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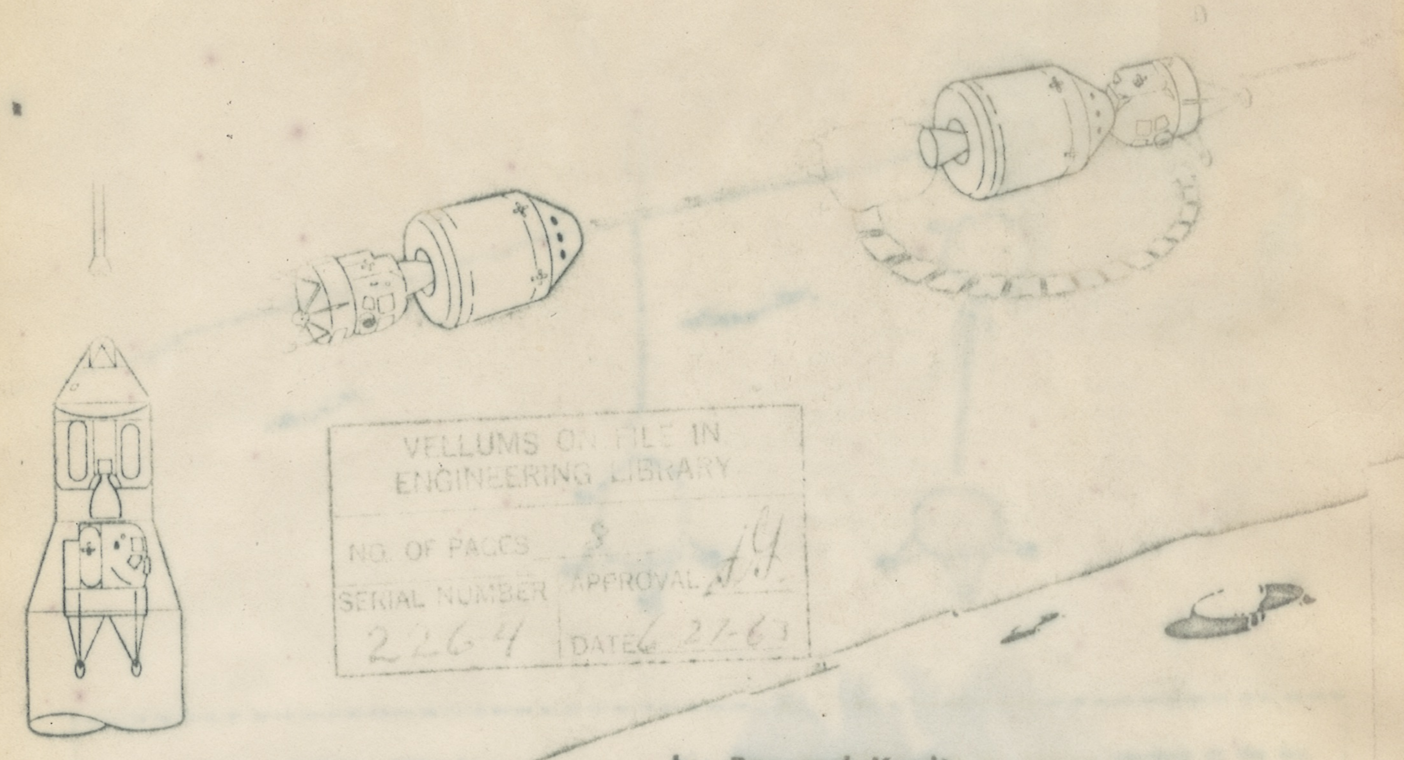


by **Bernard Kovit,** Associate Editor

THE "lunar excursion module" Grumman is building for NASA's Apollo project clearly is misnamed—an "excursion," says Webster's, is "a pleasure trip." The two men who will land on the moon in the LEM will be on anything but a pleasure trip. They will have to land on terrain that looks anything but promising, contend with temperatures ranging from 260 to −243 deg F, and let themselves be pelted by micrometeorites (according to some predictions) and perhaps by several forms of radiated energy as well. As NASA's and Grumman's plans stand now, the LEM might try its "lunar legs" as early as 1967 (*Table 1*). By 1970, it must be on the moon, or we'll all have to eat crow.

Neither date really leaves much time for the development of a vehicle such as we have never built before. The LEM is quite unlike the Apollo command module even (which will be a direct descendant of the Mercury capsule)—the LEM is the first U.S. vehicle that will operate exclusively in space. This unique distinction will color the entire LEM development effort.

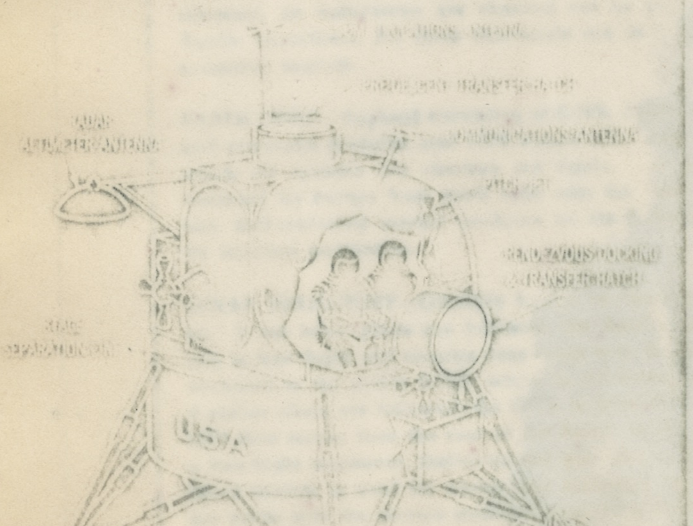
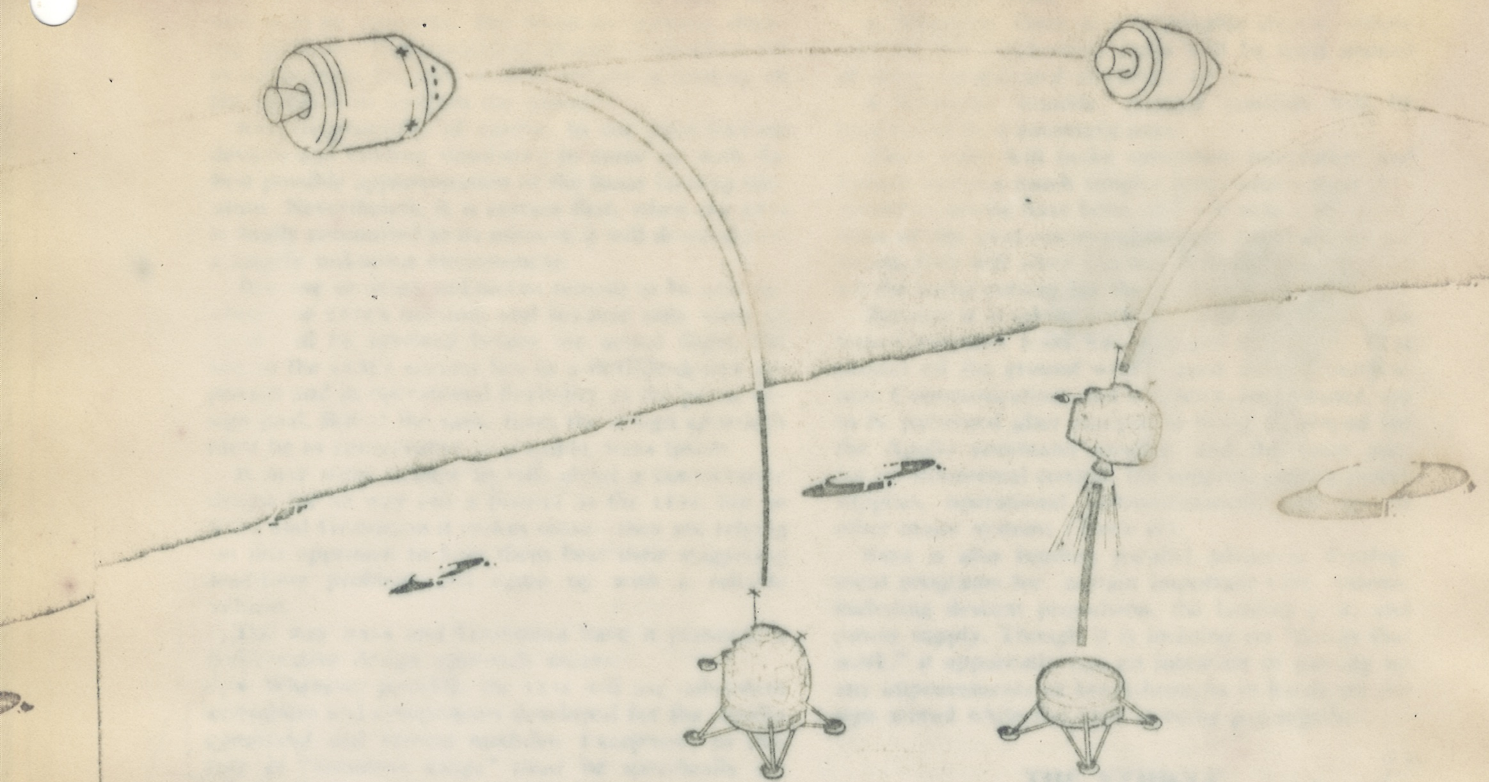


FIGURE 1: Grumman's working model of the LEM. The hatch protruding from the pressurized cabin may be replaced by a probe for mating with a drogue on the Apollo command module. In that case, the LEM astronauts will leave their vehicle through the same hatch at the top through which they will have entered.



LEM's Mission

COUNTDOWN AND LAUNCH—LEM is stowed along the longitudinal CG of the Saturn C-5, legs folded and antennas retracted. Its subsystems are checked out as part of the Apollo countdown. All three astronauts are in the Apollo command module.

EARTH ORBIT—Payload consisting of S-IVB, Apollo service and command modules, and LEM makes 1½ orbits, during which all systems are checked out again. The S-IVB is restarted for escape from earth orbit onto the lunar trajectory. Self-contained inertial guidance on the S-IVB is used for injection navigation.

LUNAR TRAJECTORY—Officially known as "translunar orbit." If the latest plans are followed, the Apollo turns 180 deg in free flight and couples nose-to-top with the LEM still anchored to the stable S-IVB, which is jettisoned later on; if earlier plans are followed, the S-IVB is jettisoned and the LEM then moves from the rear of the Apollo to the front in a free-flight maneuver. Stellar-inertial guidance in the command module is used for navigation; trajectory corrections are made with the service module's propulsion system.

LUNAR ORBIT—After about 60 hours in transit, the service module's engine is retro-fired to bring the three-module ship into a circular 50-100-mile moon orbit. Two astronauts enter the LEM through the docking interface at the top, activate and check the LEM systems, and extend the landing gear.

LUNAR LANDING—The LEM is uncoupled from the Apollo and its lander engine fired to bring it onto its descent trajectory. At about 1000 ft above the moon, the LEM hovers —moving horizontally as much as 1000-1200 ft—while the crew picks the landing site. For the final descent, auxiliary gas jets are used in addition to the lander engine.

SURFACE OPERATIONS—After landing, one astronaut leaves the LEM for a brief walking recon, carrying a four-hour oxygen supply in his back pack. The LEM serves as communications center and as the oxygen supply source whenever the roving astronaut returns for replenishing his back pack. The stay on the moon is expected to last two days but can be extended to three days if necessary.

ASCENT AND RENDEZVOUS—The LEM's upper, manned stage takes off, leaving the landing stage behind. Its ascent path brings it within maneuvering distance of the still orbiting Apollo, and it docks to the command module. (If the LEM is disabled, the Apollo performs the docking maneuver.) The astronauts leave the LEM and re-enter the command module, the LEM is jettisoned, and the service module's engine is fired to put the Apollo on the escape trajectory for the return to earth.

The Apollo-LEM schedule calls for a series of increasingly complex suborbital and earth-orbital flight tests in which as much as possible of the lunar mission is to be simulated. But while rendezvous, docking, guidance, and navigation all can be checked out in earth orbit, the only way to test out a landing on the moon is to land on the moon.

NASA is planning, of course, to use pilot-training devices and landing simulators to come up with the best possible approximation of the lunar landing situation. Nevertheless, it is certain that, when the LEM is finally committed to its mission, it will descend into a largely unknown environment.

Because so many unknowns remain to be resolved about the LEM's mission, and because only some of them will be resolved before the actual flight, the key to the LEM's success lies in a flexible design approach and in operational flexibility as the prime design goal. But at the same time, the design approach must be as conservative as possible, NASA insists.

It may seem strange to talk about a conservative design for so way out a project as the LEM, but to NASA and Grumman it makes sense—they are relying on this approach to help them beat their staggering lead-time problem and come up with a reliable vehicle.

The way NASA and Grumman have it planned, a conservative design approach means:

- Wherever possible, the LEM will use subsystem assemblies and components developed for the Apollo command and service modules. Exceptions to this rule of "common usage" must be specifically requested by Grumman and O.K.'ed by NASA-Houston.
- Existing types of sensors (e.g., Doppler radar) will be used rather than sensors that have yet to be fully developed (e.g., optical radar).
- Proven reliability methods will be used, including subsystem backup and redundancy in circuits and critical components.
- Whenever there is a reasonable choice, simple and reliable mechanical items will be used instead of more complicated electronic ones.
- Wherever feasible, manual controls will be used rather than automatic ones.

These rules will make subsystem integration and launch logistics much simpler propositions than they would otherwise have been, and will reduce the problems of the LEM-command-module interface. In addition, they will allow Grumman to get an early start on the metal-cutting for the final LEM structures.

Because it is taking such a cautious approach, the NASA-Grumman team has managed to get the LEM project off the ground with a good deal of momentum. Communications and telemetry, for instance, are to be patterned after equipment being developed for the Apollo command module, and the same goes for environmental control, life support, electric power supplies, operational instrumentation, and several other major systems (*Table II*).

NASA is also funding parallel advanced development programs for certain important LEM systems, including descent propulsion, the landing gear, and power supply. Though it is insisting on "things that work," it apparently has no intention of passing up any improvements or breakthroughs in hardware design scored while the LEM is being put together.

THE VEHICLE

The working design for the "bug" calls for a vehicle that is divided into two powered stages made basically of aluminum alloy and measures 10 ft in diameter,

Table I: LEM Timetable

1963

Prime contract signed with Grumman (end of February); all subcontracts signed (mid-July)

Electronics packaging and form factors worked out

Start final phases of propulsion design; first test firings

Full-scale mock-up completed (wood and metal)

Propellant-flow tests of Rocketdyne lander engine; engine mockup (by year's end?)

Mock-up of Bell takeoff engine; start of R&D on ablative nozzle for this engine

Start of work on alternative lander engine

1964

White Sands, N.M. base readied for LEM tests (orders for range instrumentation, communications and data processing)

Start fabrication of finalized structural sections

Distribution of structural sections among electronics and propulsion subcontractors for start of subsystem integration with structure.

Start of dynamics and stability tests and computations on subsystems

Start of simulated lunar landing tests

Start of prototype attitude control system (late '64)

Completion of boiler-plate version of LEM (by year's end)

1965

Start of tests at White Sands

Work on interfaces and interstage structures and dynamics between LEM and Apollo command module

Rendezvous simulated tests

Performance verification in vacuum for all equipment

Final development of landing gear

Three-stage C-5 and perhaps Saturn-Apollo combination ready for test (by year's end)

1966

Flightweight LEM ready for advanced tests at White Sands

If possible, Apollo and LEM in earth orbit to test separation, some free flight maneuvers, limited braking, etc.

All telemetry, life support, and other auxiliary equipment installed and environment-tested

1967

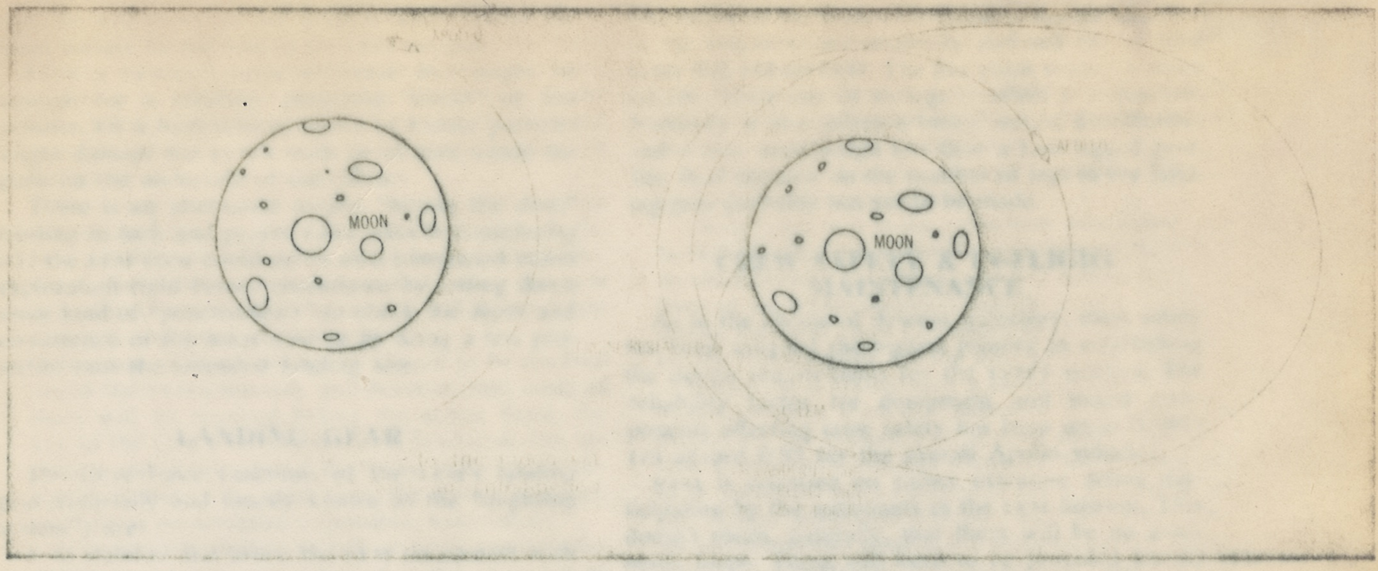
Rendezvous tests in earth orbit with Apollo (by mid-year)

Details of earth rendezvous in orbit worked out

Firing of LEM engines in space

Tests of crew personnel transfer from Apollo to LEM

First lunar landing (by year's end)



stands 17 ft high, and weighs 24,000 lb (*Fig. 1*). The manned stage consists of:

- a generally spherical two-man pressure cabin fitted with twin seats, life-support equipment, some electric storage units, various electronic subsystems, and a display and control panel;
- a slab-like unpressurized portion enclosing the 4000-lb-thrust takeoff rocket engine, the common tankage for this rocket and 16 reaction-control units, and portions of the navigation, guidance, communications, and electric power systems. The nozzle of the takeoff rocket actually protrudes beneath the slab and fits into the hole in the center of the landing stage in which the lander engine is installed.

This second stage consists of a wheel-shaped frame housing the 10,000-lb-thrust throttleable lander engine and spherical propellant tanks. Attached externally is the landing gear, which probably will consist of five extensible, tubular aluminum legs ending in circular pads. After serving as a support cradle for the manned stage, this stage will be left standing on the lunar surface while the manned stage ascends for its rendezvous with the Apollo mother ship in lunar orbit.

DYNAMICS

Where will LEM land? The final decision about this little detail will be up to the crew, but the general landing area will be preselected from the earth (on the basis of astronomical observations and what space-probe data may be available). This general area will be a four-mile-square region approximately athwart the lunar equator in the zone illuminated by earthshine. Its corrected lunar orbit ideally should bring the Apollo vehicle directly over this area.

The descent trajectory that the LEM will follow after uncoupling from Apollo and a very short coast in Apollo's circular lunar orbit will be timed to bring it over the preselected general landing area, and from there the crew will then choose the actual touchdown site. Of the various descent trajectories that could be used, the simplest probably is the "continuous burn" (*Fig. 2*). In this maneuver, the LEM's engine is ignited once at the proper point along the Apollo lunar orbit. The braking effect of the retro-engine is such that the LEM is pulled down towards the landing area by the moon's gravitational attraction (with the crew making reaction-control corrections).

Actually, present plans call for the LEM to descend via a "grazing, equal-period" orbit, which involves a more complicated maneuver than the continuous burn but also less of a risk. The grazing orbit is elliptical and, over the preselected landing area, comes within 60,000 ft of the lunar surface. The LEM engine is ignited twice in this descent—once for the transfer from the circular Apollo orbit to the grazing orbit and the second time for the steep descent from the grazing orbit to a hovering point about 1000 ft over the surface. From there, the crew can maneuver horizontally for the final approach and touchdown.

The restart will require only moderate amounts of additional fuel. In return, three safety factors will be achieved:

- If the LEM must abort while coasting in the grazing orbit, it will have a "free return rendezvous," since the grazing orbit intersects the circular Apollo orbit.
- The grazing orbit offers best assurance of a line of sight between the LEM and the Apollo for a last-minute abort during the final hover and landing phase.
- The grazing orbit, providing a shallow approach to the lunar surface, gives the crew some chance to examine the landing area.

Since we know woefully little about the surface of the moon, predicting all the dynamics of the LEM touchdown is beyond us (*Table III*). In particular, we can't predict the exact danger from either lunar surface dust or micrometeorites and other particles.

Estimates of the depth of the lunar dust layer range from two inches to many meters (*Fig. 3*). If there are meters of dust, the downward blast of the LEM's rockets plus the 5-15-FPS sink rate at touchdown might be enough to bore out a hole in which the LEM might promptly be buried by cave-ins and resettling waves of dust. The best reassurance against this unpleasant prospect probably is that only a few astronomers believe in a lunar dust layer measured in meters—our unmanned moon exploration program is not comprehensive enough to give us any certainty that we will know all we need to know about the lunar surface by the time of the LEM mission.

Even a two-inch layer of lunar dust might be enough for a blinding, persisting "cloud" of fine powder. Or a high-velocity spray of harder particles might damage the LEM's walls or at least erode the glass on the underside of the cabin.

There is an alternative to just "hitting the dust," trusting in luck and prayer (and NASA is considering it): the LEM crew could do its own unmanned moon exploration right before touchdown by letting down some kind of "penetrometer" to check the depth and consistency of the lunar dust or by firing a test projectile into the intended landing site.

LANDING GEAR

The three basic functions of the LEM's landing gear (officially and fancily known as the "alighting system") are:

- to stabilize and arrest the LEM on contact with the lunar surface;
- to provide a stable support for the LEM during its stay on the moon.
- To provide a stable platform for launching the manned stage of the LEM into its rendezvous trajectory with the Apollo for the trip back to the earth.

As the landing gear will be a one-shot affair, its structure does not have to recover its original shape and shock absorbency for re-use. On the other hand, not just any old "safe" landing will do. For one thing, the LEM must wind up fairly level if it is to take off again. (Its tilt may be limited to something like 15 deg.) There might thus be some merit in a system whose leg struts could be telescoped *after* landing to adjust LEM's attitude.

An impressive variety of designs has been studied for the alighting system, including both single- and multi-point-contact arrangements. Even a spring-type shock-absorbing mechanism was considered at one point (only to be rejected as of doubtful reliability). NASA and Grumman now seem to favor some kind of crushable, or compressible, material like aluminum honeycomb, balsa wood, or Styrofoam, to be used both within tubular, extensible legs and for cushioning circular foot pads.

Bendix Products' Aerospace Division has proposed a four-legged design that uses crushable aluminum honeycomb capsules within hollow telescoping struts made of thin aluminum alloy. The inner strut cylinder compresses the capsule in the outer one, so that energy is absorbed at the same time that the structural loads are carried from the pads to the vehicle body.

An actuator-and-latch mechanism in the main strut of each leg is used to extend the leg to the surface if not all the legs are firmly implanted after touchdown. Each extended leg locks automatically as soon as its pad rests on firm footing. The pads are made of aluminum, too, with honeycomb bonded to their undersides. Such a landing gear, says Bendix, could absorb a landing speed as much as 23 FPS (roughly twice the maximum expected for a normal touchdown), would exert a pressure of only 200 PSI at each pad, and would adapt itself to the characteristics given in NASA's model of the lunar surface.

Grumman itself has proposed a five-legged landing gear that NASA considers a simple yet ingenious alternative to the somewhat different system specified in the requirements originally outlined to the nine firms that bid on LEM. The five-point system is more reliable, since one of its legs in effect is redundant. Naturally it also offers a better weight distribution, and it may even weigh less than a four-legged gear. The final decision on the number of legs in the landing gear probably has yet to be made.

CREW SAFETY & IN-FLIGHT MAINTENANCE

As in the choice of descent trajectory, crew safety has been assigned the highest priority in establishing the design requirements for the LEM's systems. The reliability factor for equipment and major components affecting crew safety has been set at 0.9999 (as against 0.95 for the overall Apollo vehicle).

NASA is counting on rather extensive active participation by the astronauts in the LEM mission. This doesn't mean, naturally, that there will be no automatic loops. These will have to be provided for all tasks that exceed human capabilities, or might exceed them under an adverse condition arising out of an in-flight mishap. On the other hand, though, there is clearly no need for back-up servo controls for every manual operation. Which leaves Grumman with its most urgent design problem: just how much to automate.

The big problem of automatic control is, of course, that it costs weight. Grumman faces a similar problem in deciding how much maintenance the crew should be able to do. The more tools and spares are carried on board, the more reliability is gained—but is it worth the inevitable design trade-offs?

Any LEM system for which Grumman specifies in-flight maintenance probably will have to be installed within the pressure cabin, which then would have to be made that much larger and heavier. Even if such a system does not have to be located within the cabin, it will have to be accessible to the crew. Which raise the question: Accessible from where? From the lunar surface? The cabin? From outside during orbital flight? In any case, what effect will even this kind of accessibility have on the structural design and the weight distribution? It will be in working out these trade-off problems that Grumman will really earn its share of the $387.9 million NASA is paying for the LEM.

ELECTRIC POWER

It appears fairly certain that the LEM will carry a fuel cell as well as batteries. The fuel cell will be used during the descent to the moon, when the power demands are expected to reach their peak.

At present, a hydrogen-oxygen fuel cell is favored —because it has a high thermal efficiency, produces drinkable water, and is well along in development. The leading contenders for the fuel-cell contract include Allis-Chalmers (with a capillary membrane cell); GE (with an ion-exchange membrane cell), and P&WA (with the Bacon medium-temperature cell, being developed under license from Leesona-Moos).

LEM's overall power requirements are expected to range from a normal minimum of around 100 W to a maximum of 500 W. Provisions will be made for a temporary emergency overload of up to about one kilowatt. By staging the power—drawing

Table II: Contract Scorecard*

Contract	Amount (millions)	Contractor	Remarks
Prime	$387.9	Grumman	Cost plus fixed fee. Subcontracts will be let on cost-plus-incentive-fee basis, will require Pert contract-performance procedures. About 24 LEMs will be built.
Descent propulsion	$50**	Rocketdyne	For throttleable 10,000-lb-thrust rocket with fixed-area injector (gross aeration). Another contractor has yet to be selected for parallel development of a variable-aeration engine; contenders include Aerojet-General, Thiokol, UTC. NASA and Grumman will select one of these two engines for the actual LEM mission.
Takeoff propulsion	$30**	Bell Aerosystems	4000-lb fixed-thrust rocket with ablative nozzle.
Guidance & navigation	$50**	probably AC Spark Plug	MIT Instrumentation Lab responsible for system design, writing design specs, will recommend subcontractors.
Communications, telemetry, TV, displays, instrumentation	$40**	probably Collins Radio & RCA	Collins probably will supply major portions of telemetry communications; RCA probably will act mainly as system design consultant. MIT Instrumentation Labs responsible for radars. Grumman responsible for systems integration as well as overall communications, stability and control, and instrumentation design. It will rely on "make or buy?" decision rather than subsystem contract awards; may call for competitive bids on major components.
Structure & landing gear		Grumman	Grumman may buy design studies, materials, sections, and major parts.
Environmental control	$20**	Hamilton Standard	Ham-Stan also developing astronauts' suits and back packs.
Reaction control		Grumman, Marquardt	Marquardt will supply 16 100-lb thrusters and valving; Grumman will handle system integration.
Fuel cell		probably Allis-Chalmers, GE or P&WA	GE and P&WA already working on the furl cells for Gemini and Apollo, respectively; A-C has a NASA contract for another advanced fuel cell.

*As of February 15. The total LEM subcontracting can reasonably be forecast at $220-250 million. Grumman originally estimated $175 million (half of a $350 million overall contract), but by now no one figures on less than $200 million.

**Estimated.

on the fuel cell for the descent to and on the batteries for the ascent from the moon—the weight penalty is significantly reduced.

Silver-cadmium batteries are being considered for the conventional power supply. Whether these will be rechargeable (from the fuel cell or possibly from a solar cell array) is not yet clear.

ENVIRONMENTAL CONTROL

Hamilton Standard's environmental control system will provide an internal atmosphere in which the astronauts can operate with their face plates up. Theoretically the crew could work in "shirt sleeves" (as in the Apollo command module), but actually there won't be room enough in the LEM for them to put their suits on or take them off.

The atmosphere in the LEM cabin will be pure oxygen with a partial pressure of 5-7 PSI, and the internal temperature probably will be held between 68 and 74 deg F. How the latter requirement should be met after the landing on the moon—where extremes are expected of as much as 260 deg F during the lunar day and —243 deg F at night—is still a matter of some concern to the LEM's designers.

GUIDANCE & NAVIGATION

The guidance system recommended by MIT for the LEM reportedly will be a modified version of the Polaris' three-degree-of-freedom stable platform feeding information into a miniature digital computer. Data from several on-board sensors (including radar, optical, IR trackers, a radar altimeter and a digital clock) as well as some manual inputs will also be cranked into the computer. The latter will operate in real time for the computation of the descent and ascent trajectories, abort, attitude control, and the like, and on demand for other operational routines and for checks. It will probably take up no more than one cubic foot of space and have a 4096-word capacity. Micrologic and pre-programed operational control are being studied for it.

In addition to this primary guidance, the LEM will carry a strapped-down guidance system as a back-up. Furthermore, a sun tracker and/or a moon-horizon sensor may be used for takeoff guidance.

At both NASA and Grumman, there is considerable support for the idea of letting the astronauts handle most of the guidance, with the automatic guidance system used as reference and back-up. Another idea under discussion is to drop some sort of navigation beacon on the landing site in advance of the LEM. Even if such a beacon is used, however, NASA intends to keep the LEM independent of outside aids and so give it as much mission flexibility as possible. NASA also seems to fear that the crew's confidence in their ability to "fly" the LEM might be impaired if the beacon were essential for a successful landing.

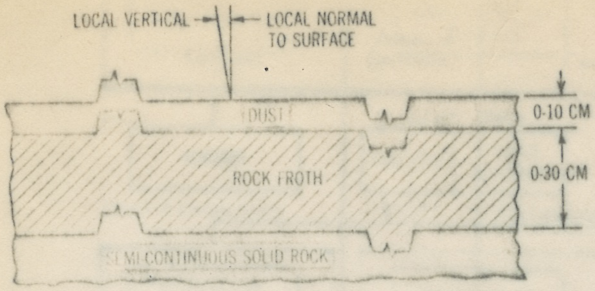


FIGURE 3: NASA's model of the lunar surface. The protuberances and depressions in each of the three surface layers may range up to 10 cm. The bearing strengths of the three layers are estimated at 12 PSI average for the dust, 200 PSI average for the rock froth, and 400 PSI for the semi-continuous solid rock. Particles of 0.3 mm diameter are expected at the top of the dust layer; others of 0.2 mm diameter at the bottom of the layer. The average angles between the local normal to the surface and the local vertical are given as three degrees for lunar maria and five degrees for craters.

Table III: Touchdown Conditions and Requirements

Surface slope	0-5 deg
Vehicle attitude to local vertical	0-5 deg
Vertical pitch rate about CG	0-0.1 rad/sec
Vertical velocity of CG	0-10 FPS
Horizontal velocity of CG	0-5 FPS
Friction coefficient	0-∞
Ambient pressure	10^{-14} torr
Ambient temperature	260 to −243 deg F
Max. CG acceleration	
Axial	193.2 ft/sec^2
Lateral	48.3 ft/sec^2
Component design frequencies	25 CPS
Design factors	impact = 1.0*
Safety factor	
Yield	1.0
Ultimate	1.5

*To be confirmed by dynamic analysis and tests.

COMMUNICATIONS

The LEM must have at least two communications links:

- *To the Apollo Command Module*—For this link, existing UHF equipment will probably be used. Typical operating frequencies under study are 72 and 982 mc. (It's believed that there will be no ionization problems in the area of the moon, but NASA is still supporting studies intended to confirm this belief as well as to determine the effects of high dust clouds.) The command module will be orbiting the moon at either 50 or 100 miles altitude. In the higher orbit, it would be in line of sight from the LEM for roughly 28 minutes during every hour.
- *To the Surface Explorer*—As the astronaut who will step out of the LEM probably will not venture farther than a mile or so from the safety of the ship, it should be fairly simple to provide ship-to-explorer communications on VHF bands with omnidirectional antennas. VHF would not be disturbed by a local dust cloud.

Major LEM Guidance Requirements

LANDING

Determining exact attitude and closure rate at all times

Maintaining correct attitude (with 16 reaction jets)

Maintaining astronauts' equilibrium reference (gyro-panel and/or the lunar horizon)

Precise stopping and restarting rocket of lander engine at essentially zero g

Soft touchdown with impact of no more than five g (lander engine probably will be throttled 1000 ft above the lunar surface; final descent vernier controlled with gas jets)

TAKEOFF

Obtaining a good sighting reference

Maintaining equilibrium and attitude control immediately after takeoff, when the most severe disturbing moments will occur

Programing of correct ascent path to rendezvous with the Apollo command module

Programing the final approach to rendezvous and docking

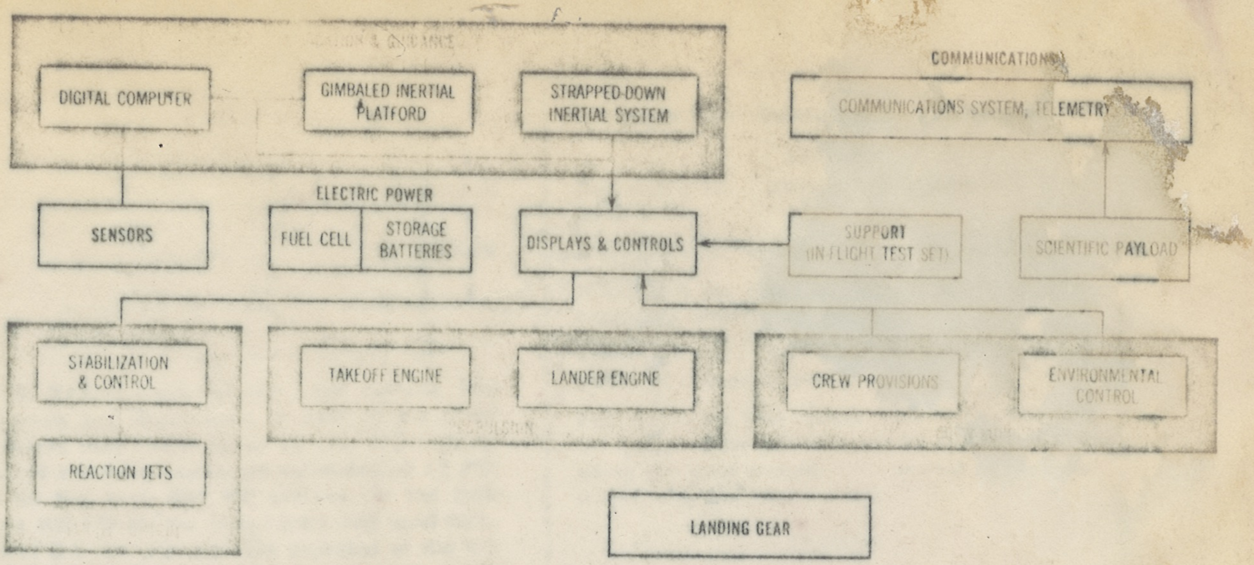
Whether a direct LEM-earth link should be provided, too, is still a matter of considerable debate. Under the present official plans, in any case, only the command module would communicate with earth stations. It will use UHF-FM and several VHF channels, probably operating on a frequency of around 108 mc. PCM telemetry will definitely be used. An S-band data link with DSIF stations at Goldstone, Calif., Johannesburg, South Africa, and Woomera, Australia, is also under consideration.

The pros and cons of TV in the LEM have been argued for some time. The proponents of TV have a good point when they note that, by 1967, we can use the 210-ft-diameter antennas of the DSIF net, which will use up less bandwidth than today's 85-footers. In fact, right now it looks as if the LEM will use TV, though probably only black-and-white and not in the early models. If TV is used, it will almost certainly operate in real time, using a half-field range and a half-line scanning rate.

To add to the reliability of voice and data transmission on the LEM mission, the interesting suggestion has been made to use a Relay-type moon satellite. This link could provide communications while the LEM and the Apollo are on different sides of the moon and would also insure longer periods of contact with the earth. Furthermore it could serve as an orientation reference for the LEM takeoff. Such a satellite would be placed in its lunar orbit before the Apollo is launched.

SENSORS

For the critically important measurements to be taken from the LEM current plans apparently call



MAJOR LEM systems and subsystems.

for a mix of discrete sensors: a radar altimeter, an optical horizon sensor, a tracking radar, and perhaps an IR horizon scanner and a simplified version of a laser range-finder. In addition there is to be a precise digital clock.

As an alternative, Sperry Gyroscope has proposed a multi-purpose radar for concurrent measurement of range, altitude, horizontal and vertical velocities, and local vertical. Sperry is pushing a coherent pulse radar (at X-band) with a scan coherent Doppler attachment. The whole unit would weigh 36 lb, the company says, take up 0.5 cu ft, and use components (including a two-foot dish) and modulation techniques that are within the state of the art.

PROPULSION & REACTION CONTROL

Of the LEM's two propulsion systems, the main engine in the lander stage will be a widely throttleable, gimbaled helium-injection rocket burning hydrazine and nitrogen tetroxide to produce a thrust of 10,000 lb. It will be developed under two parallel contracts, one of which has already been let to Rocketdyne. Rocketdyne has come up with at least two fixed-area injector designs based on gross aeration principles that can provide the necessary high combustion efficiencies while avoiding the large injector pressure drops with wide variations in fuel flow rate that have usually defeated this kind of design approach in the past. The throttling range is said to be 10:1. The second lander-engine program has been set up by NASA to develop a rocket using a mechanically controlled variable-area injector.

The takeoff engine, being developed by Bell Aerosystems, does not have to be gimbaled, for the CG of the LEM's ascending manned stage will be relatively stable. Reaction control should suffice for any adjustments necessary en route to rendezvous with Apollo. The Bell engine probably will use the same propellants as the lander engine and a fixed-area injector with a throttling range of roughly 3:1.

For reaction control, Grumman has designed a system using sixteen 100-lb thrusters, which will be supplied by Marquardt. These small rockets again will use the same storable hypergolic propellants as the primary propulsion units.

Reaction control is so critically important that more thrusters are being provided than are actually needed. The thrusters must be capable of steady-state operation as well as of pulse-modulated operation for attitude control. Their thrust will always be the same, but the firing time will be varied to provide the range of velocity increments demanded by the LEM's guidance and control system. One of Marquardt's big problems lies in providing for bursts from the thrusters that are short enough.

LEM'S FUTURE

Even as it stands today, the LEM program is one of impressive scope—six manned landings on the moon are planned, for which a total of 24 LEMS is to be built. In addition, NASA and Grumman are planning to design considerable growth potential into the LEM. For one thing, propellant tanks will be oversized considerably. Then if it's decided to use the LEM for more extensive lunar surface reconnaissance for instance, the necessary extra fuel can be added without changes in the basic vehicle design. Of course, the oversized tanks also increase the safety factor for the initial LEM mission.

The chances are excellent that the LEM rather than an entirely new design will be used as an unmanned lunar logistics vehicle, or "truck," to fly in support equipment and supplies in advance of the manned LEM landings. This truck version essentially would use the LEM's landing stage, to whose controls and propulsion system would be added whatever electronic and other equipment would be necessary for the unmanned mission. Flying this mission with a LEM truck would provide an excellent opportunity for testing and perfecting the manned LEM landing.

As the basic LEM design already includes provision for remote control from the Apollo, very little (if any) new equipment will have to be installed in the truck version. Controlled from Apollo, the truck would descend from lunar orbit to the landing site in a constant-burn descent.