A LUNAR POLAR EXPEDITION

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Advanced exploration and development in harsh environments require mastery of basic human survival skills. Expeditions into the lethal climates of Earth's polar regions offer useful lessons for tomorrow's lunar pioneers. In Arctic and Antarctic exploration, "wintering over" was a crucial milestone. The ability to establish a supply base and survive months of polar cold and darkness made extensive travel and exploration possible. Because of the possibility of near-constant solar illumination, the lunar polar regions, unlike Earth's, may offer the most hospitable site for habitation. The World Space Foundation is examining a scenario for establishing a five-person expeditionary team on the lunar north pole for one year. This paper is a status report on a point design addressing site selection, transportation, power, and life support requirements.

POLAR EXPLORATION AND LUNAR OBJECTIVES

In March 1899, almost one hundred years ago, the explorer Carsten E. Borchgrevnik established the first winter camp on the "white continent," Antarctica. Unlike the north polar regions, Antarctica had never been inhabited by man. Though marine birds and animals visit the coastal regions, only primitive moss and lichen can survive the polar deserts of ice and snow. In the winter, no creature lives on the ice cap. Louis Bernacchi, a young Australian physicist who had joined the expedition, called it "... a land of unsurpassed desolation."

The International Geographical Congress, meeting in London during July, 1895, determined to make Antarctica the target of new exploration, launching an era of government-sponsored national expeditions. The British, especially, were planning a large-scale scientific expedition under the aegis of the Royal Geographic Society. But the Norwegian-born Australian, Borchgrevnik, was determined to get to the Antarctic and spend a winter there before anyone else. He sought private funding and found it in the fourth estate, a wealthy British publisher, Sir George Newnes.

Landing operations from their ship, Southern Cross, took 10 days to complete, including assembly of 2 prefabricated huts joined by a center section for ease of movement. During their 10-month winter camp, and before their relief on 28 January, 1900, expedition members collected specimens, made meteorological observations, and determined that the south magnetic pole was much farther north and east than previously supposed. Perhaps more importantly, they produced the first reliable charts of the Great Ice Barrier and conducted the first explorations by dog sled on the Ross Ice Shelf (*Kirwin,* 1960; *Huntford,* 1984; *Allen et al.,* 1985).

The expedition, despite its limited resources, achieved a lot. The scientific observations and collections, though not extensive, comprised a useful addition to detailed knowledge of Antarctica. But the expedition's true role was that of a reconnaissance team for the large, well-equipped expeditions then being planned. It proved that a party could winter ashore with comparative safety and carry out routine scientific work. Borchgrevnik's winter camp laid the groundwork and tested the techniques for a "golden age" of polar exploration in the following decades. These explorations would culminate in Admiral Robert Peary's attainment of the North Pole on 6 April, 1909, and Roald Amundson's magnificently planned expedition reaching the South Pole on 14 December, 1911. Today there are permanent residents in both the Arctic and Antarctic pursuing commercial and scientific activities. Indeed, the International Antarctic Treaty may prove a useful example for those trying to determine who "owns" the Moon.

Unlike Earth's polar regions, the lunar poles may be the most hospitable locations for early long-term human habitats, so we do not wish to press the polar exploration analogy too far. However, the critical importance of wintering over does apply to lunar exploration. The demonstrated ability to survive on the Moon for long periods is essential for advanced exploration, development, and settlement. The balance of this paper will address the requirements and advantages of an early long-duration mission to the lunar north pole.

DESIGN PHILOSOPHY

We propose a one-year stay on the lunar surface by five people as a thorough demonstration of our ability to live and work on the Moon. While a number of approaches to establishing a lunar base have been proposed, it is our intent to show that very little in the way of new technology or overly complex systems are required to demonstrate our capability to live and work on the Moon for extended periods. Specific transportation systems, base structures, life support, communications, and other techniques described may be very different from those employed for the first lunar base. However, a plausible approach is described here that would permit the next major step in lunar development within a decade for a reasonable expenditure (compared to Apollo or the space station), given our understanding of space systems to be developed for other purposes.

Several assumptions were made to guide this approach: (1) the poles afford the most hospitable environment; (2) no artificial gravity is required; (3) maximal use is made of flight-proven systems to minimize development risk and cost (sometimes with greater operations cost); (4) an abort or rescue option (except during lunar ascent) always exists; (5) an Earth-based rescue vehicle is available with a few weeks' notice; (6) the first base is a nucleus for subsequent operations; and (7) it must be kept simple.

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These somewhat arbitrary constraints are reasonable in terms of the engineering required. Air, food, and water requirements would be the same anywhere on the Moon. Near-constant illumination at a polar site may provide a decisive advantage in terms of power subsystem mass by eliminating the 14-day storage requirement and corresponding need for extra power generation during the day, or for nuclear power. While not necessarily indicative of future experience on the Moon, attempts to use nuclear power in Antarctica have been less than satisfactory. In 1962, a 1500-kW nuclear power plant was installed at McMurdo Base. It was decommissioned 10 years later after a history of fire, radiation leakage, and shutdown. The site was quarantined for six years and 11,000 cu m of contaminated rock had to be shipped back to the U.S. (*Allen et al.,* 1985).

Other advantages of a polar site include the ease of heat rejection, unobstructed astronomy, volatile resources evaluation and prospecting, and possible phenomena related to the unique thermal regime.

LUNAR ORBITER DATA

Our knowledge of the Moon's polar regions is derived from lunar orbiter photography. Five spacecraft were launched at three-month intervals between August 10, 1966, and August 1, 1967. The primary mission of the lunar orbiters was to identify safe landing sites on the Moon's nearside for the Apollo program. Target areas were photographed on film, which was then processed on board the spacecraft. These film frames were scanned for transmission to Earth where video signals were reconverted into photographic images.

Orbiters I-III successfully met all mission objectives, and consequently Orbiters IV and V were retargeted to provide photography of general scientific interest. They were placed in near-polar orbits from which virtually any part of the Moon could be photographed. Lunar Orbiter IV returned 13 high-resolution frames of the north polar region during its 70-day mission. Polar viewing was generally from an altitude of 2500-3500 km and resolution was approximately 100 m (*Hansen,* 1970). Maps prepared from this data in 1981 (U.S.G.S. 1:5,000,000 map I-1326-A) are based on the Apollo control system of 1973 and may contain positional discrepancies at the poles of several kilometers (*Kosofsky and El-Baz,* 1970; *Kuiper et al.,* 1967; *Hall,* 1981).

The Moon's axis of rotation is inclined 1.5° off the normal to the ecliptic. Using the standard lunar reference datum radius of 1738 km, were the Moon a perfect sphere, an object 595 m in elevation at the pole would be in sunlight even during extremes of libration. This is a modest elevation for crater features comparable to Peary Crater, but the elevation of the surrounding terrain is unknown. If it is typical of other highland regions, elevations 2-3 km higher than the datum are not unusual. Nonetheless, the area is illuminated in the photographs we have now. The radar altimeter planned for the Lunar Geoscience Orbiter (LGO) will provide useful new topographic data and improved geodesy will refine positional errors. In the meantime, stereometric information is available in the overlapping Lunar Orbiter IV frames and investigations are underway to estimate the heights of local features relative to the floor of Peary Crater.

It is possible that solar illumination may be periodically interrupted by shadows cast from nearby features. If these can be identified, the difficulty may be surmounted by careful choice of position or by increasing the height of the support tower for the solar arrays. Illumination will certainly be interrupted for a few hours during eclipse cycles, and this eventuality is anticipated in the reserve power subsystem design.

BASE CHARACTERISTICS

Features of this lunar base unique to its polar location have been considered in some detail, while more generic features such as habitat design, architectural layout, and equipment design have been better described by other investigators. Masses have been estimated for generic and site-specific equipment, to arrive at a total of 30,000 kg of cargo brought by four autolanders to support the crew of five for one year (Table 1).

TABLE 1. Polar base mass summary.

Category	Mass (kg)	Remarks
Habitat	7,500	40 m^3/person, 2 modules (approx. size of Spacelab double segment)
Safe Haven	2,500	4 m^3/person, isolated
Power	3,800	3 kWe/person, includes heat rejection
Consumables	8,200	only water recycled
General Equipment	2,700	science, technology, loader, miscellaneous
Rovers	600	two units, two-person each
EVA Suits	1,300	3 per person, not including flight
Personal Effects	400	85 kg per person
Reserve (10%)	3000	
Total	30,000	

Includes all cargo carried aboard autolanders. Does not include crew and their flight spacesuit/backpacks that are brought aboard the crew lander.

Power

The crew's first order of business after landing will be to verify that the autolander payload integrity is sufficient to permit an extended stay on the surface. (Initial verification will have been provided via telemetry long before the crew leaves Earth.) Within a few hours of landing, the rovers will be deployed and loaded with solar panel packages and the packaged erectable power tower. A check of stellar, solar, and topographic positions will verify that the location chosen before launch for the power tower is adequate. Three crewmembers will erect the Astromast-type tower, attaching solar panels and guy wires as the tower is motor- or hand-driven to its approximately 100-m height. The other two crewmembers, in one of the rovers, will lay up to 2 km of cable between the tower and base equipment.

The site tentatively chosen based on available lunar orbiter imagery lies at the intersection of the rim of Peary Crater and the smaller crater containing the north pole. (We refer to this as Polaris Crater. In fact, this crater may or may not contain the pole. It is about 8 km in diameter, which is about the same as the geodetic uncertainty in the polar region.) This intersection is toward the west limb (as viewed from Earth) at about the eight o'clock position on Polaris' rim (Figs. 1 and 2). Three ridges formed by the rims of Peary and Polaris afford steep slopes facing in three different directions down which the solar blankets may be rolled in the event no suitable location for the tower is found immediately. At any one time, it appears that one of these slopes will be illuminated, at least during the landing period of "high" sun elevation when the sun is 1.5° above the ideal horizon.

Batteries permit up to 15 hr of energy storage for discharge at a standby level of 500 W per person. Additional power may be possible by salvaging the autolander batteries, which are not a part

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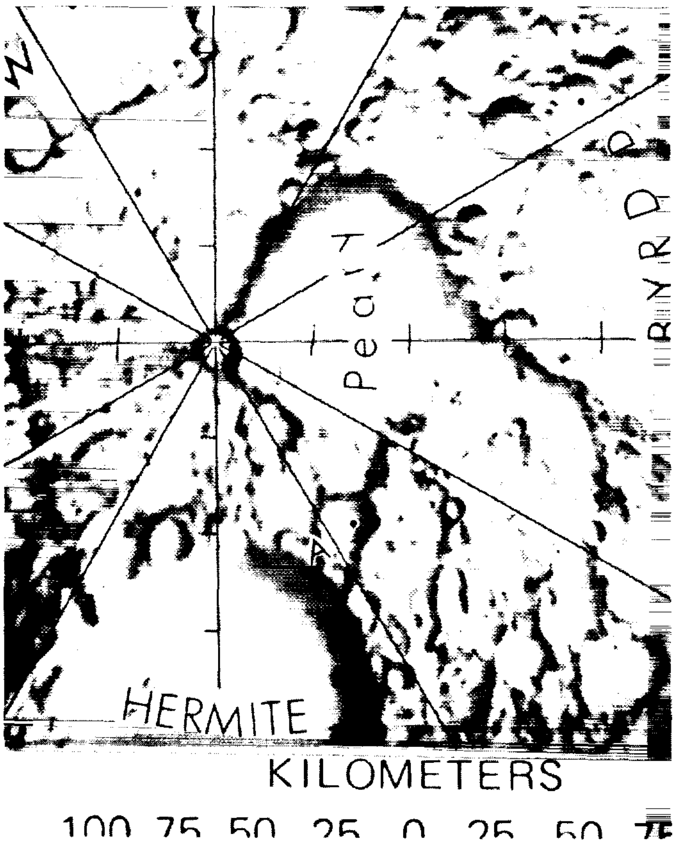

Fig. 1. Enlarged segment of U.S.G.S. Map I-1326 showing north polar region. The polar position shown here appears inside Polaris Crater on the rim of Peary. Actual position of the pole is uncertain.

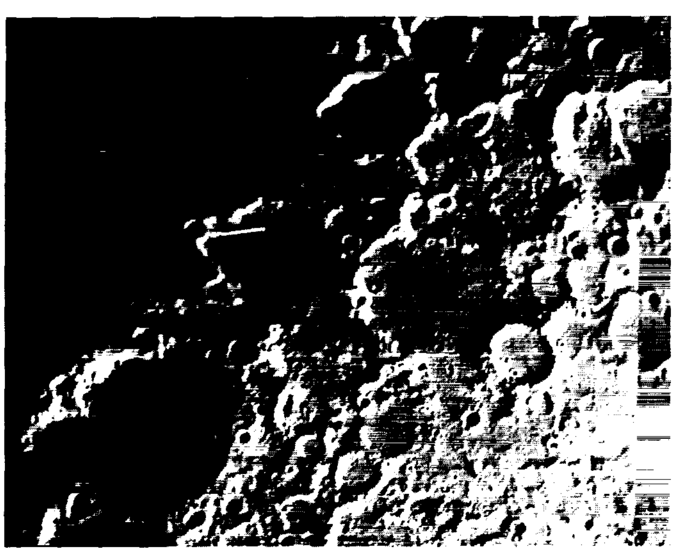

Fig. 2. Lunar Orbiter IV image showing nearside north polar region. Peary is the large crater containing the center of the frame, while Polaris is near the center of the top edge. Photo: NASA and U.S.G.S.

of the base mass budget. This energy reserve is sufficient to handle eclipses and solar obstruction by terrain features up to 8° in angular width as seen from the power tower (Table 2).

TABLE 2. Power subsystem mass summary.

Component	Mass (kg)	Remarks
Solar Panels/Blankets	1500	Si, 25% illumination factor (250 W/kg)
Cable and Connectors	1500	Depends on voltage, AC/DC?
Power Tower	250	Up to 100 m
Secondary Batteries	375	Eclipse, shadow power (37 kWhr)
Conditioning and Controls	175	External to habitat
Total	3800	

Not including equipment integral to habitats, or batteries aboard rovers, loader, or autolanders.

Habitat

No specific habitat design was considered because many different configurations and construction techniques have been proposed. The mass was estimated by comparison of published sources. One possible approach will be to have two cylindrical modules with airlocks carried by two of the autolanders in condition ready for occupation. Another autolander will carry a half-ton loader/crane that can be loaded with rock and soil for ballast. The crew-operated loader will dig trenches in an appropriate location large enough to contain the two modules. In one scenario, the modules are equipped with a wheeled cradle on which they are lowered to the ground and towed into the trench. First one module is moved, buried, and all operations verified, while the crew lives in the other module. Then the crew moves to the newly buried module. The second module is positioned and connected with the first.

Systems utilizing inflatable living quarters or other techniques may be superior. Whatever technique is employed, the living quarters are likely to be buried under 2 m of soil for protection from powerful solar flares and cosmic rays. The safe haven may then be maintained in an isolated location in case of catastrophic destruction of the two connected living modules.

Consumables

Advanced lunar operations will become dependent on highly regenerative life support systems, especially for carbon, hydrogen, and nitrogen (oxygen will be available from processing rock). To keep operation simple and development risk as low as possible for this first base, however, only water is recycled, and no "living off the land" is assumed, even in the event that ices are discovered in nearby permanently shadowed craters (*Watson et al.,* 1961; *Staehle,* 1983). Water recycling has been demonstrated in numerous live-in ground tests, while carbon dioxide and trace odor removal may be performed as aboard Skylab. A portion of the water allocation may be brought in food to permit a more palatable menu. Lunar gravity will permit more conventional food preparation and presentation than on past space missions. Pilot production of resources may be attempted in the course of technology experiments carried out by the crew. Operationally useful gases or liquids could be stored in empty autolander tanks for later use (Table 3).

TABLE 3. Consumable mass allocations.

Category	Mass (kg)	Remarks
Oxygen	2975	7.0 × body mass/year
Food	1910	4.5 × body mass/year
Water	955	9.0 × body mass/year (75% recycling)
Airlock and leakage	2360	includes 2 airlock cycles/day
Total	8200	

Assumes 85 kg body mass and safety factor of 0.2. These figures could be substantially improved by recycling of oxygen and pumping out an airlock during egress for EVA.

Equipment

A small variety of equipment is possible within the autolander mass allocation. If available, an additional autolander could be devoted entirely to added equipment, permitting much more in the way of scientific investigations and pilot production (Table 4).

Rovers and Space Suits

Two-person rovers are allocated in the mass budget at 300 kg each, compared with 210 kg for the Boeing/Apollo lunar roving vehicle (LRV). The LRV had a total of 1 hp with a top speed of 14 km/hr. A similar configuration is anticipated, somewhat ruggedized for longer use and with rechargeable batteries. A range of about 120 km would be desirable, but may be impractical from a mass, speed, and portable life support system (PLSS) endurance standpoint. If achievable, a 120-km range would allow reconnaissance of the entire floor of Peary Crater, and possible emplacement of a communications relay on the far rim of Peary. Suit/PLSS combinations are allocated 85 kg each, about the same as Apollo. However, the Apollo suits would be quite inadequate for the heavy usage expected at the lunar polar base. Three complete suits with PLSS are allocated per crewmember. In addition, each crewmember lands in a flight suit capable of surface EVA. Two surface suits would presumably be alternated for each crewmember, with the third held in reserve. Considerable development and heavy testing on the ground will be required to qualify suits for the base. Current work on zero prebreathe hardsuits suggests likely configurations (*AW&ST,* 1988).

MISSION PROFILE

At least one year before the crew is to arrive, two or three automated precursor missions are launched to survey the base site. If the LGO (*Phillips et al.,* 1986) has already flown, its imaging data will have allowed selection of a site having close to continuous illumination to within about 100-200 m. If the LGO carries an infrared thermal radiometer, a polar-temperature map with illumination from different longitudes will be available, but is not essential. If necessary, a Ranger-style imaging impact probe (IIP) will be targeted to the center of the selected base area to return imagery with resolution substantially better than 1 m. To obtain a 500 × 500-m image with 1-m resolution and 256 grey levels requires 2.25 million bits. Assuming a 2-km/sec impact velocity, if the last image is taken at a 4-km altitude and transmitted while the spacecraft is at least 2 km above the surface, a data rate of 1.1 Mbps is required, which is supportable over the Deep Space Net at lunar distance.

If the LGO has not flown, a somewhat simpler lunar imaging polar orbiter (LIPO) may be required to perform a one-month-long polar lighting survey over one full lunar day when the sun is at its minimum elevation angle of about 1.5° below the ideal horizon as seen from the north pole. If flown, LIPO would follow the original LGO mission profile carrying only the 11-kg Geodesic Imager or a similar instrument and associated support subsystems. We do not think that existing lunar orbiter imagery is adequate to select a north polar base site. Existing data could be adequate only if these images prove sufficient to target the IIP and to assure that a properly located solar panel tower of a given height will be in shadow for no more than about ten hours per lunar day.

The IIP carries with it four hard-landing navigation beacons carrying plastic sheet impact markers and strobe lights synchronized to the IIP cameras. These heavily cushioned navigational impactors (NIs) are patterned after similar devices on the first Rangers, which carried a seismometer in a balsa wood sphere designed (and successfully tested on Earth) to survive impact and transmit results for an extended period after impact. (The Rangers carrying these instrumented impactors failed for reasons unrelated to the instrument packages.) About 20 min before impact, NIs are ejected ahead of the IIP with about 10-m/sec along-track and 0.25-m/sec crosstrack velocity radially away from the IIP path. This assures their impact points will be visible within several images of the IIP. Upon impact they begin transmitting navigation test signals that are measured during the last seconds of the IIP flight. The results are relayed to Earth. The NIs then shift to a low-power standby mode, to be activated by an incoming autolander. Two or three operating beacons are required to guide the autolanders.

A rudimentary rover having a range of perhaps 10 km could supplement or replace the NIs. The rover would be landed within the target area to perform a detailed imaging survey and place several navigation beacons at locations correlated with the IIP imagery. While it would be helpful, such a rover is not essential. Two redundant IIP/NI missions are the recommended alternative, being much less costly than a rover.

TABLE 4. Equipment mass allocations.

Category	Mass (kg)	Remarks
Science Experiments	800	Selection to be made
Technology Experiments	800	Oriented towards expanded base, self-sufficiency
Loader	500	Excavation and towing
Miscellaneous Tools	400	Repairs, manual excavation
Film	100	
Communication Repeaters	100	Ridgetop relay to Earth
Total	2700	

Not including items integral to habitation modules.

Within a year after the IIP precursor, a communications relay orbiter (RO) is placed in polar orbit to verify the navigation beacons and monitor the autolander landings and the integrity of their cargo. Shortly afterward the first of four cargo missions is launched on a heavy lift vehicle (HLV), with subsequent loads landed at three-month intervals. Approximately 30,000 kg of base equipment, shelters, consumables, etc. are landed in four autolanders prior to the crew's arrival. Each autolander is guided to within 50-100 m of its chosen landing site using its onboard control system and the navigation beacons. In this manner they may be dispersed in the base area to eliminate interference, especially in the event of a failure.

When all four cargo loads are down and their integrity verified using onboard sensors, the base crew of five is launched aboard the shuttle or other crew transport into a low Earth parking orbit. Then an automated HLV launches the crew's Earth departure stage (EDS) with its payload of the command service module (CSM) and crew lander (CL) into a nearby orbit. The shuttle executes a final rendezvous and docking. The crew transfers to the command module and is ready to deport. No other mission-specific equipment need be carried by the shuttle. The crew's EDS superficially resembles the larger Apollo Saturn V S-IVB stage with the CL carried in a shroud beneath the CSM. Translunar injection (TLI) begins when the EDS cryogenic engines are ignited. After shutdown, the CSM turns around and docks with the CL. Finally, the docked CSM/CL is separated from the EDS to begin four days' transit to the Moon.

Targeted for 185-km altitude, the CSM executes its lunar orbit insertion (LOI) maneuver, placing it in polar orbit with a 2-hr period. Final observations verify the landing site, after which the CSM is put into a semidormant mode under ground control. The entire crew boards the CL, separates from the CSM, and fires the descent stage (CL-DS) engine to enter a 185 × 15-km orbit, with pericynthion about 500 km up-range from the landing site. From here, the landing essentially follows the Apollo profile (*MET,* 1971; *Staehle,* 1980), but with the navigation beacons assisting the pilots to a precision landing. With its landing close to Surveyor 3, Apollo 12 demonstrated adequate landing accuracy without navigation beacons but with ground tracking.

Following landing and a brief system check with the opportunity to abort to orbit, the crew immediately transfers to one of the autolanders with the storm shelter, habitation module, and solar panel packages on board. Power collectors are set up as the next order of business, followed by other base activities described later. The relay orbiter can provide a periodic communications link with Earth when Earth is below the horizon and with rovers or crewmembers some distance from the base site.

For the return trip, the crew reboards the CL and flies to orbit in the ascent stage (CL-AS), executes a rendezvous and docks with the CSM, transfers to the CM, and discards the CL. The CSM fires its propulsion system in the trans-Earth injection (TEI) maneuver, and carries the crew back to Earth. A few hours before entering the atmosphere the CM separates from the SM and orients for entry, and then enters, splashes down, and waits for the recovery ship just as with Apollo. Aerobraking and rendezvous with a shuttle can be used as well. All the base equipment and remaining consumables are left intact on the Moon, perhaps already in use by relief crews following the first to live and work over a year on the Moon.

Figure 3 shows the lunar mission profile and maneuver velocity roadmap. A summary of the spacecraft and vehicles to be used in the lunar mission is given in Table 5.

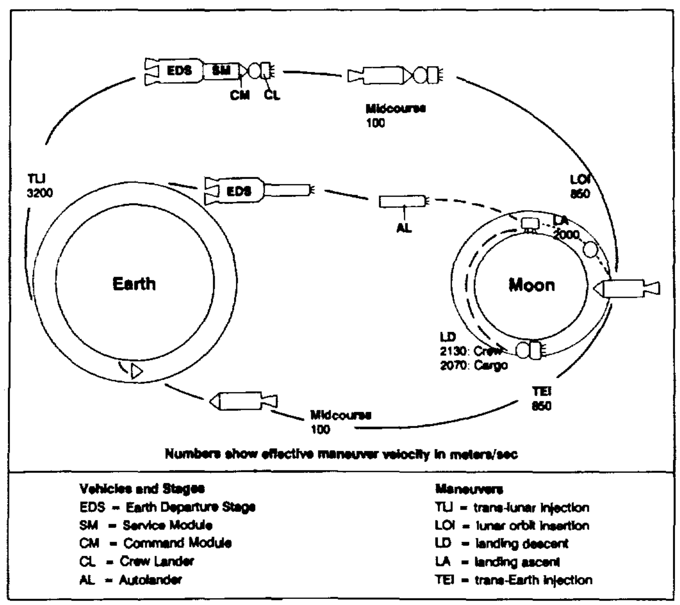

Fig. 3. Lunar mission profile and maneuver velocity roadmap.

TABLE 5. Spacecraft and vehicle summary.

# Req.	Vehicle or Spacecraft	Initial Mass (kg)	Final Mass Payload (kg)	Prop. Mass (kg)	Isp (sec)
1	Lunar Geoscience Orbiter	TBD	100-130	TBD	TBD
1	Lunar Imaging Polar Orbiter	TBD	10-20	TBD	TBD
2	Imaging Impactor Probe	TBD	100-150	TBD	TBD
1	Relay Orbiter	TBD	50-200	TBD	TBD
5	Heavy Lift Vehicle	TBD	78,000	TBD	TBD
5	Earth Departure Stage	74,000	29,000	40,000	444
1	Command Service Module	18,000	7,000	9,000	342
1	Crew Lander Descent Stage	9,900	3,300	5,200	304
1	Crew Lander Ascent Stage	3,100	1,500	1,400	342
4	Autolander	28,000	7,500	18,000	322

The number of each type of vehicle is shown for the mission description, followed by initial mass and full propellant loading. Final mass is shown excluding tankage, plumbing, and engines. Propellant mass and specific impulse are shown in the last two columns.

VEHICLE DESCRIPTION

Heavy Lift Vehicle (HLV)

All mission vehicles and base equipment are launched from Earth by an HLV. The reference mission described above uses five HLVs: four to launch the autolanders and their cargo, and one to launch the CSM/CL combination. All HLV launches are without a crew; the crew is brought up by a shuttle. The HLV payload requirement is dependent on the specific impulse of the EDS as follows (assumes HLV/EDS 5% adapter mass):

EDS I_{sp}	HLV Capability to LEO	
sec	kg	lb
420	83,000	183,000
444*	78,000	172,000
460	75,000	166,000
480	72,000	160,000

*Design point.

Each of the five lunar base flights constitutes a single launch package integrated and tested on the ground. Payload capabilities are within those contemplated for different versions of the USAF/NASA Advanced Launch System, NASA Shuttle C, Boeing/Hughes Jarvis, and of course the Saturn V and Energia. While the lunar base could be established using smaller expendables and the shuttle, this would result in a very different mission plan entailing more complex ground integration and testing and probably orbital assembly. In this case, the space station might be the logical assembly site, but the required assembly operations could interfere with laboratory and observational science contemplated for the station.

Earth Departure Stage (EDS)

As with the Saturn S-IVB stage and the Centaur, cryogenic liquid hydrogen and oxygen are the propellants of choice because of the substantial mass saving compared with storable propellants. The EDS was sized by the requirement to perform the 3200-m/sec TLI with the 27,900-kg CSM/CL combination as payload. The same EDS configuration also performs TLI for the autolanders. Adapter masses of 5% of dry weight between stages are used throughout.

Command Service Module (CSM)

Several configurations of vehicles for carrying the crew to and from the Moon were considered. The lunar orbit rendezvous technique that drove the Apollo configuration still appears the best within the guidelines of simplicity. Though a little cramped, the Apollo CM was capable of carrying five people and was configured for the eventuality of a Skylab rescue in 1974. Electrical and electronic subsystems would be totally redone today with a substantial mass saving, but the configuration, mechanical construction, attitude control, and recovery subsystems could remain essentially unchanged with a mass of 5400 kg or less upon entry. For all except the last few hours of its mission, the CM depends on the SM for utilities, consumables, and stabilization.

Fuel cells would be replaced by solar panels and nickel-hydrogen batteries for electrical power. The service propulsion system engine could be retained or replaced by a cluster of four Rocketdyne XLR-132 engines for redundancy and somewhat better performance (the latter is assumed). About nine days of consumables (plus reserves) are required to support the five-member crew during the time they are aboard the CSM. A smaller SM than used for Apollo is contemplated, with a dry mass of 2700 kg carrying 9400 kg of propellant. Provisions are made for storing the CSM in lunar orbit under ground control. Occasional maneuvers are required to maintain the orbit and be ready for an early return of the crew.

Crew Lander (CL)

Unlike the Apollo LM, the CL is not required to support the crew on the lunar surface or to carry supplies. Before undocking from the CSM, the surface navigation beacons will have been activated and tested, and the integrity of the autolander payloads (including all base equipment and provisions) will have been verified. The CL can be set down within easy walking distance of the autolanders. Consequently, the CL will be almost an "open cockpit" vehicle, which the crew will board wearing their spacesuits and PLSS. The unpressurized CL will afford thermal and sunlight protection, and possibly an oxygen and coolant supply. It is used only to carry the crew between the orbiting CSM and the lunar base. (Note that the Apollo astronauts were fully suited during landing, and that the LM could complete a landing in the event of a pressure failure.)

A single-stage CL would weigh 19,000 kg to be able to land, relaunch immediately in the event of an emergency, and return to the orbiting CSM carrying its five crewmembers with a mass of 200 kg each (including suits, PLSS, and other crew-specific equipment). Instead, the CL consists of the ascent and descent stages (AS and DS), which permits an abort at any point in the descent in the event of a descent propulsion failure. There is also a savings of 9000 kg from the single-stage version. The dry AS is 1700 kg with crew and burns 1400 kg of nitrogen tetraoxide and monomethyl hydrazine in its single XLR-132 engine. The fully loaded AS, of course, forms the payload of the DS, which is powered by a single lunar module descent engine (LMDE) burning nitrogen tetraoxide and Aerozine 50 (50% N_2H_4 and 50% unsymmetrical dimethyl hydrazine). All CSM and CL engines are hypergolic. The XLR-132 is pump fed, while the LMDE is pressure-fed (*Rockwell*, 1984; *Elverum et al.*, 1967). The dry DS is 1500 kg, with 5200 kg of propellant.

Autolander (AL)

All cargo is carried to the base site by the 28,000-kg AL, which is sized for the EDS's translunar injection capability. Total landed dry mass is 10,100 kg, of which 7500 kg is base payload. Clever use can presumably be made of much of the nonpayload mass, such as propellant tankage, batteries, and other equipment, but this is not yet factored into base design. There will be at least 500 kg of unburned propellant that could be scavenged from each AL. The tanks should be vented some time after landing to prevent corrosion and possible rupture or explosion as has happened on discarded Δ stages left in Earth orbit.

To attain the required thrust:weight ratio, throttleability, and improved performance, each AL employs two XLR-132 engines for midcourse, lunar-orbit insertion, and descent orbit insertion maneuvers. For powered descent, these engines are accompanied by a single lunar module descent engine (LMDE). Slightly under half of total maneuver velocity is executed with the higher specific impulse XLR-132s, with the rest by the LMDE. Putting the LMDE back in production may or may not be practical, but the tooling is said to be stored by TRW, the engine manufacturer (D. Lee and W. Reynolds, personal communication, 1988). There could be considerable difficulty obtaining critical valves from subcontractors, some of whom may not be in business. Nearly all the original engineering and shop talent is dispersed, so either redevelopment or a derivative from nonthrottleable engines now in production might be more practical. Similar uncertainty surrounds possible production of other Apollo-derived equipment described here, such as the CM.

In keeping with the design philosophy, storable propellants and Apollo inheritance were chosen for the ALs. If a modest departure were taken from this philosophy, a substantial performance improvement could be realized, reducing the number of ALs from four to three, and the number of EDSs and HLVs from five to four. One uprated Pratt & Whitney RL-10 engine has the thrust required for the AL. Using LOX/LH_2, its performance is significantly higher than that of storable propellants. The engine can be operated up to 89 kN (20,000 lb) thrust, and has been throttled over a 10:1 range (J. Brown, personal communication, 1988). With a better insulated hydrogen tank, the fuel could be kept cold for the four days required from launch through landing, giving the AL a 10,000-kg payload, or one-third greater than the selected AL concept with storable propellants.

A more ambitious concept proposed in the 1984 Johnson Space Center Lunar Surface Return Study calls for expendable landers capable of placing 38,600 lb of useful payload on the lunar surface. Only two such landings would be sufficient to deliver all polar base elements discussed, including the crew and AS (*Roberts et al.,* 1984).

CREW SELECTION AND BASE ACTIVITIES

The single overriding objective of the proposed polar base is to successfully live on the Moon for a year. Productivity is of secondary importance, because it is felt that the harsh environment will tax the crew and system resources. During their stay, the crew can extensively explore the local area and perform limited scientific and technological experiments. Given appropriate training and interests, the crew can remain "productively entertained" for a year near the pole. By analogy, an accountant might become seriously depressed if confined to a desolate region of mountainous terrain on Earth for a year, while a geologist might go to great lengths to secure the opportunity to explore and map virgin territory. Much of the crew's waking time will be spent in subsistence activities such as maintaining equipment, preparing meals, housekeeping, exercising, etc. More interesting activities such as base construction and training for the return flight will occupy more time. What time remains will be available for exploration, setting up and performing experiments, and "just taking it all in."

For such a long stay, the crew must have the sort of autonomy enjoyed by terrestrial explorers. Priorities set on Earth with endless timelines and requests for "one more sample" will not succeed. Crewmembers will have their own desires, objectives, and pet projects, and must also function as a cohesive team for each other's survival. Mission control in the traditional space mission sense will not work. Instead, a very few engineers, technicians, and personal assistants on the ground will need to function at the service of the crew.

The most successful terrestrial expeditions have had a single leader respected by a crew of his or her own choosing. Morale is exceedingly important and has been a critical factor on both polar and space missions of long duration. In this regard many polar expedition leaders feel a good cook is the most important crewmember! Two pilots thoroughly familiar with the vehicles will be required to fly the CSM and CL. A physician/dentist is almost a necessity, while the other two crewmembers might be accomplished in the science and technology related to the base. All crewmembers should probably have specific system responsibilities, though this is a matter of organization best left to the leader.

CONCLUSIONS

In summary, the described lunar polar expedition ranks among the more modest lunar base missions currently being discussed in terms of transportation requirements, life support, and power system design. Yet it yields major advances in our knowledge of how to live and work on the Moon. Whether this is a first mission or an adjunct to a major national or international program, it offers a threshold achievement by visiting a uniquely interesting region of the Moon and testing long-term habitation techniques. It can create a nucleus of expanding human presence beyond Earth.

A successfully established polar camp can be augmented dramatically with each additional landing, exploring new capabilities in selenogical research, astronomy, industry, biomedicine, and life support. Once operational, a solar power system can be enlarged and extended to serve other nearby regions. It could serve as the starting point for a comprehensive power distribution grid reaching southward toward the equator. Indeed, initial base expansion can contribute to virtually every aspect of lunar development: surface transport systems; closed-loop life support systems and food production; production of oxygen, ceramics, and metals; bioscience; astronomy; and architectural systems.

Earth's Moon has been called a "seventh continent," a sister planet, a "stepping stone to the stars." It is all of these. Learning to live and work productively on the Moon, our nearest celestial neighbor, will provide invaluable knowledge, resources, and experience for bolder missions into deep space.

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