project could identify a potential priority problem by defining the exact nature of the difficulty and forming a plan and schedule for solving it. When Martin made an addition to his list, a person in the appropriate organization was charged with solving the problem, and someone in the Viking Project Office monitored his progress. Weekly status reports were datafaxed from the field to Langley. At Martin Marietta, William G. Purdy, vice president and general manager of the Denver Division—through Albert J. Kullas and later Walter Lowrie, his project directors—sent weekly status bulletins on the lander's top problems, since that system seemed to have the greatest number of difficult components and subsystems. In the spring of 1972, Martin told Cortright he hoped the supervisors of employees who had one of their tasks assigned to the top 10 list would not be penalized. Martin, not wanting a stigma attached to identification of a problem, was concerned that at Martin Marietta assignment of a problem might "automatically be considered as a mark of poor performance" when promotions or raises were given. Generally, the nature of the crucial problems was so complex that punishing one individual would not solve the problem. As with the gas chromatograph-mass spectrometer and the biology instrument, the novelty of the technological task was often the source of the trouble.[2] Some problems seemed to stay on the manager's worry list forever. Others made repeat performances.

At times, Martin found it necessary to bring a particular problem to the attention of a specific subcontractor. Depending on the clout needed behind the message, Martin would sign the letter or enlist the aid of Langley Director Cortright or Martin Marietta Vice President Purdy. In extreme cases, the letter would be sent out over the signature of the NASA administrator. Early in 1973, the Viking Project Office identified six subsystems that required Administrator James C. Fletcher's personal touch: inertial reference unit, subcontractor Hamilton Standard; terminal-descent and landing radar and radar altimeter, Teledyne-Ryan; guidance, control, and sequencing computer, Honeywell; lander camera, Itek Corp.; upper-atmosphere mass spectrometer, Bendix Aerospace; gas chromatograph-mass spectrometer, Litton Systems.[3]

Fletcher wrote the president of each company asking for his personal pledge of support for Viking and seeking his fullest cooperation in resolving the problem. The administrator usually asked them to come to Washington to discuss the issues further. By setting off an alarm in the front office, NASA managers from Fletcher and his deputy, George Low, to Jim

Table 44
Top Ten Problems

Item	Added to List	Deleted from List
GCMS progress and schedule	4 May 1970[a]	July 1971
Lander gear design	4 May 1970[a]	
Site-alteration program schedule	4 May 1970[a]	
Solder joints, failure mode under sterilization	4 May 1970[a]	Dec. 1971
Post-Mars-orbit-insertion orbit determination convergence	4 May 1970[a]	May 1971
Lander weight growth	4 May 1970[a]	
Orbiter weight growth	4 May 1970[a]	
Site alteration	4 May 1970[a]	Aug. 1971
Wet tantalum capacitor failure under sterilization temperatures	Jan. 1971	Feb. 1971
Completion of data requirement list/data requirements description	Jan. 1971	Feb. 1971
Lander gear design	Feb. 1971	Aug. 1971
Lander weight contingency	Mar. 1971	Oct. 1971
Orbiter weight contingency	Mar. 1971	Aug. 1971
Lander materials	Aug. 1971	Oct. 1972
Lander processes	Aug. 1971	1 June 1972
Lander parts program	27 Aug. 1971	1 June 1972
GCMS configuration and schedule	Oct. 1971	2 Feb. 1972
Balloon-launched decelerator test	2 Feb. 1972	July 1972
Radar-altimeter design-development schedule	Feb. 1972	24 July 1973
Lander entry weight	Mar. 1972	26 Apr. 1973
Proof-test-capsule schedule	31 Mar. 1972	26 May 1972
Guidance, control, and sequencing computer development-test schedule	21 July 1972	15 Jan. 1975
Aeroshell radar-altimeter-antenna engineering release	22 Aug. 1972	5 Jan. 1973
GCMS development-test schedule	1 Sept. 1972	6 June 1975
Viking lander camera development schedule	1 Sept. 1972	2 Apr. 1974
Titan-Centaur-shroud qualification program	Sept. 1972	
Upper-atmosphere mass spectrometer development schedule	12 Jan. 1973	31 Oct. 1974
Surface-sampler boom motor	8 Feb. 1973	10 Sept. 1974
Proof-test-capsule component delivery	26 Feb. 1973	19 Feb. 1974
Flight-team facility space	11 Apr. 1973	1 Nov. 1973
Inertial reference unit	12 Apr. 1973	3 Oct. 1973
Seismometer instrument	22 Aug. 1973	20 Dec. 1973
Viking-orbiter-system data-storage-subsystem data recovery	July 1973	20 Dec. 1973
54L microcircuit particle contamination	Oct. 1973	4 Nov. 1974
Proof-test-capsule schedule recovery	19 Apr. 1974	21 Oct. 1974
Lander-test-sequence development	19 Apr. 1974	12 Dec. 1974
Building 264 construction of facilities funding	27 June 1974	29 Aug. 1974
Guidance, control, and sequencing computer flight software	2 July 1974	15 Jan. 1975
GCMS processing-and-distribution-assembly shuttle block design	29 Oct. 1974	6 June 1975
Biology instrument	26 Oct. 1973	6 June 1975

[a] Although the Top Ten Problems concept was not officially recognized until October 1971, the system was used before that date. In Jim Martin to Henry Norris, "Viking Top Ten Problems," 4 May 1970, these items were listed.

Martin hoped to impress on subcontractors their obligations to the Mars project.[4] At times, the NASA administrator had to be extremely blunt. Once his letter resulted in a meeting with John W. Anderson of Honeywell, Inc., about the guidance, control, and sequencing computer. This worrisome piece of hardware, the key to the lander's performance, controlled and arranged the sequence of all lander functions from separation from the orbiter through completion of the mission. Without this brain and central nervous system, the lander would be worthless. Schedule delays and cost increases in developing the guidance, control, and sequencing computer were in large part the result of the requirements established for this piece of equipment—energy efficiency, small size, reliability, heat resistance, longevity. Each lander had a guidance, control, and sequencing computer, made up of two completely redundant computers with 18 432-word plated-wire memories. The overall computer was 0.03 cubic meter (26.7 x 27.3 x 40.6 centimeters) and weighed 114.6 kilograms. Its most advanced feature was the two-mil plated-wire memory, making small size and low power consumption possible. Either of the twin computers within the guidance, control, and sequencing computer could operate the lander, but only one would be used during descent. The computer would have to work flawlessly if the landing was to succeed. Once the lander was on the surface, either computer could control the craft.

As prime contractor for the lander, Martin Marietta had responsibility for the important computers. In May 1971, the firm asked for proposals from 11 firms to subcontract for the guidance, control, and sequencing computer and received 5 responses. After an unusually complicated contracting process, Honeywell, Inc., was selected as the builder, largely because of its plans to use the two-mil plated-wire memory. Work began at Honeywell's Aerospace Division in Saint Petersburg, Florida, in November 1971. Honeywell also had a contract with Martin Marietta for the development of the lander's data-storage memory, a digital-data-storage device used in conjunction with the lander's tape recorder. The data-storage memory would have the same plate-wire memory units. Combined projected costs for the guidance, control, and sequencing computer and the data-storage memory in 1971 was $6.1 million, with a ceiling cost of $6.8 million.

A preliminary design review for the computer was held on schedule in April 1972. At this review, plans called for development testing to be completed by December 1972, following which Martin Marietta and NASA personnel would hold the critical design review. Because of difficulties in fabricating the sense-digit transformers, the plated wire, the memory tunnels, and memory planes, the critical design review was rescheduled for March 1973. As problems continued with component deliveries and memory fabrication, the date for the review was slipped several times. Finally held in August 1973, the critical design review indicated that the design was acceptable in theory, but more development tests were required. Because Martin Marietta needed early delivery of the computers to keep lander fabrication and testing on schedule, Honeywell had to proceed with a parallel program in which the development units and the flight-style computers were built at the same time.

Throughout 1973, Honeywell had difficulties with the plated-wire memories. Engineers could not produce sufficient quantities of the plated wire with the proper magnetic characteristics, and they had problems in fabricating the matlike tunnel structures in which the wire was manually inserted. The magnetic keepers applied to the exterior of the sandwiched memory planes also became troublesome for Honeywell. The subcontractor faced another setback when faulty plated-through holes were found in many of the printed circuit boards, which had been purchased from a commercial supplier. These 18- x 23-centimeter Honeywell-designed circuit boards had up to 16 layers of circuits and 3000 plated-through holes for making electrical connections. A great many of the original circuit boards had to be scrapped and reordered from another supplier.[5]

The various problems with the guidance, control, and sequencing computer led NASA Administrator Fletcher to ask Honeywell Vice President Anderson in for a serious talk. Anderson had previously met with Fletcher on 15 February 1973, and subsequently Deputy Administrator Low told Fletcher that some of the computer problems had apparently been solved as a result. But, still unhappy, the administrator wrote again: "During our meeting I was . . . disturbed by the inference in one of your remarks, that Honeywell is unable to put forth its best efforts on this job because of the type of contract. . . . I hope I was mistaken in my impression that this is so, and I trust that Honeywell will fully live up to all of its obligations." Only Fletcher could talk this firmly to corporation executives. Jim Martin, for all his crustiness, was not in such an authoritative position.[6]

Anderson responded in the positive manner Fletcher was seeking: "In spite of my comments of philosophical concern, I had hoped to have left you with the conviction that Honeywell was applying the best of its resources in a prudent and expeditious fashion. I believe it would be agreed by both the people from NASA and the Martin Company that we are going to find solutions to problems."[7] However—despite all the efforts of the agency, Martin Marietta, and Honeywell—the guidance, control, and sequencing computer, which first made the top 10 list on 21 July 1972, was not removed from the chart until 15 January 1975.

By late 1973, Honeywell had exceeded the $6.8-million ceiling by nearly $3.5 million. Working under a fixed-price contract, the contractor had no profit incentive to improve the situation. Martin Marietta took several steps, at NASA's urging, to improve the Honeywell operation. The contract was changed from a fixed-price to a cost-plus-incentive-fee contract, with Honeywell accepting a $3.5-million loss. The project was rescheduled, and its cost reestimated to $24 million. Honeywell doubled the number of employees assigned to the computer, as special teams worked to solve specific problems and expedite production. Alternatives to the two-mil plated-wire memory were also examined. While the engineers in Florida attacked these problems, Martin Marietta began a backup program to develop an alternative memory system.[8]

Also in late 1973, Martin Marietta established a resident management office with a staff of 20 at Honeywell's Saint Petersburg factory. This team, and NASA personnel from Langley, assisted Honeywell's managers with scheduling, managerial, and engineering tasks. Everyone was clearly concerned about the fate of the computer. Langley Director Ed Cortright told Deputy Administrator Low on 30 October 1973 that a meeting with top computer industry experts indicated that Honeywell's problems were not unique. "It appears that the major difficulty is one of schedule time available to reliably produce and test computers needed to support the building of flight" landers. Money might buy more people, but neither people nor dollars could purchase more time.[9]

In January 1974, the Viking Project Office team decided to change all the flight-model computer memories to a new two-mil plated wire known as "coupled-film wire" because it had a second magnetic layer. It was easier to produce, had higher electrical output, was less subject to mechanical damage, and was affected less by temperature changes. Honeywell became more optimistic about meeting schedules. The first flight-model computer was delivered to Martin Marietta in April 1974, nine months late according to the original schedule. Although this proof-test-capsule model had a great many deficiencies, it did permit Martin Marietta to go ahead with its lander tests. Unhappily, delivery schedules continued to slip during 1974 as Honeywell faced more technical difficulties. Faulty components were uncovered. One lot of transistors was rejected. More unsatisfactory printed circuit boards came to light.[10]

Continuous monitoring of the subcontractor's troubles was rewarded, however, in late 1974 when the computers were finally ready for delivery. On 15 January, Jim Martin received the following message from Walt Lowrie at Martin Marietta:

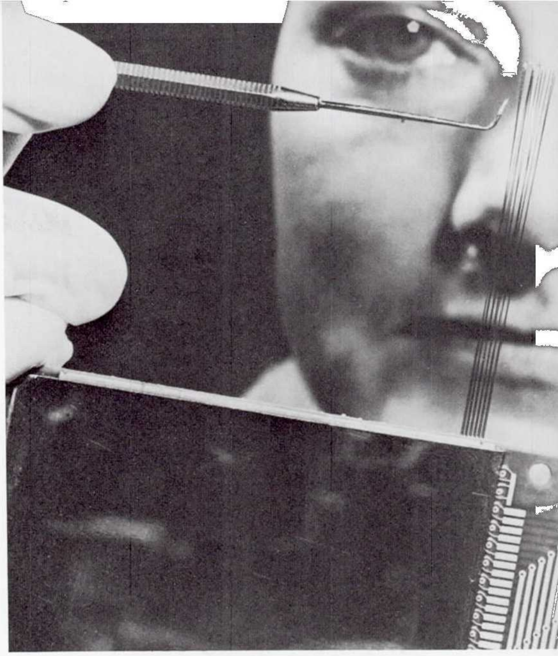
> Oh ye of little faith—We gave birth to the last computer today. I don't know how you feel on the subject but it would appear to me that this top ten has now died of old age.
>
> Seriously—although the path has been extremely tortuous I really feel we now have an excellent computer on Viking.[11]

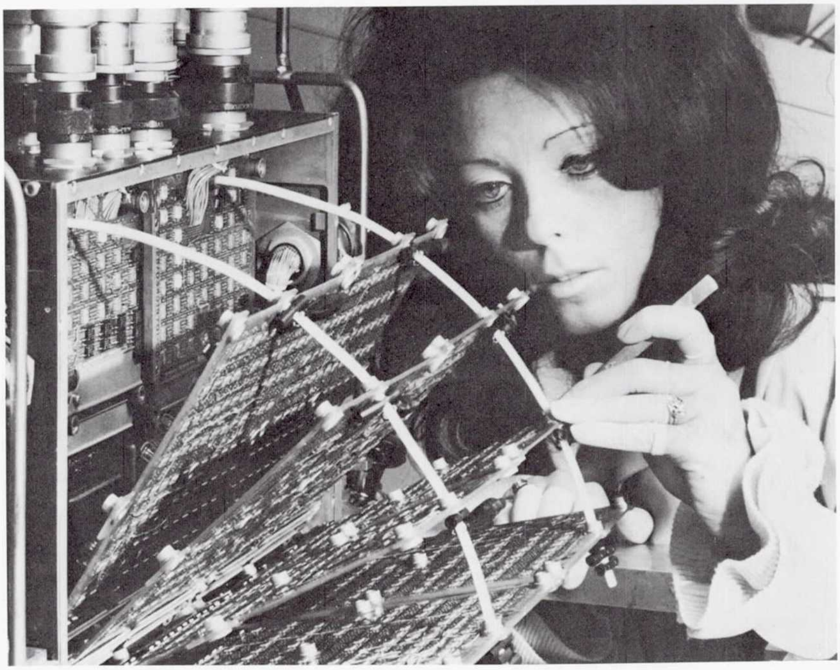
Martin removed the lander computer from his list of major problems. Thus it went, step by step—problems identified and then solved. At this stage in Viking's existence, there was very little glamor, just long hours, hard work, and an occasional antacid.

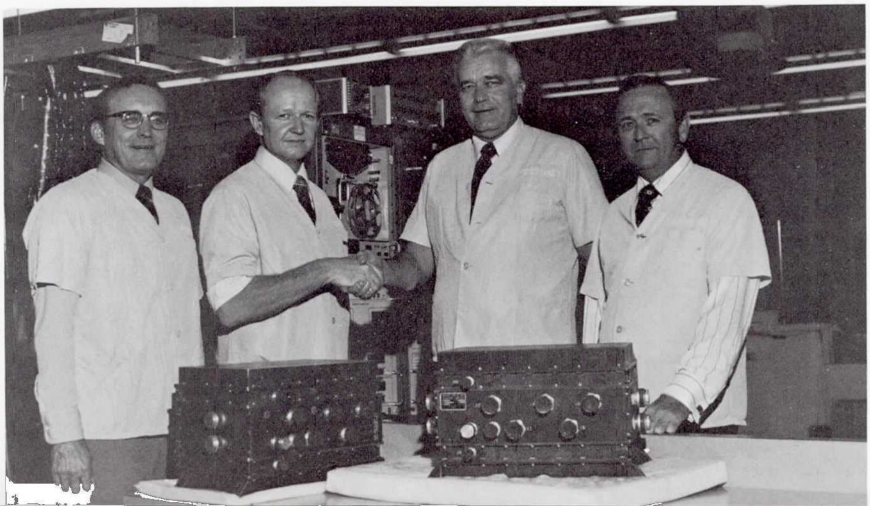
TESTING THE LANDER

Another phase of the lander's evolution was the multiplicity of tests to which the components, subassemblies, and assemblies were subjected.

The guidance, control, and sequencing computer was the Viking lander's brain. At right, magnetic wires as fine as human hair are inserted into the computer at Honeywell Aerospace, Saint Petersburg, Florida. In testing below, the HDC-402 computer, part of the lander's computer, looks like pages of a book. At bottom, Jim Martin (second from right) on 10 January 1975 congratulates Barton Geer (left), director of system engineering and operations at Langley; R. Wigley, Honeywell's Viking program manager; and F. X. Carey, Martin Marietta resident manager at Honeywell. GCSC flight article 2 and the qualification unit are in the foreground.







Again, this was not terribly exciting work, but it was essential to producing spacecraft that could be relied on to function far from Earth.

As with the Viking orbiter, a number of simulators were developed to verify analytical predictions of lander system performance, to investigate the effects of the thermal and dynamic environment on the craft, and to permit tests of subsystems, such as the scientific experiments. The major Viking simulators included:

Lander (structural) dynamic-test model (LDTM). A flight-style structure with partial flight-style or equivalent propulsion lines and tanks. Mass (weight) simulators were used for nonstructural hardware. The LDTM was used for structural vibration, acoustic noise, separation tests, and pyrotechnic shock evaluation.

Lander (structural static-test model (LSTM). A flight-style structure used for qualification of the primary structure under steady-state and low-frequency loads.

Orbiter thermal effects simulator (OTES). A simulator used to study the orbiter's thermal and shadowing effects during the lander-development thermal environmental tests.

Proof-test capsule (PTC). A complete Viking lander capsule assembly assembled from flight-style hardware, used for system-level qualification.

Structural landing test model (SLTM). A ⅜, geometrically scaled model of the lander, dropped at various velocities and attitudes to determine landing stability boundaries. The ⅜ scale was chosen because the Martian gravity was ⅜ that of Earth's.

Thermal-effects test model (TETM). A full-scale model incorporating developmental thermal control systems and flight cabling test harness. Flight equipment thermal effects were simulated by special equipment. The TETM was used to verify the system developed for controlling the temperature of the lander.

Electrical thermoelectric generators (ETGs). Generators used in testing in place of the radioisotope thermoelectric generators (RTGs). ETGs had electrical heating elements that simulated the electrical and thermal characteristics without the hazard of nuclear radiation.[12]

There were three broad categories of tests: system development, qualification, and flight acceptance. Development tests determined the levels of performance that components and subassemblies would have to meet to be acceptable. They also provided early identification of design deficiencies. These trials used primarily the dynamic-test model, the orbiter thermal-effects simulator, and the thermal-effects test model. Qualification tests used hardware attached to the proof-test capsule and the static-test model. During the "qual tests," hardware was subjected to stresses and environmental conditions that exceeded any expected during the mission. Environmental tests included heat compatibility, acoustic noise, launch sinewave vibration, landing shock (drop test), pyrotechnic shock, solar vacuum, and Mars-surface simulation. These and additional tests were performed at the component and subsystem level. The flight acceptance tests were performed on flight hardware before qualification testing. Only the thermal sterilization and solar vacuum tests were made with assembled flight landers.

Environmental Tests

The proof-test capsule, encapsulated in its bioshield, was subjected to the heat compatibility test to verify that the system could withstand heat sterilization. During this test, the chamber atmosphere consisted of dry nitrogen containing about three percent oxygen and other gases. The capsule was subjected to 50 hours of 121°C heat, and flight landers were exposed to 112°C for 40 hours. Components were subjected to five 40-hour cycles and three 54-hour cycles at 121°C.

The vibrations of liftoff were computed by analysis of data from earlier Titan-Centaur flights and the February 1974 proof flight of a Titan IIIE-Centaur D-1T launch vehicle (this flight and preparation of the Viking launch vehicle are discussed in appendix E). Despite the necessary destruction of the Centaur stage on this flight after its main engine failed to start, some information was gained to help define the ground-based simulations (launch sinewave vibration tests) of the low-frequency vibrations encountered during launch, stage separation, and spacecraft separation. Through combined analysis, flight-derived data, and simulations, the engineers were able to determine if the lander components could withstand the predicted vibrations.[13] The acoustic noise test simulated the effects of the sounds of powered flight. Levels of the individual components were determined by earlier tests using the lander dynamic-test model and proof-test capsule.[14]

Random vibration tests were applied only at the component level, to screen out faulty workmanship and design defects. Laboratory simulations of the levels of vibration encountered during actual flight proved not to produce satisfactory data. Borrowing from procedures devised during the Apollo program, the vibration levels were raised to a level that would screen out bad components but not damage good ones. Component vibration levels were the same for both qualification and flight acceptance testing, but the latter was shorter so that multiple tests could be run without exceeding the qualification test levels. In the pyrotechnic shock tests run at the system level, a series of pyrotechnic devices was fired to simulate the effects of actual mission events and at the same time demonstrate the actual performance of the pyrotechnically actuated mechanisms. Components were subjected to vibrations similar to those expected with the Viking pyrotechnic devices and to contained explosions that replicated the impact of explosions and gas pressure buildups on specific assemblies.[15]

Solar vacuum tests, held in a nearly complete vacuum in Martin Marietta's test chamber (4.5 meters in diameter and 20 meters high), simulated the worst predictions for thermal heating and cooling during the flight to Mars. Both the effects of heating and cooling and the performance of the lander's thermal control system were evaluated. Each mission phase was completed twice for the qualification tests of the proof-test capsule and once for the flight acceptance tests of the flight landers.[16]

Deorbit-entry-landing thermal simulation tests, conducted on a component level, duplicated the effects of entering the Martian atmosphere—pressure increase, entry heating, and the post-landing cooldown. Components were placed in the vacuum test chamber at 1/760 of an Earth atmosphere, heated to a temperature of 149°C, and held there for 530 seconds. Chamber pressure was then raised to 5/760 of an Earth atmosphere with cooled nitrogen gas, to provide an atmospheric temperature of -101°C. In this manner, the lander's passage through the Martian atmosphere with the attendant heating and cooling was duplicated. The change of 250°C represented the wide range of temperatures that the lander would be exposed to on Mars. Such extremes were part of the reason the engineering of the lander had been such a complicated task. For all components, the most critical period would be the 15 to 20 minutes after landing, since by that time all equipment would be operating and the entry heat buildup would not have had time to dissipate.

In the landing shock tests, the proof-test capsule, with landing gear extended, was dropped from a height necessary to achieve a velocity of 3.36 meters per second on impact. Each drop produced the worst possible dynamic loads on a different landing leg and footpad. In addition to these drop tests, the shock stresses generated by the opening of the parachute were evaluated analytically and then measured during the balloon drop tests (balloon-launched decelerator tests) at the NASA White Sands Test Facility in New Mexico in the summer of 1972. They were carried out successfully despite postponements caused by uncooperative weather. As a consequence of these tests, new techniques were developed to unfurl the parachute progressively, minimizing the deployment shocks to the lander.[17]

During the Mars-surface simulation tests, the lander configuration of the proof-test capsule was subjected to thermal conditions worse than those expected on the surface of Mars. By subjecting the lander to different conditions and varying the vehicles' internal electrical power, three basic tests were performed—hot extreme, cold extreme, and the predicted norm.[18] In consultation with the Science Steering Group, the test engineers chose argon for the chamber atmosphere during the cold extreme, because preliminary data from the Soviet Mars probes had indicated that as much as 30 percent of the planet's atmosphere might be composed of this rare gas.* Since argon promotes electrical corona and arcing in electronic components, the test teams were to determine whether there would be any adverse effects on lander subassemblies if the concentration of argon was that high.

Science End-to-End Test

One of the most significant activities during the lander testing cycle was the science end-to-end test (SEET), conducted during the Martian-

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*Subsequent Viking data indicated that the argon content in the Martian atmosphere was only about 1.5 percent.

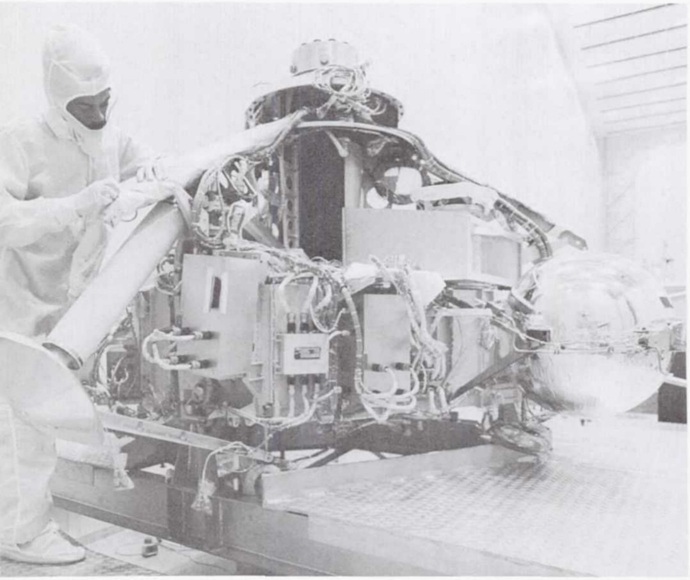
Table 45
Mars Surface Thermal Simulation

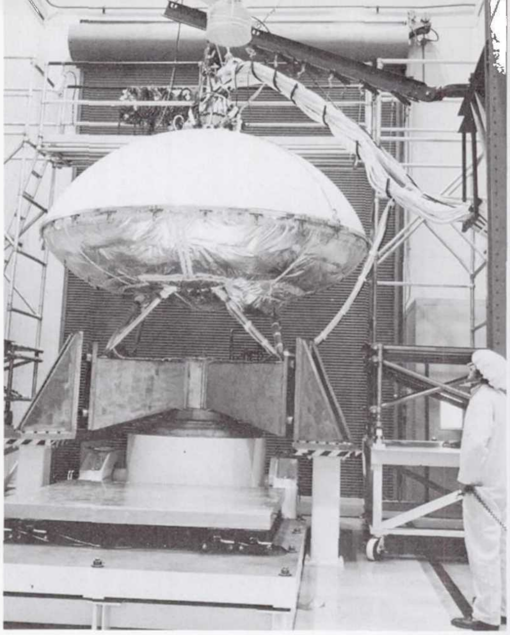
Parameter	Hot Extreme	Cold Extreme	Nominal
Shroud temperature	-129°C ± 5°C	-151°C to -81°C	-112°C ± 5°C
Chamber pressure and atmosphere	2 ± 0.1 mb, CO_2	35 ± 2 mb, Argon	4 ± 0.1 mb, CO_2
Solar radiation	1078 ± 47 watts/m^2	0 watts/m^2	539 ± 31.5 watts/m^2
Solar duration	12.33 hrs.	None	12.33 hrs.
Vehicle power	1395 watt-hrs	1345 watt-hrs	1371 watt-hrs
Ground simulator	-46°C to +24°C	Uncontrolled	Nominal
Thermal coating	Degraded	Original	Original
ETG thermal output	Maximum (680 ± 2 watts)	Minimum (630 ± 2 watts)	Nominal (673 ± 2 watts)
Test duration (PTC)	3 days	4 days	3 days before hot extreme; 3 days before cold extreme

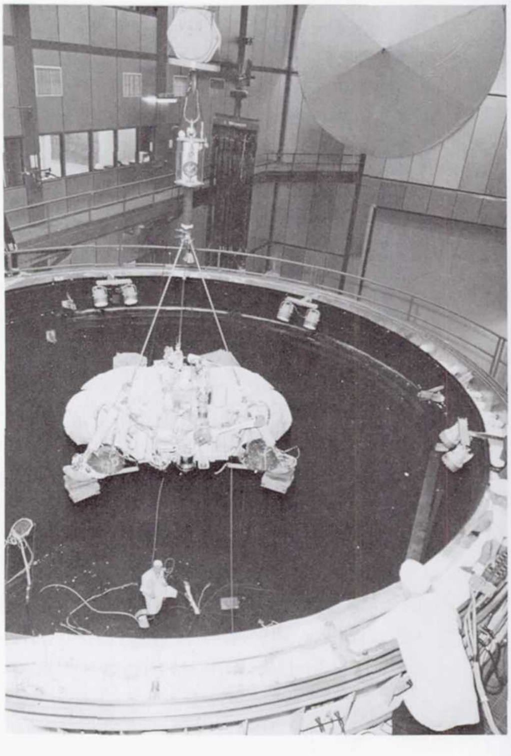
surface simulations at Martin Marietta. The two major SEET objectives were "to verify the adequacy of the implementation of the scientific investigations from sampler collection to interpretation of resulting data by the scientists" and to "familiarize the Viking scientists and other flight operations personnel with *total operation of the investigations* and their respective characteristics." In the course of carrying out these basic objectives, any hardware or procedural problems were to be resolved, to avoid similar difficulties during the actual mission.[19]

Getting the science end-to-end test started took some effort. It was postponed several times because of problems with the motor used to load samples into the oven heating assembly of the gas chromatograph-mass spectrometer. When the pumpdown of the vacuum test chamber began on 17 September 1974, the proof-test capsule lander used in the operation had a GCMS simulator aboard instead of the actual test unit. SEET was also run without the biology instrument. Despite the absence of these two major experiments, the test was useful.

The lander systems were examined rigorously. During the thermal vacuum chamber operations, a Martin Marietta computer facility sent commands via cable to the guidance, control, and sequencing computers. The plated-wire memory, once a leading top 10 problem, performed very well in the simulated Martian atmosphere. In addition, JPL processed data recorded on computer tapes from lander subsystems much as data would be during the real mission. Tests of the ultrahigh-frequency (UHF) radio link







Viking simulators went through intensive environment tests to ensure the final spacecraft would function far from Earth. Above left, Viking program technician Alonzo McCann adjusts a cable on the proof-test capsule-decelerator assembly, as lander and capsule are prepared for January 1974 heat-verification tests. One of the lander cameras is to the right of center. Above right, a technician watches as an acoustic shroud is lowered over the proof-test capsule before acoustic tests in mid-June 1974. At lower right, the proof-test capsule is lifted out of the vacuum chamber at Martin Marietta, Denver, in October 1974 after a month-long series of rigorous tests to qualify it for operations on Mars.

for data transmission and the lander tape recorder also indicated that those systems were ready for flight.

Other subsystems were given a thorough examination: the surface sampler, the lander's imaging system, the weather sensors, the x-ray fluorescence spectrometer, the seismometer, and the biology sample processor.

The multipurpose surface sampler (boom-and-scoop assembly) successfully delivered soil samples to the x-ray spectrometer and biology processor unit and to the GCMS position. The only significant problem occurred when the sampler arm snagged on the holder of a brush used to clean a magnet on the magnetic properties experiment. This problem was cleared up by minor hardware modifications and a new mission rule that prohibited cleaning the magnets until all of the biology samples had been taken. The lander facsimile cameras made nearly 100 images, including pictures of trenching exercises with the backhoe and of particles adhering to the magnets. The meteorology instrument performed well in Marslike conditions that could not be duplicated in a standard wind tunnel. Although the biology instrument was not on board, the processor containing the screens and cavities for the measurement and separation of the materials scooped up by the surface sampler was tested and proved satisfactory.[20] During the seven days (18-23 September) that it took to simulate five days of experiments on the surface of Mars, many important lessons were learned as procedural and hardware "glitches" were encountered and overcome, and much needed experience was gained with the meteorology, seismology, camera, x-ray fluorescence spectrometer, and magnetic properties experiments.[21]

Priestley Toulmin, team leader for the inorganic chemical investigation (x-ray fluorescence spectrometer) had been uncertain about the merits of SEET as it was planned, however. Toulmin's experiment, a late addition to the lander science payload, would determine the nature of inorganic compounds (minerals) in the Martian soil. As early as 1968, the Space Science Board had suggested it in recommendations to NASA for planetary explorations. But the priority given inorganic analysis was much lower than that assigned the search for biologically derived compounds—although, with the exception of this experiment, the original payload for Viking had followed the board's suggestions closely. Information gathered from the lunar samples returned by Apollo astronauts and early *Mariner 9* results suggested the need to reconsider the utility of inorganic analysis. Mariner 71's findings were particularly evocative because they indicated that Mars was geologically younger and more active than had been expected. As a result, in the fall of 1971 the space science community lobbied the NASA management, especially John Naugle, associate administrator for space science and applications, to include an inorganic experiment on the lander. Of two possible investigations, the one designed by Martin Marietta and the team led by Pete Toulmin was selected. (The other instrument, designed by a team led by Anthony L. Turkevich at the Enrico Fermi Institute of the University of Chicago, had been under development for a longer time, but the XRFS was expected to cost less, be lighter, and require less space and power.)[22]

As time for SEET approached, Toulmin was concerned about the manner in which it would be conducted. Both he and Klaus Biemann, team leader for the molecular organic analysis (the GCMS), had insisted strongly on the inclusion of "blind" samples in the analyses to be done by their instruments. These materials, unknown to the teams, would be identified by the results of the experiments, to simulate the interpretative work of the actual mission. In addition to making certain that this aspect of the SEET experience was carried out, Toulmin told Jerry Soffen in early September 1974 that he was concerned about the validity of the trials since the x-ray fluorescence spectrometer to be used in the test was different from the actual flight article. The test version had several shortcomings that had already been corrected in the flight units. A final reservation centered on the seeming inflexibility of the test plans.[23]

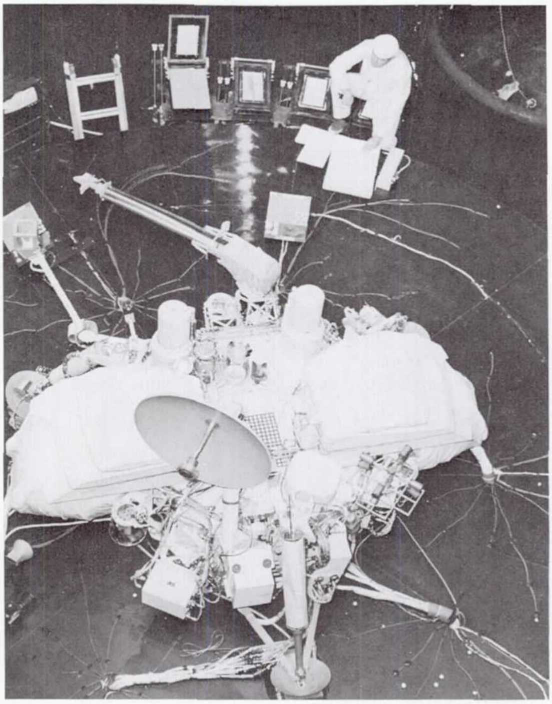
By the end of the science end-to-end test, however, Toulmin believed in its worth. He had previously discussed with Jerry Soffen "some reservations and qualifications the Inorganic Chemical Investigations Team felt were applicable to that program." In most instances, Toulmin believed that "the events proved us correct in our concerns regarding the state of the hardware, the software, and ourselves" and they had predicted several of the breakdowns that occurred. But in one major respect Toulmin felt he and his colleagues had misjudged the testing program: "I . . . grossly underestimated the tremendous value of the experience for those who participated in it. We learned things about the operation of the instrument and its relations with the rest of the lander, and about the recognition, diagnosis, and correction of problems and malfunctions that we would never have learned by any other method." Although the actual mission would differ greatly from the simulations, "it was an invaluable introduction to a whole new world." In his report to Martin, Toulmin singled out "for special mention the three unflappable controllers of the SEET data room: Henry von Struve, Frank Hitz, and Ron Frank."[24]

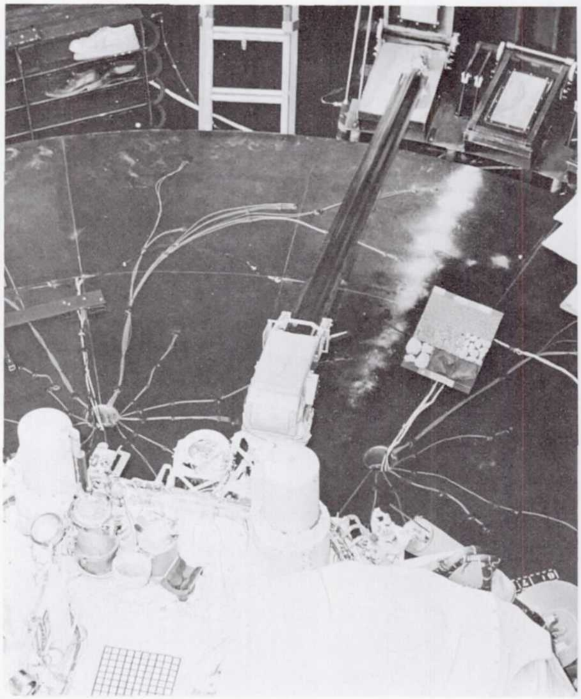
Phase B of the science end-to-end test was less satisfactory. Begun on 7 October with the reworked gas chromatograph-mass spectrometer, it had to be terminated on the 10th when additional problems were encountered with that instrument. These difficulties led to a special test of the GCMS in conjunction with the biology instrument's performance verification test in February 1975. Despite some additional functional difficulties, Klaus Biemann was able to identify from the GCMS data tapes the five compounds in the blind samples.

Whereas the mass spectrometer went through the end-to-end functional and operational exercise, the biology instrument did not. The biology instruments were delivered too late for proper testing. By the time the hardware became available, limited time, money, and manpower argued against the thorough test. To questions about the adequacy of the functional testing of the hardware on the proof-test capsule lander in Martin Marietta's thermal vacuum chamber and the biological operation of the experiments, Cal Broome told Martin on 30 June 1975, less than two months before liftoff, "The current planning assumes that the testing already accomplished is adequate, i.e., the combination of Biology [performance verification] at the lander level (instrument 103) and soil biology at the instrument level (instrument 102 and 103) is adequate to provide assurance of proper operation on Mars." He added, "There is no question that this program does not provide ultimate verification, i.e., operation of a flight instrument in a lander with real flight sequences and verification of proper results," but said, "Our position has been that risk of the current approach is acceptable." Broome was responding to a NASA Office of Space Science inquiry about the possibility of conducting a biology end-to-end test after the Viking spacecraft had been launched.[25]

Four major factors influenced the scope of the biology instrument acceptance test program. One, the introduction of soil or experiment nutrient into an instrument would render it unusable for flight. Cleaning the instrument was impossible without destructive disassembly. Thus, the functions of the flight instruments (S/N 104, 105, and 106) had to be tested only by simulating their operations on Mars. Soil testing was necessarily limited to components and units not reserved for flight use. Two, the complexity of the instruments, the multiplicity of their functions, and the operational pace (one minute between commands) meant that complete functional tests would be extremely time-consuming. The minimum time required for an entire end-to-end electrical and pneumatic checkout of a biology instrument was one month on a round-the-clock schedule. Only abbreviated functional tests could be performed. Three, given the long turnaround time required to repair and retest instruments if a component failed, all components and subassemblies had to be tested before assembly in the integrated instrument, where accessibility was a problem. And four, a substantial number of design changes were incorporated into the flight units after the manufacture and test of the qualification unit (S/N 102), requiring additional qual tests. Functional tests were then carried out to ensure that the flight instruments had not been harmed by the qualification test stress levels.

Each flight version of the biology instrument was subjected to a sequence of acceptance tests: operational system checkout, vibration test, functional verification, thermal verification, sterilization, and operational system checkout. The operational checks were computer-controlled, testing the electrical functioning of the instrument. Mechanical and structural quality was verified through vibration tests, while the functional verification tests were complete validations of all instrument systems. Computer-controlled electrical and pneumatic sequences assessed individually the functioning of each critical component or subassembly. The thermal verification tests were performed with the biology instrument in a Marslike atmosphere of carbon dioxide through a temperature range of -18° to 30°C. Instruments were sterilized in a biologically filtered nitrogen atmosphere at





Science end-to-end tests sought to verify complete performance of the Viking scientific instruments and familiarize scientists and flight operators with the total operation of Mars investigations. Above, a technician prepares the proof-test-capsule lander for the environment and SEET tests. At right, sample boxes are positioned for testing the lander's surface-sampler assembly.

120°C for 54 hours. The total acceptance test spanned three to five months, depending on problems encountered during the process.[26]

Although this was a busy test schedule, no flight-model biology instrument had been tested as part of the total lander system, and in the fall of 1975 Harold P. Klein, leader of the biology team, and his colleagues argued for such a test. Langley and headquarters personnel resisted any lengthy additional testing. Such an examination could not take place before January 1976 and would interrupt a number of schedules. In late September, the Viking Project Office proposed a committee led by Gary Bowman, biology instrument team engineer, to take an in-depth look at the biology instrument test data from a lander systems point of view. From the team review, areas of specific concern could be identified and a decision about additional tests made.[27]

Klein responded on behalf of his teammates in November after Bowman's group and the biology team had looked at the testing issue again.

Ideally, the biology team would have liked to install the flight-model S/N 104 biology instrument in the proof-test capsule at Denver, to make biological examinations of soil samples, but the S/N 104 unit had to be kept sterile until after the mission, when additional tests might be necessary.

What the biology team could do was install the proof-test-capsule unit (S/N 103) on the proof-test-capsule lander to observe real data being processed from the biology instrument detectors through the lander system. The biology instrument simulator was not similar enough to the flight hardware to provide a meaningful test of the lander–biology instrument interface, but the test could simulate the sequence of biology instrument operations from soil collection through processing, analysis, and data return. Not only would experimenters have a chance to see if the instrument would function as planned, but they could watch their hardware in action, in preparation for the days when the instruments would be operated on Mars.[28]

Jim Martin and his staff on 25 November 1975 decided at least part of the tests the biology team wanted could be carried out during the flight-operations-software verification tests scheduled for the proof-test-capsule lander in February 1976. Only the tests that would not require extra funds could be done. Martin told Klein: "We have neither the dollars to extend the test nor the people to analyze the data." Other aspects of the biologists' plans for testing were likewise impossible:

> . . . your request for lander/biology tests with transmitters/antennae in real operational modes is also difficult to accommodate. As you know, this test would require use of an anechoic chamber (very expensive) or moving the entire lander to an outdoor location to avoid RF reflections (also expensive). We made a fundamental decision in 1973/1974 that the lander [electromagnetic compatibility] test program had to proceed without a real biology instrument because such an instrument did not exist until much too late. Instead, we have relied upon the positive results of a rigorous EMC test on the instrument at TRW. In today's dollar limited environment, the dollars to plan, set up, and conduct another radiated EMC test for biology are prohibitive. We must rely on analysis and instrument level test experience.[29]

While not enthusiastic about any additional biology testing, Martin informed Noel Hinners at NASA Headquarters that the "potential return from [the partial testing he had agreed to] is sufficient to incorporate it into our plans." He believed that the project management had "done everything reasonable to satisfy the concerns of the Biology Team as to the adequacy of the pre-landing test proram." Martin wanted to turn to other more important issues: "Following the test, we must and will devote the full biology flight team resources to preparation for landed operations, . . . including training contingency analysis and preparation of pre-canned sequences to be ready for the multiplicity of possible required reactions to data from Mars."[30]

REORGANIZATIONS AND ADDITIONAL CUTBACKS

During the remaining year and a half before the Viking launches, a number of changes were made in the top management structure at NASA. The first of these was announced by Administrator Fletcher on 5 March 1974. Rocco A. Petrone, director of the Marshall Space Flight Center, was appointed NASA associate administrator, the number three position at headquarters, replacing Homer Newell who retired in late 1973. John E. Naugle, named Petrone's deputy, continued to act as associate administrator for space science until Noel W. Hinners, director of lunar programs in the Office of Space Science,* was selected in June to fill the space science slot. When Petrone left NASA for a job in industry in April 1975, Naugle assumed his duties on an acting basis until 23 November, when he was appointed to that position.

Fletcher in March 1974 also announced a headquarters reorganization, with two primary objectives. First, he sought to consolidate under one senior official, the associate administrator, the planning and direction of all NASA's research and development programs. And second, by creating a new position—associate administrator for center operations, to whom the center directors would report—the administrator funneled the responsibility for the field centers to one office. George Low, deputy administrator, temporarily took on this new task until Edwin C. Kilgore was appointed in May 1974.

Fletcher stressed that the changes were necessary in this era of consolidation, an era of tightening budgets and reducing manpower levels.

> As we approach the time when the Space Shuttle becomes operational, there needs to be a mechanism for the orderly phaseover from conventional launch vehicles to the shuttle; at the same time we need to take an innovative and coordinated approach in planning and developing all of our future payloads—manned and unmanned, science, applications, and technology. Our aim is to achieve this consolidation of all Aeronautics and Space Activities through the office of the Associate Administrator.

NASA's administrator believed that the future of the agency's activities depended entirely upon the strength "of NASA's most important resource—the 25,000 people located primarily at our field centers." This figure was down from a peak of nearly 36 000 in fiscal year 1967.[31]

Petrone and Hinners had the unenviable task of keeping Viking project costs from escalating further. When Petrone assumed his responsibili-

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*In December 1971, a reorganization set up an Office of Space Science and an Office of Applications, replacing the Office of Space Science and Applications.

ties as associate administrator in March 1974, the projected completion cost of Viking had risen to $927.5 million, and nearly all of the cost problem was associated with the lander—the biology instrument, the gas chromatograph-mass spectrometer, and the guidance, control, and sequencing computer were among the leading troublemakers. As table 46 illustrates, the price of the orbiter was repeatedly pared to help pay for the lander. Money for support activities was held relatively constant. Actual costs for the orbiter and support activities were below the June-July 1970 estimates, but the lander was costing nearly $200 million more than it was projected to in 1970.[32]

Table 46
Viking Cost Projections, 1974

(in millions)

Date	Lander	Orbiter	Support	Total Estimated Cost at Completion (Estimated Total + APA[a])	Cumulative Total
July 1970 baseline	$359.8	$256.0	$134.2	$750.0 + $80.0 = $830.0	$ 51.0
Dec. 1970	359.8	256.0	134.2	750.0 + 80.0 = 830.0	54.5
June 1971	358.0	256.3	135.7	750.0 + 80.0 = 830.0	81.8
Jan. 1972	384.6	256.7	143.7	785.0 + 44.7 = 829.7	150.6
June 1972	414.4	252.3	134.5	801.2 + 28.2 = 829.4	223.8
Dec. 1972	426.1	251.3	132.2	809.6 + 19.8 = 829.4	366.6
June 1973	436.2	247.5	143.0	826.7 + 11.3 = 838.0	466.5
Dec. 1973	456.7	241.0	140.3	838.0 + 0.0 = 838.0	595.2
Mar. 1974	511.9	242.4	140.2	894.5 + 33.0 = 927.5	646.7
Apr. 1974	518.2	242.8	140.2	901.2 + 18.8 = 920.0	667.9
Dec. 1974	545.2	242.1	139.1	926.4 + 3.6 = 930.0	805.2
July 1975	548.7	243.0	138.0	926.2 + 3.5 = 929.7	855.2
July 1976	558.2	243.0	134.1	935.3 + 0.3 = 935.6	898.9
Jan. 1977 actual costs	558.2	240.5	115.8	972.4[b]	914.5

[a] Allowance for program adjustment (APA), or reserve funds.
[b] Estimate through end of prime mission.

In October 1974, Petrone and Hinners tightened the purse strings considerably. Viking budget ceilings were established for fiscal 1975 and 1976, and deviation from these amounts required Petrone's personal approval. Before any increase in the budget would be permitted, Petrone wanted to see documented evidence of steps taken to squeeze the dollars from elsewhere in the Viking budget. The reserve funds (allowance for program adjustments) were directly controlled by Petrone. Hinner's staff provided Petrone with weekly status reports on project costs and manpower levels for Martin Marietta, JPL, TRW, and Honeywell throughout the winter of 1974.[33]

Two important management changes also took place at the centers during the summer of 1975. At Langley in September, Ed Cortright, after 27 years of government service, retired and entered private industry and also served as president of the American Institute of Aeronautics and Astronautics. He was replaced by Donald P. Hearth, who since leaving the Lunar and Planetary Programs Office at NASA Headquarters in 1970 had been deputy director of the Goddard Space Flight Center in Greenbelt, Maryland. On the West Coast at the Jet Propulsion Laboratory, Bruce Murray had been appointed in April to succeed William Pickering, who was retiring after having led the laboratory since 1954. Hearth and Murray were old Mars program men. Occasionally they had disagreed over budget, manpower, and managerial issues during Mariner and the early years of Viking, but they would cooperate on the team that would launch, fly, and land the Viking spacecraft. Present from nearly the beginning of the search for life on Mars, Hearth and Murray would see the fruition of years of work from the inner NASA circle.[34]

In September 1974 when the second flight orbiter was canceled and the proof-test orbiter converted to a flight article, the third lander, the backup, was also terminated. By this move, Petrone and Hinners hoped to save an additional $9 million. As the project moved closer and closer to the billion-dollar mark, members of Congress had told NASA that no further reprogramming of funds, like shifting $40 million of the fiscal 1974 budget to Viking, would be allowed. In an across-the-board cost-reduction exercise, Jim Martin's project office searched for ways to save dollars to cover the expense of such items as the biology instrument and the GCMS.[35]

Three landers had been planned originally to ensure that at least two would be ready for launch. Had one of the prime landers suffered a last minute problem that required a violation of sterilization procedures and then reassembly and resterilization, the backup could have been used. With this third lander gone, only parts would be available for substitution should either flight lander have preflight troubles. The need for a backup orbiter had never been as critical as for the lander, since the orbiters did not have to go through the subassembly and completed assembly rigors of sterilization. Resterilization of either lander would have required precious time during the 65-day Viking launch window. The process at the Cape would require about 5 days, although only about 48 hours would actually be spent in the oven at microbe-killing temperatures.

If the first lander should fail at the time of launch, the second lander could replace the first with a minimum of lost time. If difficulties occurred during the second launch, however, it could take up to 27 days to remove the lander from its sterile capsule, disassemble it, find the malfunction, repair it, reassemble the lander, and then resterilize it. Under such a contingency, Martin and his people believed that they could carry out the work and still launch the second craft in time; it would be tight, but if the lander was repairable they thought they could get it on its way.[36]

PREPARING FOR LAUNCH

The first Viking flight hardware arrived at the Kennedy Space Center (KSC) during November and December 1974. This material included the Titan IIIE core vehicle (liquid-fueled rocket stage), the solid-fueled rocket motor components (strap-on booster stages), and the Centaur upper stage.* All of the elements were as close to flight configuration as practical when delivered, so that the major tasks remaining were only assembly and testing. The Centaur standard shroud, the "nose cone" that protected the orbiter and lander during ascent through Earth's atmosphere, was delivered ready for the addition of such bolt-on items as electrical harnesses, instrumentation, and insulation. Upon delivery, launch vehicle B, which would be used for the first mission, was prepared for the mating tests scheduled for April 1975.

Viking lander capsule 1 arrived at the Cape on 4 January 1975, and engineers made a detailed inspection and subjected the capsule and lander to a series of verification tests, which included compatibility checks between the S-band radios and the Deep Space Network. Last minute modifications followed, based on the test information, after which the radioisotope thermoelectric generators were installed and the lander system was finally built up for mating tests. Meanwhile, the first Viking orbiter arrived on 11 February and was put through the same rigorous verification tests.

Up to this point, the flight lander and orbiter had never been physically or electrically in direct contact, having been assembled over 1600 kilometers

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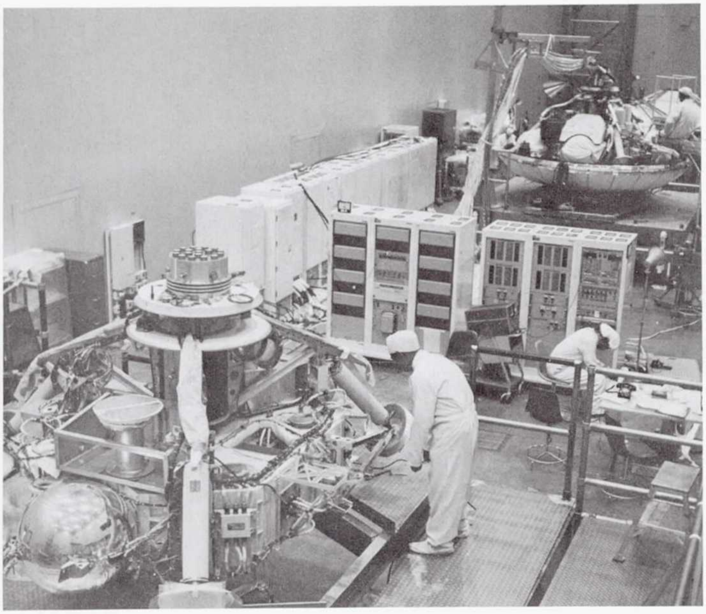
*The Titan IIIE core vehicle was shipped by C-5A aircraft from Denver, where it had been manufactured by Martin Marietta. The Centaur stage, built by General Dynamics Convair Division, was also flown to Florida on a C-5A from the factory in San Diego. United Technologies Chemical Systems Division shipped the solid rocket motors from Sunnyvale, California, by rail.



Work progresses on the Viking lander 1 (foreground) and 2 at the Martin Marietta plant in Denver in the fall of 1974.

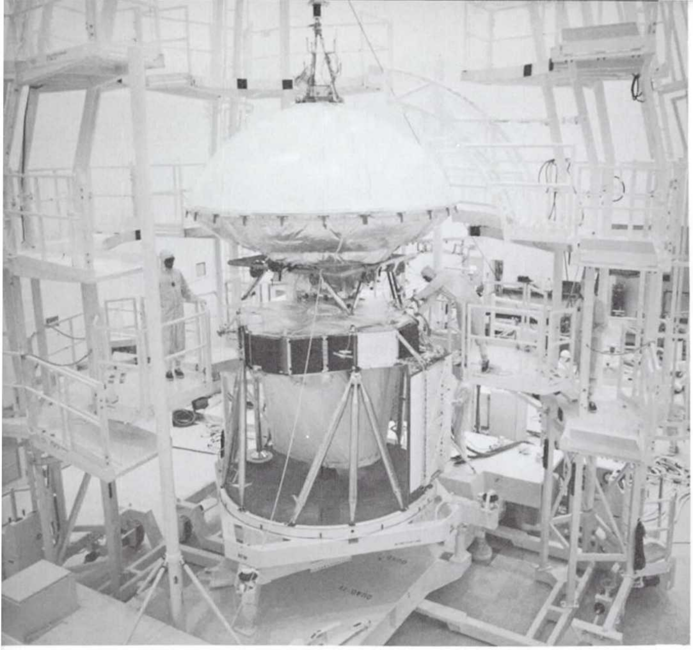
apart. Viking orbiter 1 and Viking lander capsule 1 were mated for the first time on 8 March. More than two weeks of interface and system testing indicated that they would work together satisfactorily. The next hurdle was encapsulating the orbiter-lander assembly inside the Centaur shroud on 27 March. The specialists in Florida would then run some additional tests before the whole unit was moved to launch complex 41 where the Titan IIIE stood assembled. After the assembly had been hoisted and mated to the launch vehicle on 31 March, another series of tests were carried out on this 48.5-meter-high stack of hardware. A flight events demonstration, Viking orbiter precount, Viking lander prelaunch, and terminal countdown—all were completed successfully.

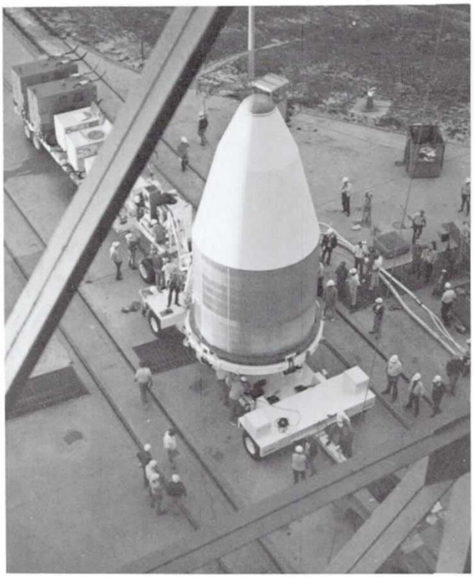
After mating tests, the orbiter and lander were removed from the launch vehicle and returned to the assembly facility for flight compatibility tests. The Viking flight team monitored these examinations from the Viking mission control and computing center in building 230. The Deep Space Network provided communications for telemetry and spacecraft commands. Concurrently, the second orbiter and lander were going through the checkout process so successfully that it became feasible to use either of the two craft for the first launch. This additional capability gave Jim Martin and his people a dose of extra confidence.

As work on the hardware moved along according to schedule, the men who would control and command the craft during the flight were also simulating mission activities. Members of the orbiter performance and analysis group participated in seven separate tests during April. For each activity through launch, the group had at least one test exercise that would prepare them for the real thing. The flight path analysis group simulated a midcourse maneuver exercise on 14 April, and the results were so successful that a repeat exercise was canceled.[37]

May was an equally active month at Kennedy, with some occasional troubles. Grounded circuitry delayed for two days the important plugs-out test (during which the spacecraft was on internal power) of Viking lander capsule 1, and some communications problems between ground data system and the Deep Space Network required additional tests. Orbiter performance and analysis group personnel experienced some difficulties with a computer program and had to reschedule orbiter simulations. Still, buildup and checkout of both Viking spacecraft were proceeding according to the latest schedules. All flight equipment, except for the gas chromatograph–mass spectrometer, had been installed on the first lander. Viking orbiter 1 was undergoing the system readiness test at the end of May, while installation of the high-gain antenna was begun on Viking orbiter 2.[38]

A lightning bolt that struck the Explosive Safe Area Building caused momentary excitement. Electrical charges from the strike induced currents that damaged two pressure transducers on the orbiter propulsion module S/N-005. After a quick review, the Viking managers decided not to fly this unit. Instead, S/N-006, being readied for the second launch, was assigned to the first spacecraft. Once again, the modular approach to building space-





Viking orbiter 1, top left, is mated to Viking lander 1 at Kennedy Space Center on 8 March 1975. Above, technicians lower the launch shroud over the spacecraft on 27 March. At left, the shrouded orbiter and lander move toward 31 March mating with the Titan IIIE launch vehicle, for more tests.

craft had paid off. To be able to substitute assemblies when required was clearly advantageous. Caution was a major element in preparing for a successful mission. Orbiter propulsion module S/N-005, its propellants unloaded, was refurbished as a spare. The previously designated backup was upgraded to flight unit status and assembled to the second orbiter. Buildup and checkout continued into June, interrupted now and then by thunderstorms and lightning alerts. To protect personnel and hardware, safety regulations at KSC stipulated that all activities had to be halted when a lightning alert was declared.[39]

A major milestone many people had worried about was passed when the first lander capsule (VLC-2) was successfully sterilized. Much of the trouble with the design, development, and testing of the lander subsystems had centered on building components that could withstand the high temperatures required to kill all terrestrial organisms. Eliminating microbes without degrading or destroying the hardware had been one of the major challenges of the project. Viking lander capsule 2 was placed in the sterilization chamber at Kennedy on 15 June. For more than 43 hours, the craft and its capsule were subjected to temperatures up to 116.2°C as heated nitrogen gas swirled around the hardware. The poststerilization short test verified that all subsystems were functioning properly. A number of minor glitches arose, but none proved to be a major concern.

Once the Viking management was assured of the first craft's good health, the second, VLC-1, was moved into the sterilization chamber for almost 50 hours. While lander 1 was readied for propellant loading, lander 2 and orbiter 2 were mated for a last time, officially becoming the Viking A spacecraft. By mid-July, the long process of designing, building, assembling, testing, and flight preparation was drawing to a close. The Viking A spacecraft was mated to its Titan launch vehicle on 28 July at launch complex 41. The 3500-kilogram spacecraft was ready to go to Mars. Preparations for Viking spacecraft B were proceeding for the second launch, while emphasis on personnel training increased during the last two months before the first liftoff.

System-level flight operations test and training continued with a series of verification tests. Verification test 3 on 12 June checked out the portion of the mission that included the launch of spacecraft B while spacecraft A was in its cruise phase. All the verification tests up to this point had been classified "short-loop"; their data—commands and the like—had been generated inside the Spaceflight Operations Facility at JPL. Beginning with verification test 4, data were exchanged between JPL and the tracking stations in Goldstone, California, and in Spain, test 4 verifying the design and execution of the spacecraft B midcourse maneuver. Verification test 1B was still more elaborate, and the loop was even longer. Simulating the launch portion of the Viking A mission, computers at the Kennedy Space Center generated data for the Viking Mission Operations Facility at JPL. Deep Space Station 42 at Tidbinbilla, Australia, also participated in this test, since it would be responsible for first communication with the spacecraft after launch. The launch phase of this simulation was normal, but trainers threw in a malfunction—an early cutoff of the Centaur engine—to test the reactions of the flight team. The team had to plan and execute an early emergency maneuver with the orbiter propulsion system to place the spacecraft on the proper trajectory to Mars. While no one really expected the Centaur upper stage to give any problems (it had been performing well for nearly a decade), the trainers wanted the flight team to prove its readiness for any contingency.

With these tests completed, the flight team was certified by the successful operational readiness test on 6 August.

Table 47
Viking Demonstration and Training Tests

Date	Test	Nature and Results
2 July	DT-2	Processing uplink commands to lander through orbiter for cruise checkout. Data processing went well, but flight team needed more training.
13 July	DT-3	Fifty-hour cruise operation test culminating mock midcourse maneuver. Working around the clock, flight team met several problems. Successful test.
25-26 July	DT-1	Three-part exercise. Part 1 covered spacecraft powerup through launch to 6 hours into mission. Part 2 covered midcourse maneuver. Part 3, conducted at request of Deep Space Network personnel, covered lander memory-readout sequence. All 3 parts successful.
10 July	TT-1	Simulation of midcourse maneuver with simulated emergencies. Not successful.
28 July	TT-1 rerun	Successful retest of TT-1.

SOURCE: R. D. Rinehart and H. Wright, "Daily KSC Status (FAX)," memos dated 23, 24, 25, and 26 June 1975; and VPO, "Mission Operations Status Bulletin," no. 7, 23 June 1975, and no. 8, 8 July 1975.

During the last week before liftoff, final preparations were made:

29 July	Orbiter precountdown checkout and lander cruise-mode monitoring tests completed.
30-31 July	Lander computer prelaunch checkout.
1 August	Composite electrical readiness test completed.
2 August	Super Zip installed on Viking A shroud. (Super Zip is a linear explosive charge used to separate the clamshell halves of the shroud after launch.)
3 August	Pyrotechnic ordnance devices installed on Viking A.
6-7 August	Propellants loaded into Titan IIIE launch vehicle.

Although a faulty valve and a battery discharge problem would delay the beginning of the journey to Mars by nine days, Viking was otherwise ready. Many had labored mightily to get the project to this point, and the adventure was about to begin. A great amount of work lay ahead of the Viking teams, however, before the landers could touch down on that distant, alien planet. One of the most important tasks, preparation for which had paralleled hardware development, was the selection and certification of scientifically valid but technologically safe landing sites on Mars. Before examination of the Martian environment could begin—and even while the Viking spacecraft headed out through space—many hours would be spent looking for safe havens for the two landers.[41]