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Critical Design Phase Ending on Lunar Excursion Module

Major system concepts now frozen; first mockup tests under way at Grumman; fuel cell, cryogenic tankage only big subcontracts left

by Michael Getler

HOUSTON—NASA-industry effort to design the spacecraft that will carry two U.S. astronauts to and from the lunar surface is now emerging from what is probably its most important but least glamorous phase—detailed design studies, initial weight-vs.-reliability trade-off decisions, and subsystem specification writing.

Seven months after selection of the Grumman Aircraft Engineering Corp. as prime contractor for LEM, NASA engineers at the Manned Spacecraft Center here report the major concepts and system design "are just about frozen."

Design study will continue in some areas for several years. Vital inputs concerning rendezvous and in-flight test and repair capabilities will come only after *Gemini* experience in 1964-65. Breakthroughs in knowledge of the nature of the lunar surface could cause a major redesign of the LEM landing gear, which has already undergone one significant shift.

But in contrast with the past and continuing perplexity of paper studies for this task, the first trio of wooden mock-ups now line the hangar bay at Grumman's Bethpage, N.Y., plant. In these models, engineers sit in wooden flight chairs and visually guide another wooden model of the *Apollo* command module into its LEM docking hatch.

• **Major subcontracting complete**—With approval late last month by NASA of RCA's $40-million role as a major LEM subcontractor for certain electronic subsystems (radar, communications, and portions of in-flight and ground testing, and some stabilization and control—S&C—units) plus engineering support, the LEM industrial team of major subcontractors (M/R, Feb. 4, p. 10) is virtually complete.

Two other sizable awards remain—a contract for development of the fuel cell for LEM, which will deliver primary on-board power, and the award for a single cryogenic tankage system that will supply oxygen for both the fuel cell and crew support.

The fuel cell contractor has been selected and announcement is "imminent." Completion of all major subcontracting and negotiations is expected by fall.

LEM should put the U.S. on the Moon by 1968, though "within the decade" is the official NASA prediction.

• **Mission profile**—Its journey starts aboard a *Saturn V* booster launched from the Atlantic Missile Range into Earth orbit. LEM will be tucked beneath the *Apollo* command and service modules (CM & SM). *Apollo* spacecraft weight at lift-off will be about 85,000 lbs. LEM accounts for 25,000 lbs. The three-man crew will ride in the CM at launch. The LEM cabin is not "man-rated" for Earth launch operations.

After in-flight and ground-directed checks in Earth orbit, the *Saturn's* third-stage (S-IVB) engines will be re-started, injecting *Apollo* and the stage into the lunar trajectory.

During early stages of the translunar flight, after passage through the Van Allen radiation belt, a transpositional docking maneuver will take place. Pyrotechnic devices will separate the CM & SM from the LEM and S-IVB. Using reaction control system (RCS) jets, being developed by Marquardt Corp., the attached CM & SM portion will rotate 180 degrees in a free-fly maneuver, approaching the LEM docking interface in a manner similar to the *Gemini-Agena* maneuver.

The unmanned portions of the vehicle, LEM and S-IVB, will be rate-stabilized, also in similar fashion to *Agena*, and may also have some degree of attitude stabilization, depending on mission plans.

The CM will dock "nose first" to the top docking hatch of LEM. After docking, pyrotechnic devices (probably shaped charges for large sheet areas and explosive bolts for the discrete attachments, the same type used for the escape tower) will separate LEM from the S-IVB stage adapter section.

The *Apollo* SM engine will then be used for mid-course corrections. Since the S-IVB will be in essentially the same trajectory, NASA is also studying possible changes in velocity associated with altering either section.

• **Lunar approach**—*Apollo* will follow what is described as a "free-return" trajectory, which is not as simple as the name implies. With this maneuver, if the spacecraft approaches the retro-fire point to enter lunar orbit but does not fire the SM engine, it can continue around the Moon, and, with the aid of the RCS, get back safely to pre-determined Earth recovery areas.

Throughout the *Apollo* and LEM flight plans, NASA engineers point out, every effort is made to use the natural capabilities of each trajectory chosen, each step becoming both more advanced and more precarious.

After a decision is made to enter

TRIO OF FIRST LEM face mockups lines Grumman hangar area. Center mockup is being used for crew-transfer-after-docking tests, also has favored 45-degree canted window arrangement. The vehicle is slated to land two men in the Moon in 1968.

lunar orbit, the retro-fire point will be reached on the back side of the Moon, and the SM engine will brake *Apollo* into a nominal 100-mi. two-hour circular orbit.

While in lunar orbit, two astronauts will enter LEM and perform in-flight checks. LEM will land near the lunar equator on the side facing Earth. This will facilitate communications with Earth stations. Roughly 90° from the chosen landing area, LEM will separate from the CM & SM at about 5 fps and begin a maneuver—using its descent engine facing away from the Moon—to put it into a highly elliptical equi-period orbit.

The closest approach to the lunar surface in this orbit will be about 50,000 ft. At its highest point, LEM will be considerably beyond the 100-mi. CM altitude. The LEM and CM orbits intersect, however, facilitating join-up if a decision is made not to land.

With this kind of orbit, which can be maintained for more than one pass around the Moon, the crew will experience an order-of-magnitude improvement in site reconnaissance before landing (they will have a Kollsman Instrument Corp. 3X telescope on-board to aid in site determination). Also, LEM and CM will be in visual contact at all times in this orbit.

• LEM descent details—From the equi-period orbit, the LEM crew will rely heavily on the widely throttleable (over a thrust range from 1,000-10,000 lbs.) descent engine and the RCS to get it onto the lunar surface.

NASA has awarded parallel development contracts to the Rocketdyne Div. of North American Aviation and to the Space Technology Laboratories subsidiary of Thompson Ramo Wooldridge, Inc. for this engine (M/R, June 3, p. 24). Selection of the winning design will probably come next summer.

The descent engine will burn continuously from about 50,000 ft. to a point a few feet above the surface, but at widely varied burning rates and at different engine orientations.

LEM descent will be automated (for more efficient fuel management) to a point about 1,000 ft. above the surface, where the craft will hover and shift to pilot control for the final let-down. NASA points out that the last 1,000 ft. could also be negotiated automatically, using the inertial measuring unit (IMU) and landing radar.

The landing radar will be used to update the IMU at about 20,000 ft. for accurate control of the flare maneuver, and will also be used as needed in this manner before the final control transition and hover.

LEM will be able to hover with some forward velocity to pick the best landing site, using the RCS to change pitch and direction. To approach setdown, the descent engine must be able to throttle below the effective weight of the vehicle on the Moon. The engine will be turned off a few feet above the surface, land with a near-zero velocity, nominally 10 fps vertically and 5 fps horizontally.

The entire descent from lunar orbit to the surface will take about 2½ hrs., with the final descent from 50,000 ft. lasting less than 10 min. The LEM mission is designed for a 48-hr. separation from the CM, with about a 24-hr. stay on the lunar surface.

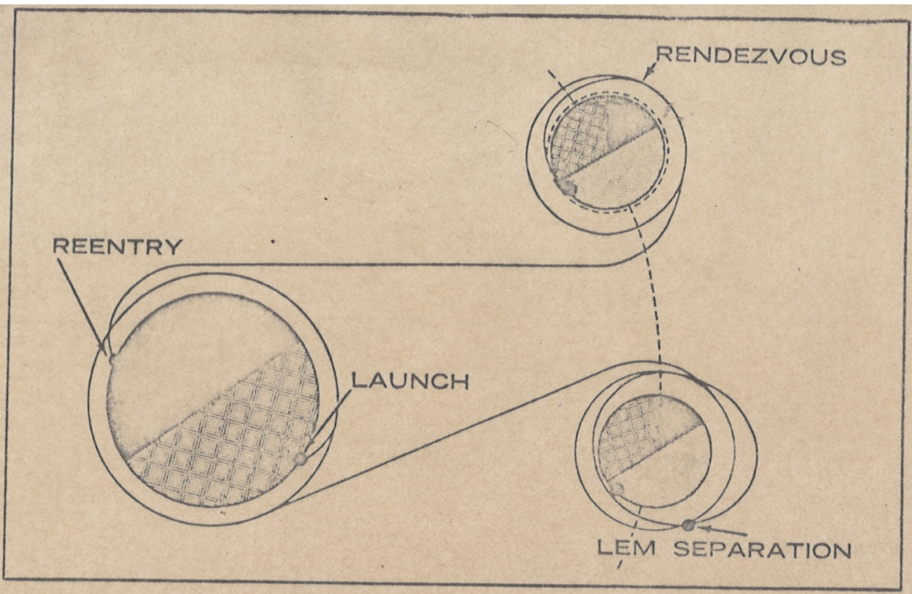
• Moon surface uncertainty—Composition of the lunar surface is still a matter of conjecture. Many observers believe its nature will be uncertain until someone actually sets foot on it. However, at this stage, NASA reportedly has assumed that the lunar surface cannot support as much weight as was originally suggested in the LEM RFP's. As a result, design of the landing gear has changed significantly.

While Grumman originally favored a relatively small-radius, five-leg fixed gear, they will now go to a deployable (while in translunar flight) four-leg gear, which is said to offer more flexibility and a larger radius.

The gear, to be built by Grumman, is described as a space-frame structure with discrete energy-dissipating rather than energy-absorbing shocks. The gear will have about a 30-ft. spread. The five-leg version had a spread just over 20 ft. Each leg will have a 3-ft.-dia. bearing pad at the foot, with a crushable structure on the bottom for energy dissipation. Gear radius and retraction techniques could undergo minor changes.

LEM is being designed to a lunar surface model of locally deep dust deposits which are probably only inches thick in large areas, covering a rock/froth-like substance. The model assumes a nominal 5° terrain slope. Superimposed on this, NASA reports, is the requirement to handle a 2-ft. difference in height between opposite legs of the LEM gear.

MSC engineers feel the craft might have to break through the surface 1-2



APOLLO-LEM FLIGHT PROFILE *shows possible lunar parking orbit.*

ft. to develop enough bearing pressure. "This is sort of like landing in a field of 2-ft. boulders," one engineer says.

Despite NASA's position, some recent reports by scientists credit the lunar surface layers with a bearing strength significantly higher than had previously been thought, claiming there is strength sufficient to support current landing craft design (M/R, June 10, p. 27).

In any case, testing the LEM gear for Moon use in an Earth environment is apt to be complicated. The answer probably will be found in either 1/6-scale tests or with full-scale restrained drop tests.

The LEM 4,000-lb.-thrust ascent stage, being developed by Bell Aerosystems Co., will give LEM abort capabilities even as it is touching down on the surface. "Fire-in-the-hole" temperature and pressure build-up problems associated with firing the ascent stage at close range to the descent engine are not serious, engineers report, because of the rapid thrust build-up in the ascent stage and some additional venting being incorporated into the design. One engineer says that operating in a 10-14 mmHg environment makes for a pretty efficient pump to aid venting.

• **LEM ascent**—LEM will weigh about four tons for lunar take-off. The ascent engine will lift it clear of the landing gear and descent stage, which serve as a launch pad and remain on the lunar surface.

The vehicle will rise to 50,000 ft., where it will be injected into a "home-and-transfer" trajectory aimed at rendezvous with the parent craft in lunar orbit at a point not quite 180 degrees from the lunar launch site. Rendezvous is to take place at 100 mi.

This type of trajectory, NASA says, also gives a low ΔV requirement for the engine. In the event conditions are not right for rendezvous, or in case of premature lift-off or emergency, LEM can stay in a 50,000-ft. lunar parking orbit until conditions improve.

• **Communication needs**—An elaborate communications network is being planned to support the LEM astronauts both on their way to the Moon and on the Lunar surface.

The major component of this, operating in the 2,000-mc range, will be the S-band DSIF-type link between Earth and LEM. Probably two more stations will be added to this net, which now services Jet Propulsion Laboratory's lunar and planetary probe requirements. One will be in the central U.S. and another in southern Europe, specifically in support of *Apollo* (M/R, July 8, p. 33).

This link will be used for TV, telemetry, two-way voice, and will also allow two-way Doppler track of the spacecraft from the ground, which NASA reports will provide a range fix accurate to within 15 meters regardless of range. LEM will carry a side-mounted steerable S-band antenna.

The S-band link will also serve as a backup LEM-to-CM link, operating from LEM-to-Earth-to-CM, in the event of failure in the primary VHF LEM-CM link. Use of the S-band network for this will extend communications time between LEM and CM to about 70% of CM orbit time. This will be the normal route when CM is not in line-of-sight (LOS) of LEM.

The LEM-CM VHF link uses two separate frequencies and will handle two-way voice only. The same VHF link will exist between LEM and an astronaut on the surface. In addition to two-way voice, a small telemetry capability will be added for suit temperature and biomedical sensors. VHF links aboard LEM will use fixed antennas.

Communications between two astronauts on the surface outside LEM will use the same VHF link, but the signal will pass through the LEM, shifting frequencies as it does. Should this loop break down, there is still another single frequency backup VHF mode directly between astronauts.

The LEM astronauts will also be able to carry a small TV camera onto the lunar surface. The camera will be attached to a 64-ft.-long cable, long enough for a crewman to move outside the vehicle and take pictures that include LEM against the lunar background to give an idea of size and perspective.

• **Guidance systems**—Guidance requirements for LEM will be met with the same basic package Massachusetts Institute of Technology and its industrial support team (A.C. Spark Plug Div. of General Motors, Raytheon, and Kollsman) is developing under contract from MSC for the *Apollo* CM guidance. The IMU and associated digital computer are essentially the same for LEM as for the CM, though there are some hardware variations and a different computer program. Grumman engineers say the firm, in conjunction with MSC, has already incorporated LEM requirements in the MIT-*Apollo* effort.

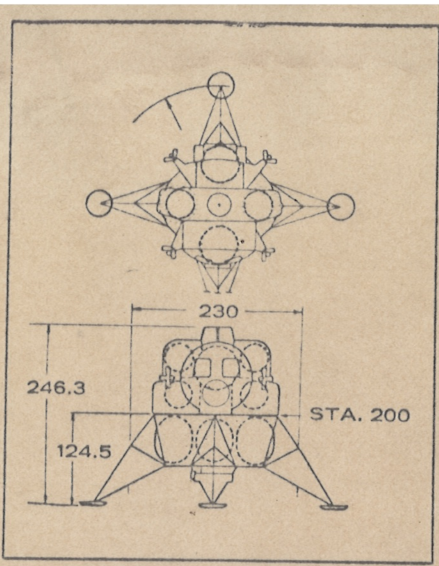
In addition to the prime IMU, LEM will have a backup guidance system that will depend mainly on gyro and accelerometer elements of the LEM S&C system for guidance information in event of degradation of the IMU.

Supporting the basic IMU will be a considerable radar package now under RCA's jurisdiction. There is widespread industry interest in the amount of subcontracting RCA will do on this, but to date there is no clear indication. Observers close to the program expect that some of the radar package will be subcontracted by the firm's Burlington Mass., Div.

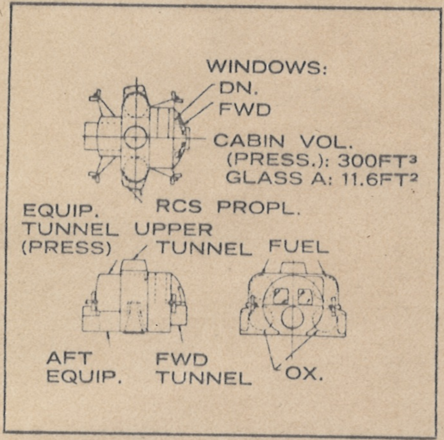
LEM will carry two basic radars—one for landing and one for rendezvous. Though design specs are not entirely firm, MISSILES AND ROCKETS has learned some of the "likely" details.

Both will operate at X-band and both will have individual antennas. The landing radar probably will be mounted on the bottom of the descent stage and have a forward-and-downward looking capability. This radar, which will make three component-velocity measurements plus altitude, is likely to be a coherent X-band device using three-beam Doppler with two-directional positions.

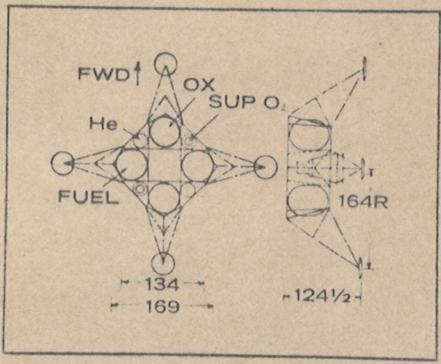
The rendezvous radar, mounted on the forward quarter of LEM (possibly on top of the ascent stage, looking forward and up) will be a gimballed coherent X-band unit operating in conjunction with a CM transponder. It will measure range, range rate, LOS and LOS rate.



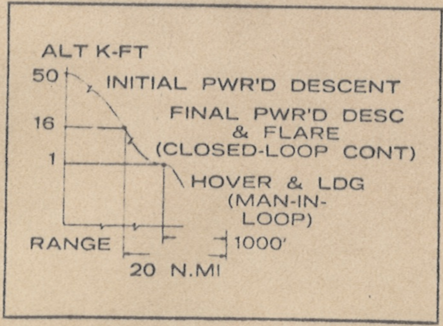
ENGINEERING DRAWING of LEM gives size. Dotted lines show fuel areas.



ASCENT STAGE ARRANGEMENT



DESCENT STAGE ARRANGEMENT



NOMINAL LANDING PROFILE

● **Power requirements**—The on-board LEM power will be supplied primarily by the hydrogen-oxygen fuel cell, in conjunction with some backup and "peaking" batteries for periods of extreme demand.

Current power profile looks like this: while in "idling operation" in trans-lunar phase, LEM will require about 300 watts; operating as a manned flying machine, levels will rise to about 1.5 kw, with peaks rising perhaps 50% above this, and even higher peaks of milli-second duration (RCS is a major user of on-board electrical power); lunar surface operations are expected to require about 1 kw.

These power demands are admittedly high in current design, but NASA hopes to knock the figures down "by as much as 50% as soon as 'power budgets' are introduced within a few weeks."

In recent weeks, NASA reports several other key studies of subsystem detail have been essentially completed, contributing to making the broad LEM concept firm.

It was decided, for example, that the LEM descent stage would have a gimbal-for-trim-only capability, and would not be used as an S&C element. This cuts down on RCS needs.

It was also decided to use baffles instead of bladders for ascent stage tankage—to avoid potential "fuel slosh" problems and difficulties with the roughly 40-in.-dia. tanks.

The basic form of tankage for the highly redundant RCS, layout of the electrical power system, stage tankage, fuel cell size, and lunar landing simulator inputs are also understood to be essentially completed.

● **Astronaut visibility**—One of the major areas still under study is crew visibility. Three interchangeable "faces" for LEM have been modeled in wood at Bethpage. All three have four windows, two facing forward and two downward. The downward-facing windows in two models are horizontal. The other model has a 45° "canted deck" window (which can be seen on the center mock-up in hangar bay photo), which is now said to be favored.

Overall visibility with this configuration is said to be best. It also allows the crew seat to remain in a single 16° forward position. At eye level, an astronaut can see 10 degrees up, 70 down, and, at the horizon, 21 degrees left and 23 degrees right with this arrangement.

The LEM crew station and inboard equipment bay will have the same shirt-sleeve environment as CM, but lack of space will keep it an open-face-plate affair. The cabin will have an oxygen atmosphere in the 3-5 psi range, with CO_2 removal via lithium-hydroxide canisters.

A spacesuit-type system will be used for waste control; the considerable input from *Gemini* experience is expected to influence final design. Hamilton Standard Div. of United Aircraft Corp. has responsibility for LEM life support.

One of the major design objectives in LEM was to make maximum use of equipment developed for the CM, a task made slightly easier since some of the CM hardware was designed for a landing mission before the shift to lunar orbit rendezvous. Most of LEM's "commonality" is found in the guidance, RCS, instrumentation system (PCM link and associated equipment), and the basic onboard communication gear.

In addition to common usage, there is also a critical trade-off continually going on concerning the measure of redundancy in LEM. "This is one of Grumman's key chores," NASA states.

Also continuing under study is the degree of in-flight repair. NASA says the concept of in-flight test and on-board spares wherever feasible is pretty firm, but some industry sources estimate it will be two years before the basic parts and man-maneuvers can be pinned down.

● **Eleven flight vehicles**—Grumman's funding of just under $390 million for LEM includes delivery of nine engineering development models, or LEM Test Articles (LTA's), and 11 flight versions. Before any of these are built, Grumman will also build five wood-and-metal mockups, and four test models, which are closer to engineering specs than are the mockups, but still relatively crude in comparison to the LTA's.

The first mockup (M-1) is built and has been in service for three months on visibility and crew-access studies. Portions of two others are also completed.

Work on two test models is already under way. One will be a full-scale antenna model using a copper screen around the wood frame. TM-4 will be used to check ascent/descent engine interfaces.

LTA planning is progressing, but no hardware is available yet. The first LTA (though not necessarily LTA-1) is expected to be completed at the end of '64. It will be used by Grumman as an integration model—to check electromagnetic interference and perform several other partial checks, including those of some propulsion systems.

LTA-2 will be used by Grumman and Marshall Space Flight Center for structural and landing gear evaluations. LTA's 3 and 4 will also be for Grumman structural and environmental tests. LTA-5 will go to White Sands, N.M., for propulsion checks. North American Aviation will run integration tests with LTA-6. MSC will get LTA-7, for environmental qualifications.

LTA's 8 and 9 will go to White

Sands to be used in conjunction with highly important piloted research programs, probably in 1966, which tie into both the flight and simulation program planned for LEM. In addition to the White Sands project, major LEM simulator inputs will come from the fixed-base simulator at Grumman, the Langley Field lunar landing facility, and the Flight Research Center vehicle at Edwards AFB.

The LTA's to be used in the White Sands test will be modified for piloted research in that most systems not having to do with the prime landing requirements will be off-loaded. Using only the descent stage for lift and descent, the LTA's will have roughly two minutes free-flight time, enabling some pilot experience and landing-system checkout.

● **Booster considerations**—Though details of the LEM flight vehicle schedule are closely guarded, it is known that the flight test program will include *Saturn IB* and *Saturn V* flights and probably two unmanned *Little Joe II* flights from White Sands.

Delivery of the first flight-model LEM is expected in 1965. A rough timetable for first suborbital unmanned launchings, using LEM plus a fairing to simulate the CM and SM, indicate the *Little Joe II* flights could go from White Sands late that same year.

Use of the 800,000-lb.-thrust version of *Little Joe II* would allow NASA to proceed with LEM development and flight tests without hampering *Saturn* development schedules, and would probably be less costly. The White Sands tests would all be suborbital, close-to-vertical firings, which would allow for LEM propulsion system tests including vacuum starts, staging checks, and shutdown and re-start of the ascent stage.

There are reported to be four LEM flight versions, including spares, earmarked for unmanned shots.

First manned three-module *Apollo* orbital shot is slated for 1966 aboard the *Saturn IB*. This mission is also expected to include some limited docking and rendezvous maneuvers. NASA says it hopes to fully qualify LEM on board the *Saturn IB*, bringing the *Saturn V* into the program in 1967 for launchings with LEM before the lunar attempt.

One reason for closely guarding the NASA flight schedule for LEM is that it is still not certain how many vehicles should be programmed for the mission's different phases. About four of the flight vehicles are now said to be planned as lunar landers, but there is considerable study within LEM program management involving use of some flight vehicles in lunar reconnaissance roles. NASA sources estimate it will be six to 12 months before the LEM vehicle programming is firm.

● **Gemini rendezvous inputs**—Decisions regarding the need and extent of actual rendezvous training in flight for *Apollo* crews, another factor in scheduling, will grow out of combined *Gemini* flight experience and simulator training.

MOCKUP OF LEM cabin with docking personnel-transfer tests in progress.

Though the complete lunar take-off and rendezvous maneuver will never be duplicated in training, many elements of long-range rendezvous can be brought into play in Earth orbit.

If a single booster were used, the spacecraft's on-board fuel requirements would be heavy. Some observers feel that this factor could lead to training using two boosters, as in *Gemini* or in the Russian "group" flights. "There is also an element of risk here," one top NASA engineer states, "that may do you no good. It is kind of like having a fighter pilot do a few parachute jumps in case he gets shot down in combat."

● **PERT taking shape**—To manage the extremely broad LEM program, NASA and Grumman will rely heavily on PERT. Grumman engineers say "first-cut" PERT charts on every subsystem are now completed, and should be applied in a few weeks.

Both NASA and Grumman officials feel that LEM has kept within contractual costs and neither foresees any overruns, barring any major shifts in a program that will not reach fruition for five years.

NASA officers here, some of whom have only recently left industry, have the feeling that "they have a better handle on this one than most other large programs." There has been some deliberation in naming subcontractors and outlining specs, but both NASA and Grumman officials feel this early drag will pay off later.

There is excellent rapport between MSC and Grumman. Though the basic LEM mission concept has not changed substantially since contract award, there is widespread praise for the manner in which Grumman has attacked the myriad of physical detail changes. ■