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# Lunar Base Launch and Landing Facility Conceptual Design

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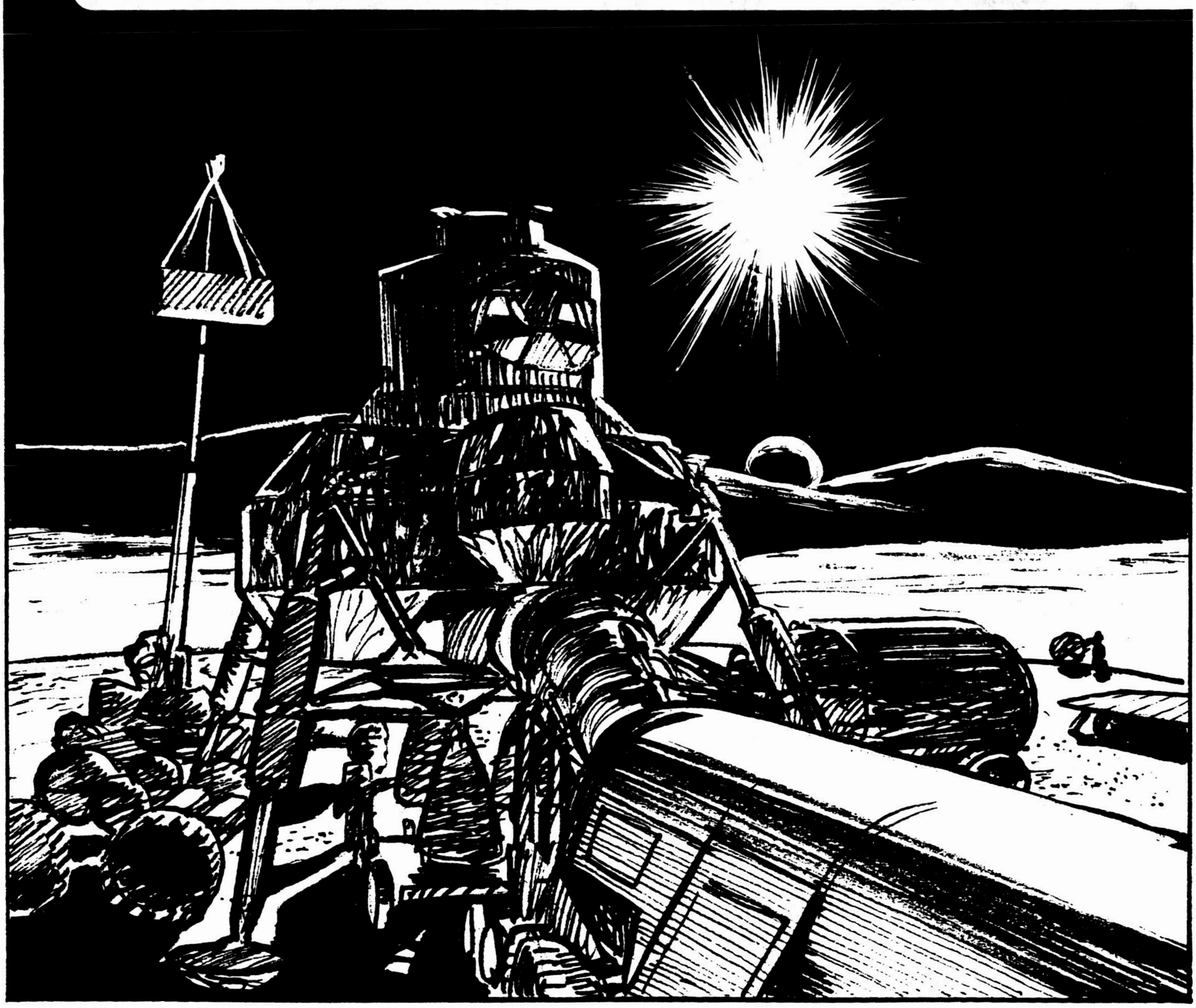

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EEI Report 88-178

EAGLE

# LUNAR BASE
# LAUNCH AND LANDING FACILITY
# CONCEPTUAL DESIGN

Lunar Base Systems Study Task 3.1

A Report to the
Advanced Programs Office
National Aeronautics and Space Administration
Johnson Space Center

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by

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## Foreword

This report is a first step toward understanding a launch and landing facility for a lunar base. The study was performed by Eagle Engineering from November 1987 through February 1988.

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## 1.0 EXECUTIVE SUMMARY

This report documents the Lunar Base Launch and Landing Facility Conceptual Design study. The purpose of this study was to examine the requirements for launch and landing facilities for early lunar bases and to prepare conceptual designs for some of these facilities. The emphasis of this study is on the facilities needed from the first manned landing until permanent occupancy. Surface characteristics and flight vehicle interactions are described, and various facility operations are related. Specific recommendations for equipment, facilities, and evolutionary planning are made, and effects of different aspects of lunar development scenarios on facilities and operations are detailed. Finally, for a given scenario, a specific conceptual design is developed and presented.

### 1.1 SUMMARY OF CONCLUSIONS

Launch and landing facilities and their growth rate depend on the base development scenario. The major emphasis of the base, the rate of emplacement of facilities, and the design of the flight vehicle will all play major roles in the requirements for facilities. Resource utilization bases will require more and different landing facilities than will science or habitation bases. The more rapidly some base capabilities are achieved, the more rapidly landing facility capabilities are required. Vehicles that require extensive surface-based servicing will require leveled permanent landing areas. These permanent reusable landing pads are not needed or desired before major resource export or vehicle servicing activities take place. For some lunar base scenarios, permanent landing pads may never be needed.

Based on the calculations done during this study, the effects of engine blast are significant. While they are not critical or life threatening, they must be considered. Equipment within 50 meters of a landing may experience severe damage due to the impact of fairly large grains of lunar soil. Equipment over 400 meters away will require only minimal protection. At 1 to 2 kilometers blast effects are very small.

Landing pads can be designed without general regard to the specific landing site because overall surface conditions are fairly uniform across the entire lunar surface. Landing pads, whether prepared or not, should be about 100 meters across. The area just outside this circle to 200 meters across should not include any major obstructions such as boulders or expended landers. Lunar derived gravel may be used to stabilize prepared landing pads.

With few exceptions, lunar landing facilities and equipment are present on the lunar surface for other reasons before they are needed for landing operations. Landing equipment and facilities will probably not be major drivers of delivery schedules and mission plans.

### 1.2 SUMMARY OF RECOMMENDATIONS

More work is needed concerning blast effects, vehicle servicing on the surface, site planning and development, and safety and rescue operations. More design definition is needed for surface stabilization methods, cryogen storage and transfer facilities, servicing and maintenance equipment, and other items.

The launch and landing facilities of a permanently occupied base need to be defined. This study was limited to the initial lunar base, and the facilities needed for extensive permanently occupied or Phase III bases have only been reviewed in a cursory fashion.

## 1.3 ILLUSTRATION

Plate 1 is an illustration of some of the landing facilities as they might appear near the end of the Phase II Lunar Base. The landing has taken place just after the lunar dawn. Earth appears over the Rook Mountains in the east across the bed of the Lake of Spring (Lacus Veris). Throughout the next month it will dip below the horizon, only to appear again after a few days. Above Earth, the Sun moves slowly higher in the lunar sky. The lander sits in the middle of the 100-meter diameter gravel landing pad where it is being readied for its stay on the lunar surface. Inside, crewmembers are shutting down the flight systems and configuring the lander for its layover.

The pressurized vehicle in the foreground is connected to the lander, waiting to take the crew back to the lunar base. The transfer tunnel has been connected between the lander and the vehicle to allow the crew easy access in and out.

Beneath the lander an astronaut begins the process of changing an engine by removing and relocating an old engine with a mounting rig. Changing modular line replaceable units is the first form of flight vehicle servicing to take place at the lunar base.

To the right of the lander, a Propellant Refill Vehicle is being used to scavenge hydrogen remaining in the tanks. This must be done as quickly as possible before the Sun heats the tanks and boils away the fuel. Still further, a supplemental cooling cart has been connected to the lander's thermal control system. The radiator on this cart will help keep the lander and its systems cool during the lunar day.

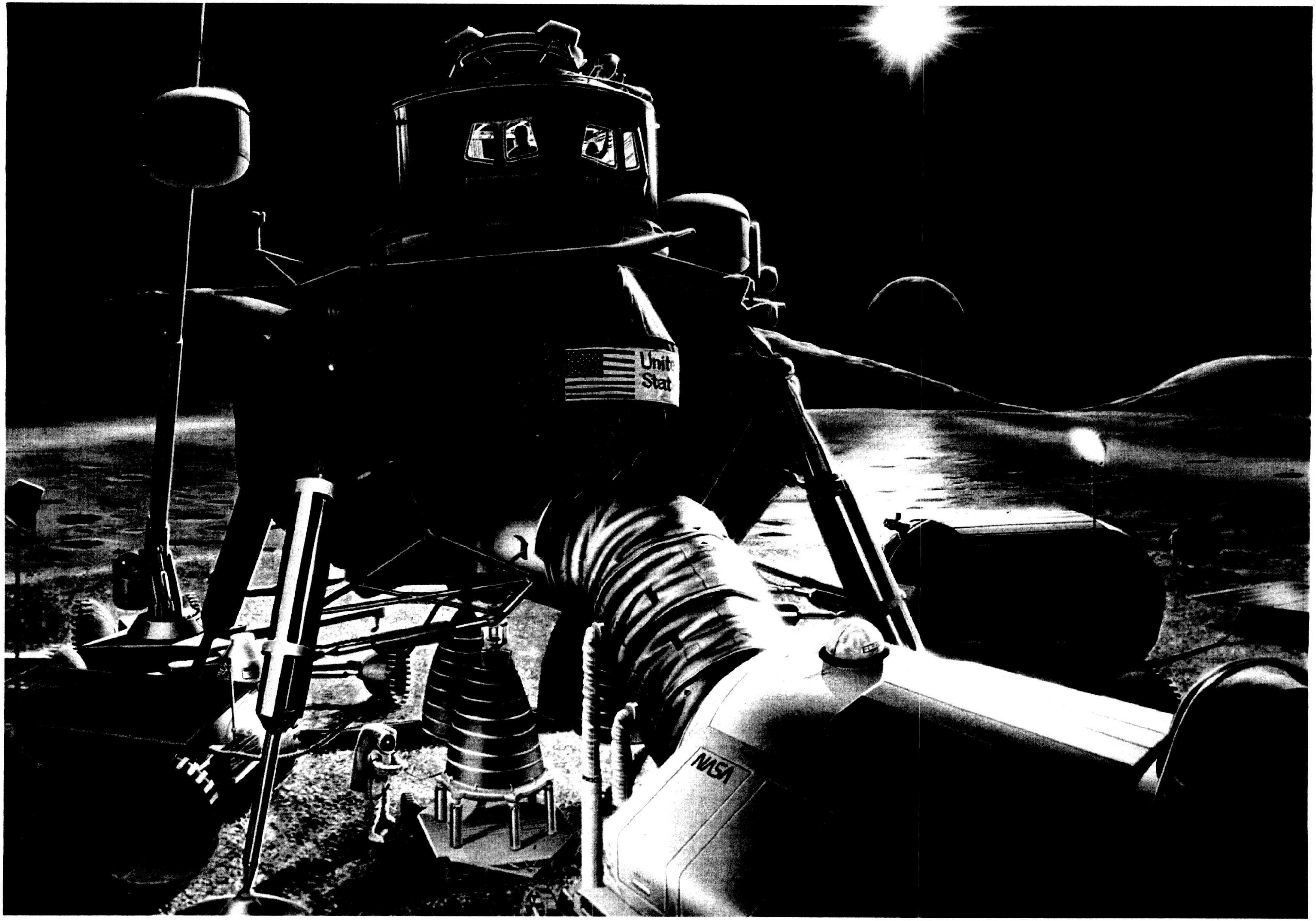
A crane removes a small canister containing the personal items of the arriving crew along with some small experiments and incidental supplies.

To provide electrical power to the lander while it is on the pad, a power cart has been moved between the lander legs on the left. Using the fuel cells and the solar panel on top, the power cart will support the lander for the next month.

Draped around the back legs of the lander, a thermal and meteoroid blanket is ready to be lifted over the lander. When all other preparations have been finished the blanket will be pulled over the lander to protect it from the relentless bombardment of micrometeoroids. It will shield the lander from the blistering Sun during the lunar day and help keep it warm during the night.

At the edge of the pad, an astronaut inspects one of the three landing pad markers for damage. Ejecta from repeated landings may have damaged the reflector, the light, or the radar transponder mounted on the marker. The transponders are vital in guiding the lander to an accurate landing. The reflector appears translucent in the intense sunlight. The mesh surface decreases the pressure effects of the engine exhaust as the lander passes over.

The landing pad is surfaced with gravel which is a bi-product of the mining operations taking place on the lunar surface. Roads and other smooth level surfaces can also be surfaced with this gravel.

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## 1.4 GROUND RULES AND ASSUMPTIONS

The following general ground rules and assumptions were made during this study:

- Landing facilities should be designed, as much as possible, without regard to the particular scenario of lunar base development.

- The facilities should be developed independent of any particular lander design. When specific lander data must be used, facility sensitivity to the data should be discussed.

- A Phase II lunar base is the primary target of this study and landing facilities should be limited to support of that type of base. A Phase II lunar base is defined as beginning at the first human return to the Moon and ending when the base becomes permanently occupied.

- The base will be located at a fixed site.

## 2.0 LANDING SITE CHARACTERISTICS

The first task in the definition of landing sites is the characterization of possible base locations. These site characteristics have general effects on the design requirements and setup operations of landing facilities. The characteristics of interest are surface roughness, soil mechanics data, lighting, and Earth visibility. The following discussion is intended to cover these characteristics in general for the entire lunar surface and then to examine the specific base sites chosen for the Lunar Base Systems Study.

For this study, four candidate base locations were chosen. Three of the base sites are on flat mare-like surfaces including the Lacus Veris, Mare Nubium and Taurus-Littrow and one is in a rugged highlands region, the South Pole. The primary base location is the Lacus Veris site while the remaining sites are not given any relative priorities. Data sufficient for certification of a landing site is available for only the Taurus-Littrow site, which was used by Apollo 17. The Taurus-Littrow imagery has a resolution of less than 5 meters. Data on the Lacus Veris and Nubium landing sites is limited to Lunar Orbiter IV imagery with a resolution of 60-65 meters. The imagery of the South Pole region is limited to a number of Lunar Orbiter IV images with almost the entire region shadowed.

In general, all the base sites may be expected to have suitable landing areas from a roughness and soil strength viewpoint assuming at least Apollo lander capabilities. The Lacus Veris and South Pole sites do present some Earth visibility problems since they are on the western and southern limbs respectively. In addition, the South Pole site may present some serious lighting problems due to the continuously low Sun angle.

### 2.1 GENERAL CONSIDERATIONS

Given its age, the lunar surface is fairly homogeneous in many respects. Expected surface properties and how they may vary over the lunar surface are discussed in the following sections.

#### 2.1.1 Surface Roughness

In general, landing sites with relatively low slopes of 4 to 6 degrees for 25-meter ranges can be found over the entire lunar surface. Landing pads can be designed without regard to base site. Some locations, such as the sides of large craters and mountain sides, may have unacceptable slope characteristics. Mountainside slopes of around 30 degrees are not uncommon. Low slope zones may be found nearby.

Data on the roughness of the surface comes from several different sources:

- Photogeologic terrain assessment.

- Photogeologic measurements of slopes based on high resolution vertical photography taken from lunar orbit.

- Counts of the number of impact craters in a series of size classes based on high resolution vertical photography taken from lunar orbit.

Terrain assessment is the most straightforward type of surface roughness evaluation. This simply involves assuring that candidate landing sites do not lie on the sides of mountains. For example, at Apollo 17, the landing site was in the flat mare floored valley with average slopes of 5-7 degrees. In contrast the slopes of the flanking North and South Massif are 20-30 degrees.

Published slope data from high resolution vertical photography is available for all of the candidate Apollo landing sites as well as a large number of other areas of the Moon as described in references 1 and 2. The data presented in Table 2.1-1 comes from reference 1. Note that although there are wide variations over long ranges, the slopes for the shortest lengths measured, 25 meters, are relatively constant for both the mare and highland plains at 4-6 degrees. Figure 2.1-1 presents the slope data in a graphical manner which emphasizes the obvious slopes are less on the mare than in the uplands or highlands, with the highland plains unit, the Cayley plains, being intermediate between the two.

Crater counting has long been used as a technique for quantifying the roughness as well as age of the lunar surface. Figure 2.1-2 presents a summary of crater counting data taken from the site selection board minutes before the Apollo 17 mission, reference 3. The data generally confirm the high resolution photography data. The graph shows clearly the variation between a highlands landing site, Apollo 14, an old lunar mare landing site, Apollo 11, and young mare landing sites, Apollo 12 and Apollo 17. Extrapolation of the data shows that the surface is virtually covered with 10-meter diameter craters no matter what the type of region. The low number of craters identified at Apollo 17 was a result of working with Apollo 15 photography taken at a relatively high Sun angle, the very low albedo of the landing site, and the presence of a thick layer of fine-grained pyroclastic debris rather than rock in the near surface layer.

### 2.1.2 Soil Mechanics Data

Bearing strength, slip resistance, and grain size are important characteristics when landing surfaces are considered with respect to landers. Strong variations are generally not found over the lunar surface, indicating that landing pad preparation and lander foot pads and legs may be designed without regard to specific base sites. Considering Apollo experience, landers can be designed for an unfinished or unprepared surface.

The lunar surface consists of a fine-grained soil with over half of the material finer than 0.075 millimeters. The fragments are mostly silicate mineral fragments and glass with a fraction of a percent metallic iron. The soil at all points studied in detail by Apollo, Surveyor, Luna, and Lunikhod spacecraft consisted of a porous zone a few centimeters thick at the surface which graded into progressively more and more compacted material with depth. Soil thickness is generally related to the age of the rocks nearest the surface. The older the rocks the thicker the soil. Table 2.1-2 derived from reference 4 shows size distribution of grains in the lunar soil.

There is significant local variation in the thickness of the soil due to the presence of craters over a hundred meters across which penetrate into bedrock. In general, the soil layers are 2 to 5 meters thick on the mare. The soil in highlands areas lacks a well defined base because the bedrock consists of coarse rubble and breccias disrupted by craters tens of kilometers to kilometers across.

Table 2.1-1, Average Slope Characteristics

| | AVERAGE SLOPE OVER DISTANCE RANGES | | | | | |
|---|---|---|---|---|---|---|
| | 25 m | 50 m | 100 m | 200 m | 500 m | 1000 m |
| TERRAIN TYPE | | | | | | |
| Mare | 4.7° | 3.7° | 2.5° | 1.7° | 1.3° | 1.2° |
| Serenitatis | 4.8° | 3.8° | 2.8° | 1.8° | 1.0° | 0.7° |
| Cayley Plain | 5.4° | 4.5° | 3.8° | 3.2° | 2.3° | 2.0° |
| Mare Fecunditatis | --- | --- | --- | --- | 3.1° | 2.0° |
| Littrow, Apollo 17 | | | | | | |
| landing site | 3.8° | --- | --- | --- | --- | --- |
| W of lndg site | 3.9° | --- | --- | --- | --- | --- |
| Uplands, | | | | | | |
| N of Proclus | 5.4° | 4.6° | 3.9° | 3.3° | 2.6° | 2.1° |
| N of Vitruvius | 6.2° | 5.5° | 5.1° | 4.9° | 4.7° | 4.3° |
| near Glaisher | 8.4° | 7.9° | 7.5° | 7.3° | 6.9° | 6.4° |
| near Censorinus | --- | --- | --- | --- | 7.8° | 6.3° |
| Hadley, Apollo 15 landing site | 5.7° | --- | --- | --- | --- | --- |

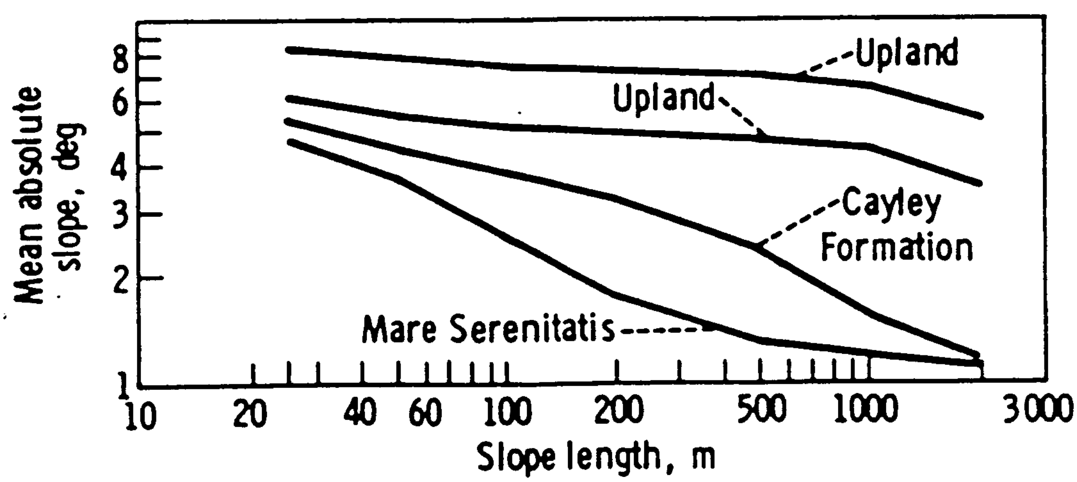


Figure 2.1-1, Lunar Slope-Frequency Distributions

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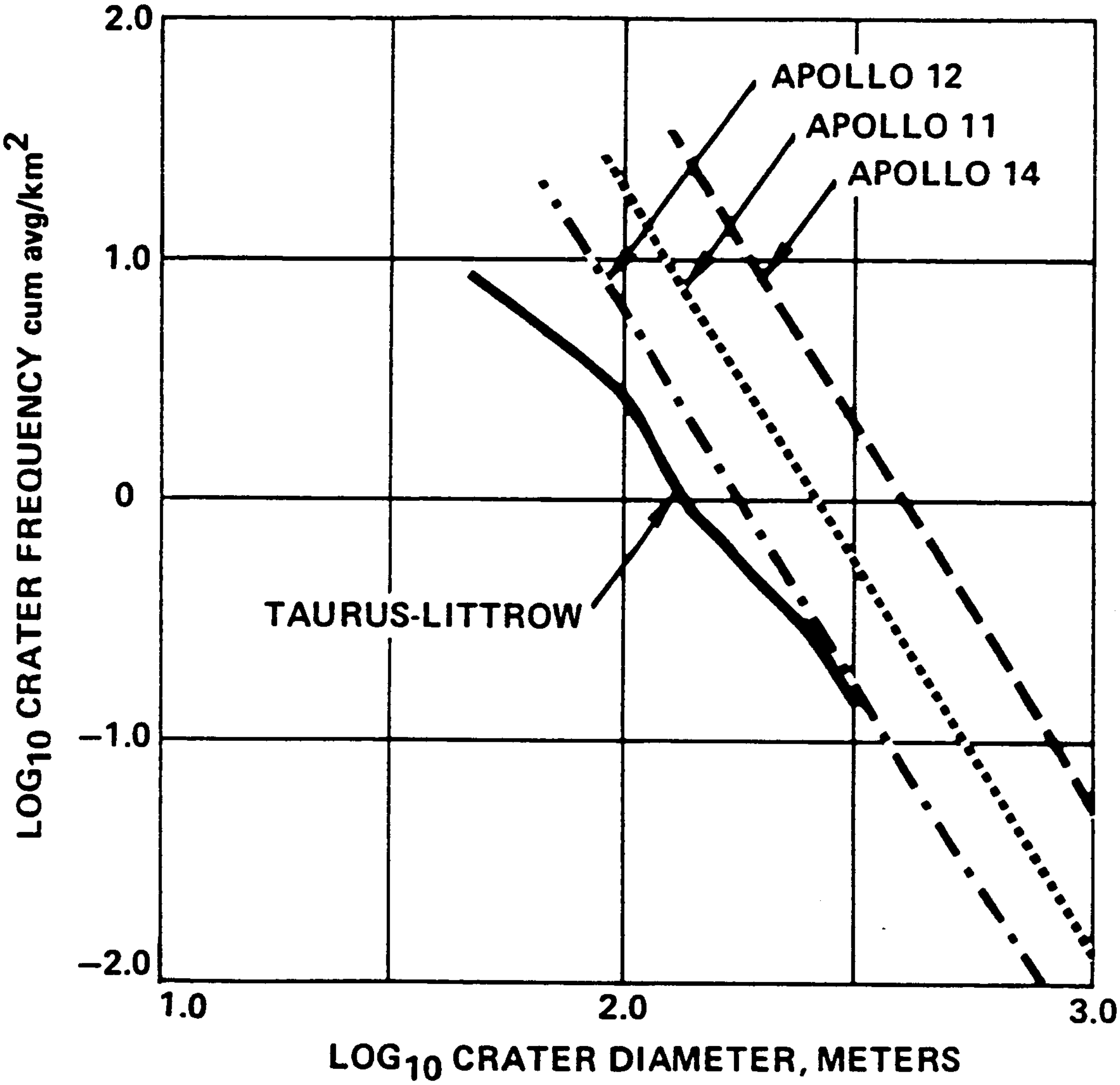



Figure 2.1-2, Size Distribution of Lunar Craters

Table 2.1-2, Lunar Soil Grain Sizes

| Grain Size Millimeters | % Finer by Weight |
|---|---|
| 1.000 | 90% |
| 0.750 | 85% |
| 0.500 | 80% |
| 0.250 | 75% |
| 0.100 | 70% |
| 0.075 | 50% |
| 0.050 | 40% |
| 0.025 | 20% |

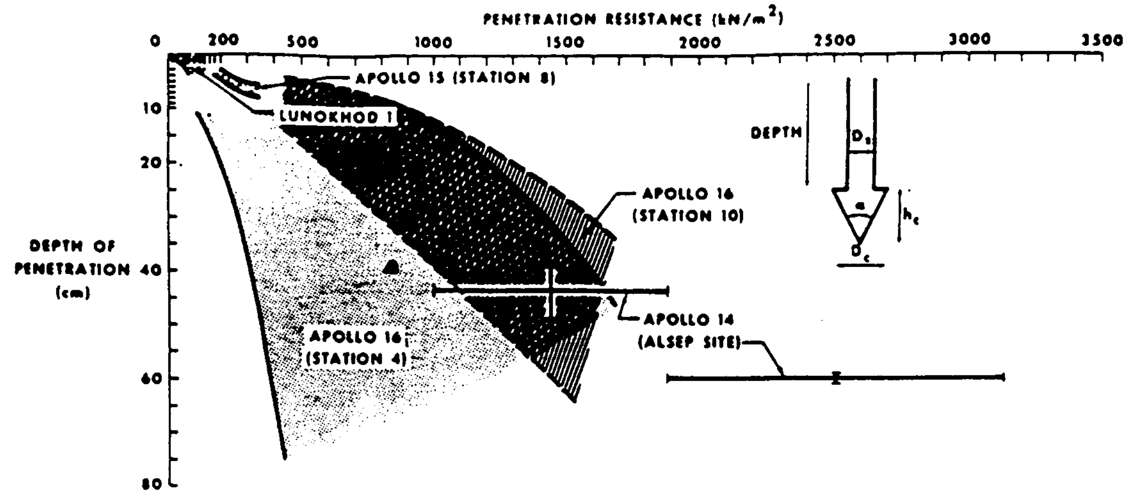
The physical properties of the soil are dominated by its degree of comminution by micrometeorites and its packing. Two trends are apparent from Apollo core data. The first observation from core samples is that the packing density is very loose at the surface and increases sharply in the top few centimeters. The second observation from core samples is that soil agglutinate content decreases and grain size increases with depth (Figure 2.1-3, reference 5). Near craters which are surrounded by light colored material and have sharp well defined rims, an abundance of blocks of bedrock is observed. The grain size of the soil is generally coarser than dark colored soils away from such craters. The process of destroying the blocks, comminuting the soil, and building up the agglutinate content is very slow in absolute terms. Some of the younger craters are 25 to 100 million years old.

Since factors which vary over a scale of a few hundred meters dominate, requirements placed on vehicles by the soil bearing strength and related factors should be treated generally for the entire Moon. Table 2.1-3 summarizes the soil physical properties for the Apollo 14 through 17 landing sites (reference 6). For reference, an astronaut boot or the lunar module both place a stress on the surface of about one pound per square inch (0.69 $N/cm^2$ or 6.9 $kN/m^2$). Such stresses result in penetration of the lunar surface of less than a centimeter to a few centimeters. The angle of internal friction of lunar soil is also summarized in Table 2.1-3. The angle of 36 degrees to 42 degrees is equivalent to the angle of repose for loose soil such as on the side of a mountain. The tangent of the angle is equal to the coefficient of internal friction, 0.73 to 0.90. The cohesion of soil is 0.01 to 0.1 $N/cm^2$.

### 2.1.3 Earth Visibility

The visibility of Earth from the selected base site will affect the degree of autonomy of the lander and its interaction with the landing site. The ability of vehicles to receive Earth-generated navigation updates will influence the need for lunar-based navigation systems. The effects must be described for each specific landing site.

Sites on the limb or the far side will not present good opportunities for updates without prior placement of either surface or space-based relays. The western limb does allow considerable Earth tracking of landers in the initial parts of the descent, but final descent will generally be invisible to Earth systems.




| MISSION | NO. OF TESTS | $D_c$ (cm) | α | $h_c$ (cm) | $D_s$ (cm) |
|---|---|---|---|---|---|
| APOLLO 14 | 3 | 0.95 | 30° | 1.78 | 0.95 |
| LUNOKHOD 1 | 327 | 5.0 | 60° | 4.4 | - |
| APOLLO 15 | 2 | 2.03 | 30° | 3.78 | 0.94 |
| APOLLO 16 | 1 | 2.03 | 30° | 3.78 | 0.94 |
| (STATION 4) | 3 | 1.28 | 30° | 2.39 | 0.94 |
| APOLLO 16 | 1 | 2.03 | 30° | 3.78 | 0.94 |
| (STATION 10) | 3 | 1.28 | 30° | 2.39 | 0.94 |

Figure 2.1-3, Penetration Resistance of the Lunar Surface

Table 2.1-3, Soil Properties

Mechanical Data

| Soil Consistency | G $N/cm^3$ | Porosity | Void ratio, e | $D_r$ | $\phi_{TR}$ | $\phi_{PL}$ |
|---|---|---|---|---|---|---|
| Soft | 0.15 | 47% | 0.89 | 30% | 38° | 36° |
| Firm | 0.76 to 1.35 | 39% to 43% | 0.64 to 0.75 | 48% to 63% | 39.5° to 42° | 37° to 38.5° |

G = penetration resistance gradient.

$D_r$ = relative density = $(e_{max} - e)/(e_{max} - e_{min})$,based on standard ASTM methods.

$\phi_{TR}$ = angle of internal friction, based on triaxial compression tests.

$\phi_{PL}$ = angle of internal friction, based on in-place plate shear tests.

Continuous, real-time communication with Earth is highly desired. Earth support of most operations will be required to make the best use of crew time on the lunar surface.

### 2.1.4 Lighting

Lighting affects the time crew-controlled landings may occur for most sites. Polar sites, however, have continuously low solar angles and landing systems, especially during early missions, and must be able to handle hidden features and long shadows. Again, these effects must be analyzed with respect to each particular site.

## 2.2 LANDING SITE SPECIFIC CONSIDERATIONS

The following discussion covers the considerations mentioned above with respect to the four sites selected for the Lunar Base Systems Study. These sites are Lacus Veris, Mare Nubium, Taurus-Littrow, and the South Pole. Only the South Pole site presents problems of landing operations. The small amount of data available indicate that selection of appropriate base locations and landing areas will be critical.

### 2.2.1 Lacus Veris

The Lacus Veris landing site is located on a mare region. The location of the landing site at 13 degrees South, 87.5 degrees West, is indicated in Figure 2.2-4 (reference 12) with a white circle. The best image of the landing site is Lunar Orbiter IV Frame 187-H2 with a framelet width of about 12 kilometers and a resolution of about 60 meters. This limited resolution of the imagery is not suitable for the subtle distinction between the more heavily cratered older mare and the less cratered younger mare. Operationally, most mare present similar surface roughness constraints and landing sites should be easy to locate. Earth visibility will depend on the position of the Moon with respect to its perigee. For about 8 days out of 28 the site is actually on the far side. Since the site is near equatorial, lighting is not an issue except as related to time of landing and site visibility. As a result, the first missions, which will need Earth-supplied navigation data, will need to be planned for times when the site is both at its highest Earth visibility and when the Sun is at the angle that provides the best illumination of lunar features.

### 2.2.2 Mare Nubium

The Nubium landing site is in an area of fairly young mare basalts. In general the conditions of the landing site will be not dissimilar to those of the Apollo 12 site nearby. The location of the proposed site at 13 degrees South, 10 degrees West, is shown on Figure 2.2-5 (reference 12). The best image of the landing site is Lunar Orbiter IV Frame 133-H2 with a framelet width of about 12 km and a resolution of about 60 meters. As with the Lacus Veris site surface roughness considerations will be similar to the Apollo mare sites such as Apollo 17. The site is very near the center of the Earth side of the Moon and Earth visibility will not be at issue. Also, the site is very near the equator and lighting will not be an issue.

### 2.2.3 Taurus-Littrow (Apollo 17)

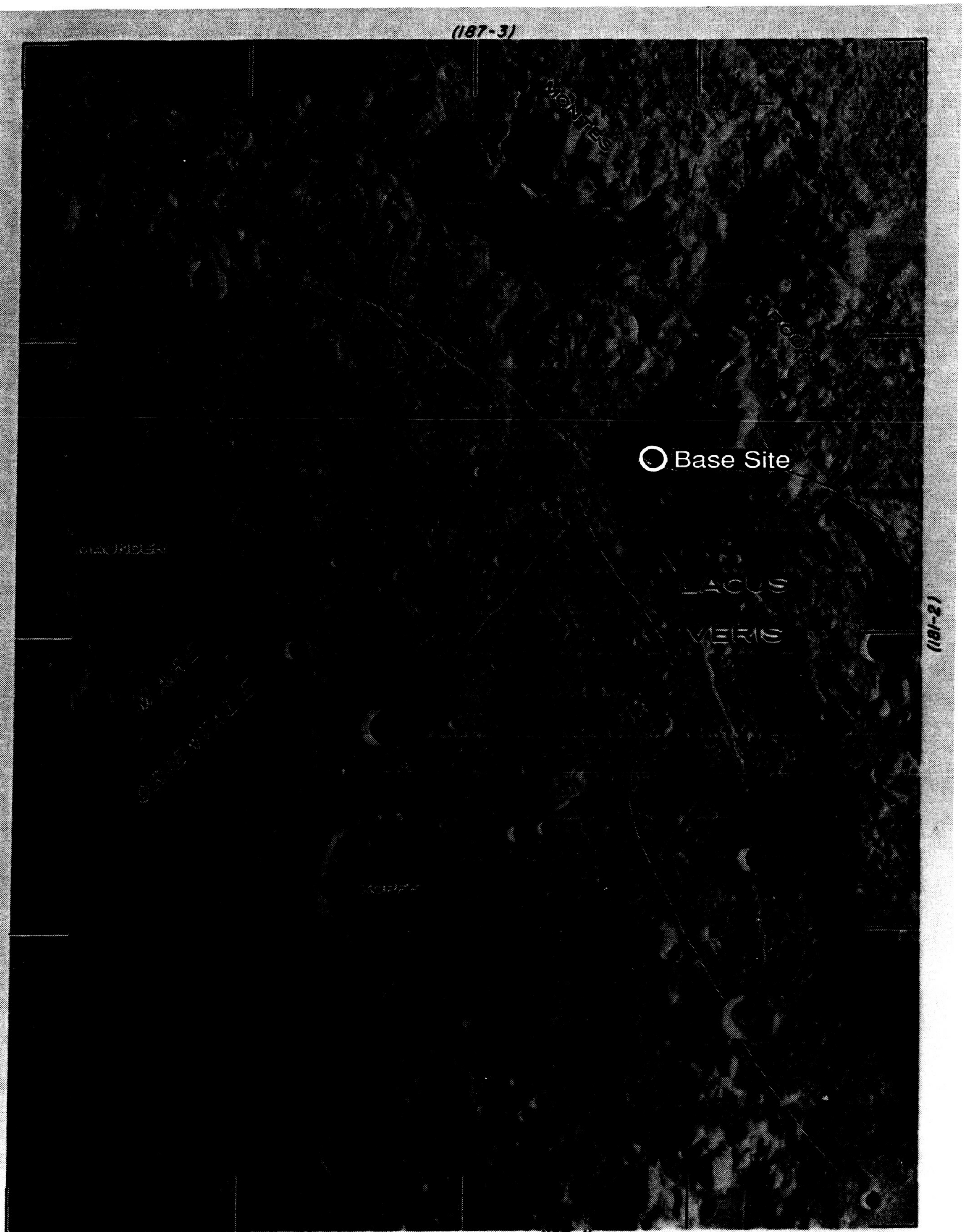
The Apollo 17 landing site is situated in an area of transition between mare and highlands regions. It was named Taurus-Littrow because it was near the Taurus Mountains and the crater Littrow. The site is located in a valley on the eastern rim of Mare Serenitatis at about 20 degrees North and 30 degrees East. The valley floor is bounded by the 1.5

kilometer high North Massif and the 2 kilometer high South Massif and is about 10 kilometers across.

The quality of the Apollo 17 landing site is obviously well characterized. The LM came to rest at an inclination of about 5 degrees from the vertical. The actual landing site lay east of Camelot crater, a 90 million year old sharp rimmed crater and just north of the 109 million year old central cluster. For comparison with the imagery of the other base sites, Figure 2.2-6 (reference 12) is the Lunar Orbiter IV Frame of the landing site, Frame 78-H3. The blowup of the section marked on this drawing is shown in Figure 2.2-7. This shot was taken from the Command Module during the Apollo 17 mission. It is a high resolution photo and the relief of the area is apparent. To complete the comparison, Figure 2.2-8 (reference 10) is a panoramic view of the landing area. The photographs in this view were taken from the surface at the edge of the Camelot crater looking east towards the landing site. The landing site is about one kilometer away and the LM cannot be seen. The foreground of this picture shows the boulder field at the edge of the crater. For scale comparison, astronaut boot prints, which are 30 to 40 centimeters long, can be seen amongst the rocks. The background shows the Lunar Rover Vehicle (LRV) and an EVA astronaut on a clear, flat area. Again for scale, the wheel of the LRV is about 80 centimeters high.

### 2.2.4 South Pole

The South Pole landing area is not well characterized at this time. It appears to have a combination of problematic features and may present unacceptable risks of landing failures. The only imagery available is from Lunar Orbiter IV. The best of a series of poor images of the landing site is LO IV Frame 82-H1. The location of the South Pole is annotated on Figure 2.2-9 (reference 12). From this image, the region appears to be a rugged highlands area. Selection of landing sites will be critical and difficult but, based on the data discussed above, should not be impossible. Earth visibility will be poor as will lighting angles. Combining poor lighting and a high probability of unacceptable surface features, landings, especially the first landings, will have high risks of aborts. Without some sort of communications relay system in place, the problem will be magnified.




187-2

Figure 2.2-1, Lacus Veris Landing Area



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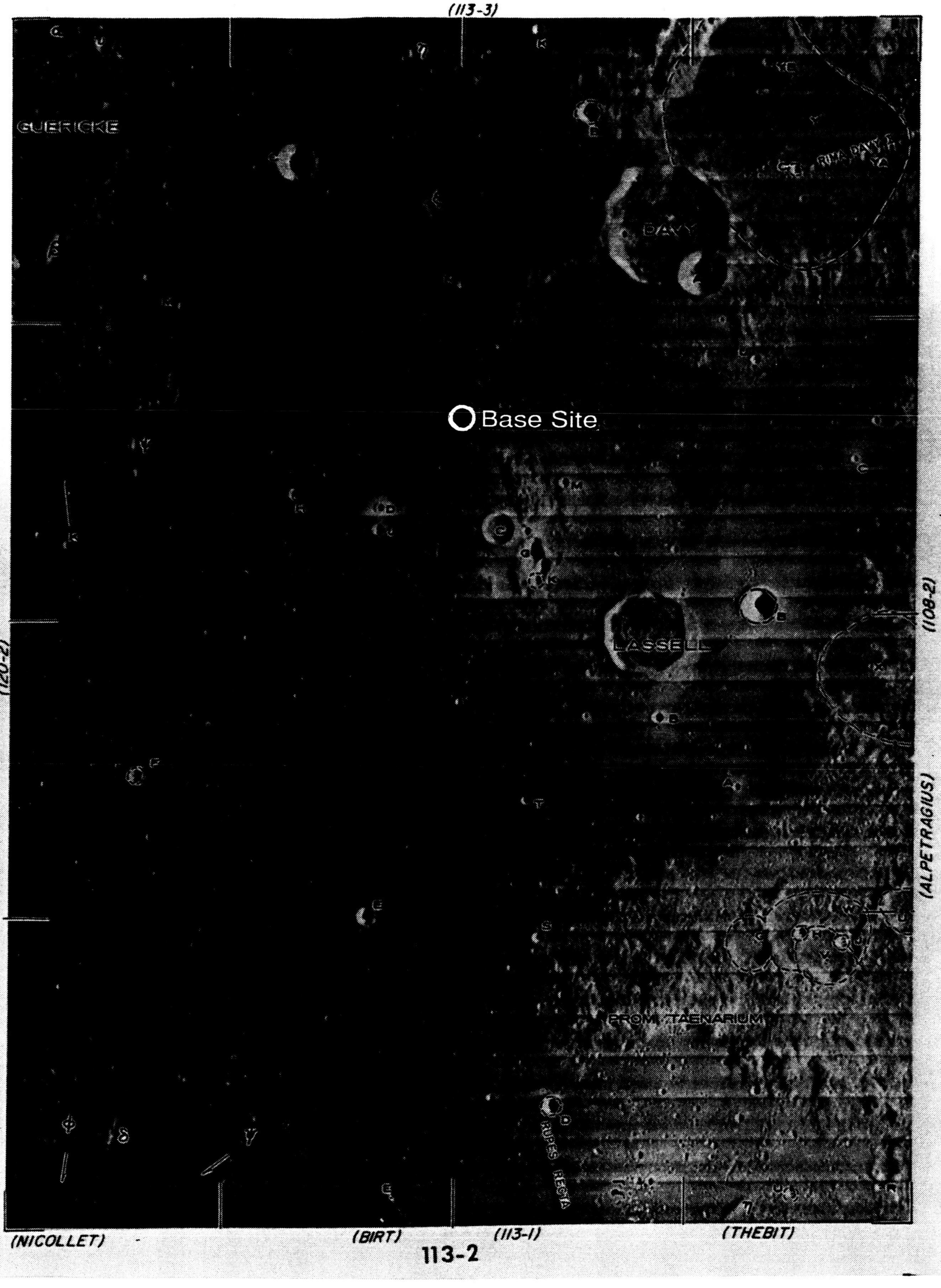


Figure 2.2-2, Mare Nubium Landing Area



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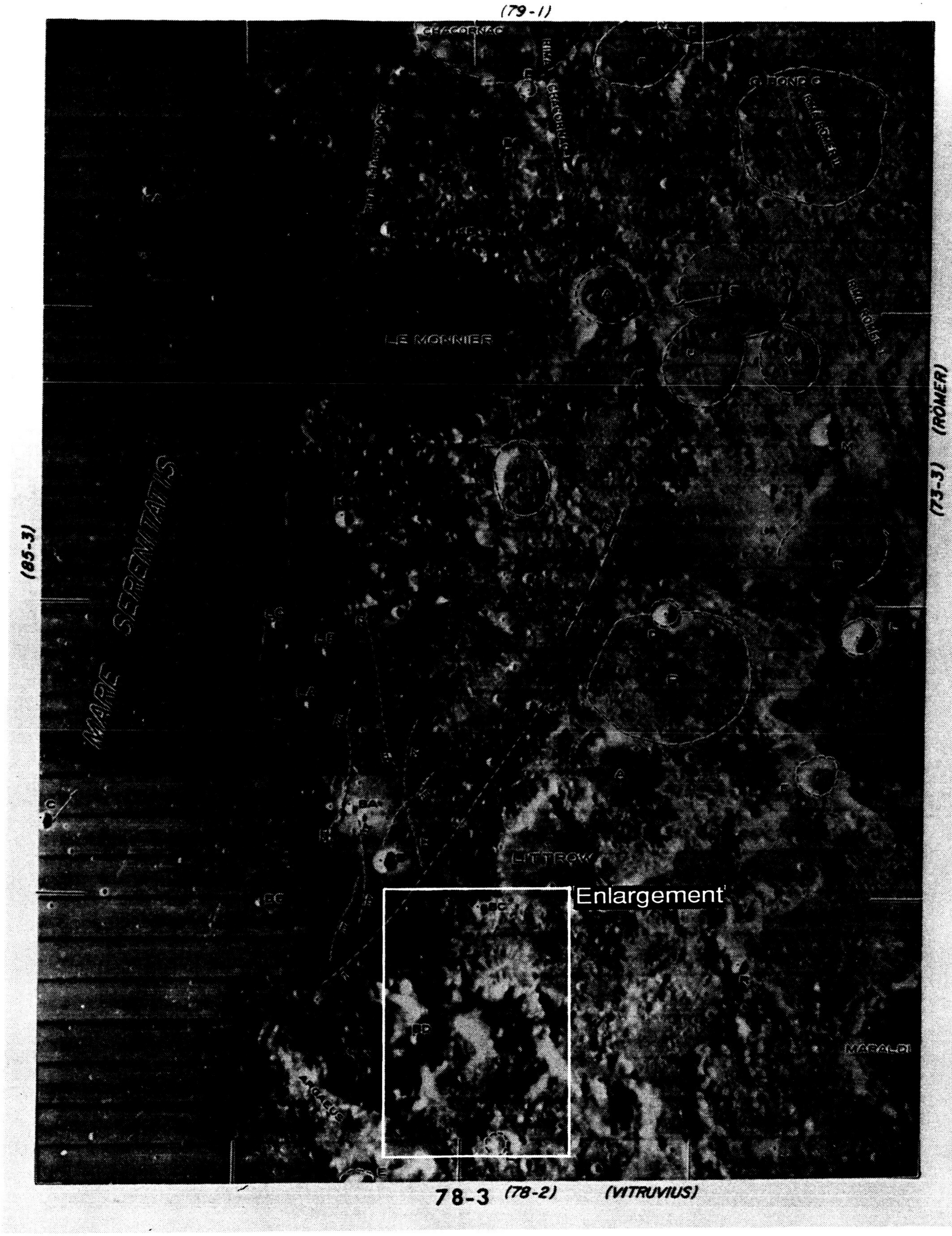


Figure 2.2-3, Taurus-Littrow Landing Area



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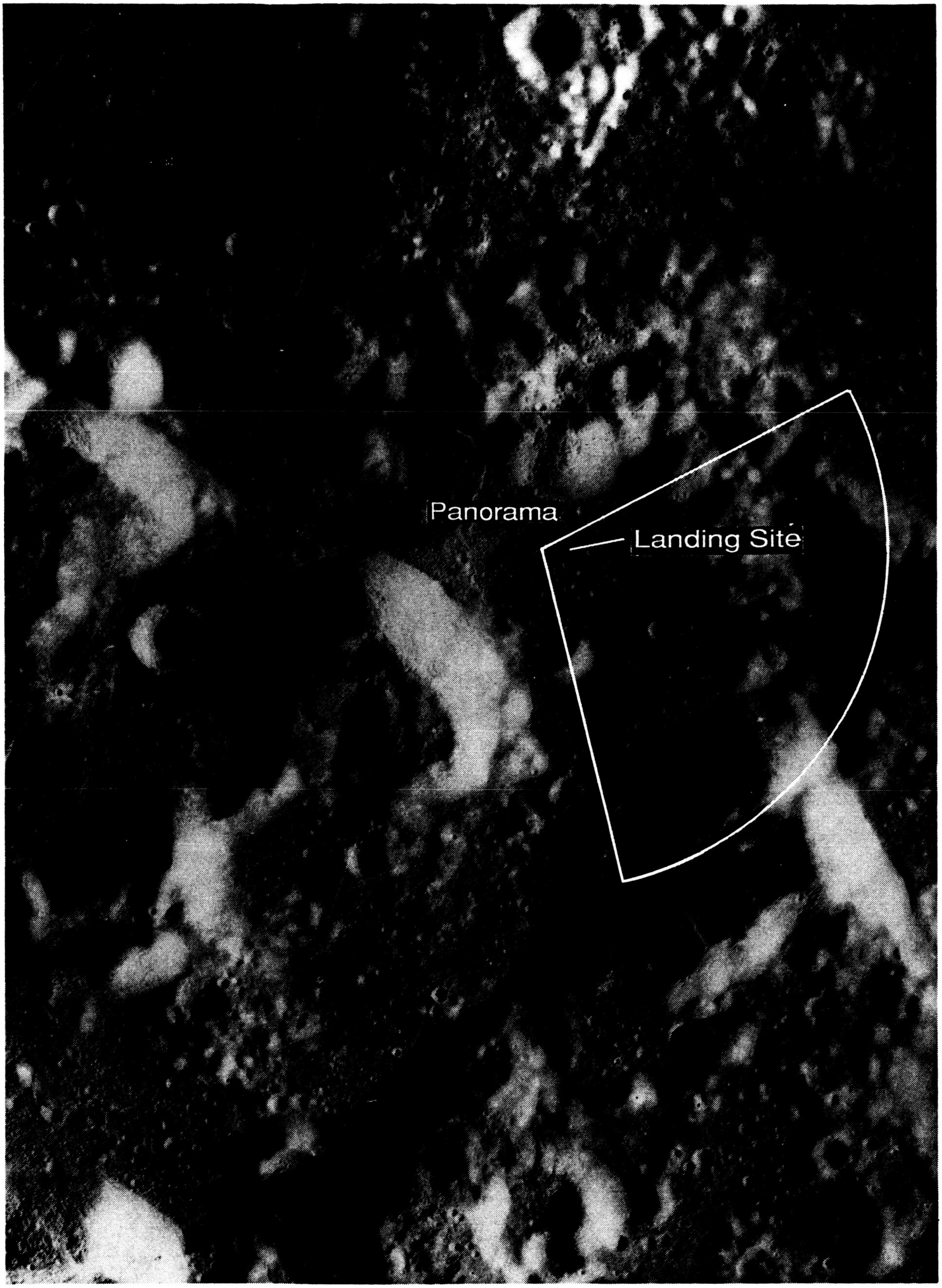


Figure 2.2-4, Taurus-Littrow Blowup View



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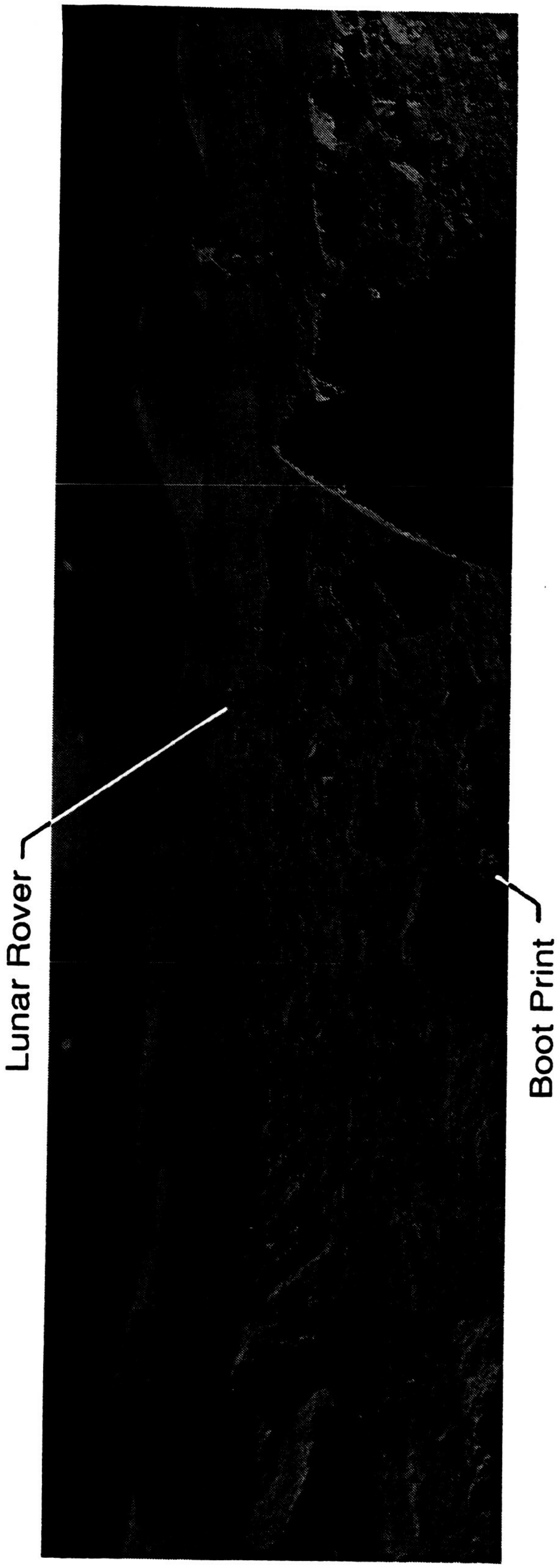


Figure 2.2-5, Taurus-Littrow Panoramic View

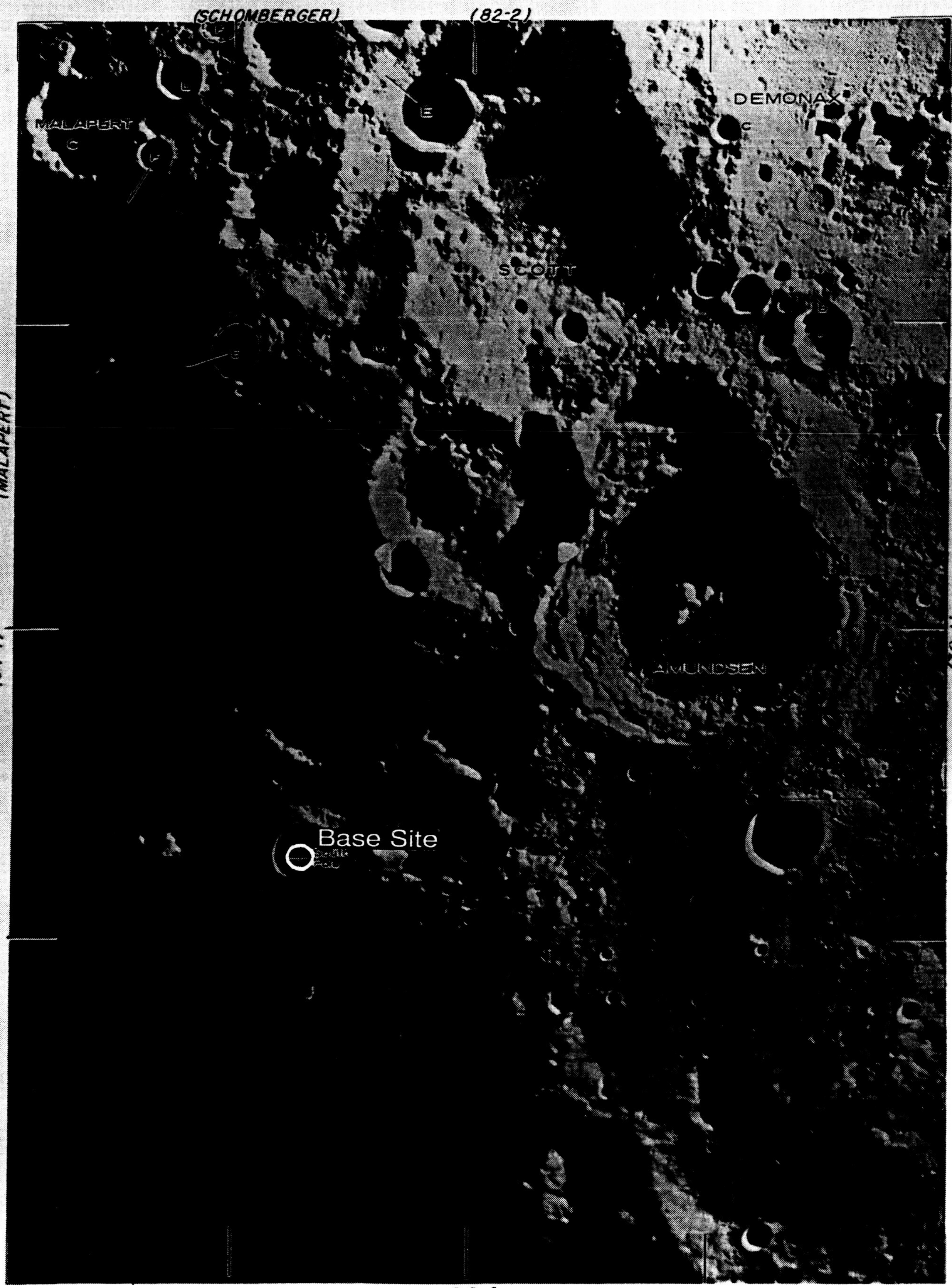


Figure 2.2-6, South Pole Landing Area



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## 3.0 FLIGHT VEHICLE INTERACTIONS

The interaction of flight vehicles and landing facilities is a major issue in the design of the facilities. These interactions are defined as the support for, and the effects of, the flight vehicles during descent, ascent, and landing operations.

The interactions covered here fall into three categories including the effects of the lander engine blast on the lunar soil, the support from surface-based, vehicle, and other navigation systems, and the effects of the landing surface on the landing gear systems. Taken together these interactions will affect designs of both the vehicles and landing facilities.

The effects of engine exhaust blasting the lunar soil is one of the most far reaching of any considered in this study. They dictate the proximity of landing pad to surface equipment and facilities, the protection that must be provided, and how landing surfaces should be stabilized. The effects will not present insurmountable problems but serious consideration must be paid to them in the design of nearby facilities.

Flight operations are intended to result in landings with meter accuracy. Current vehicle and simple surface-based navigation systems appear to facilitate consistent, close proximity landings. These systems would consist of fairly simple onboard radar systems with terrain recognition for powered descent operations in combination with surface transponders for final approach and landing.

Interactions between the landing surface and the landing gear will provide a basis for trade-offs between landing site preparation and landing gear design. It appears that landing gear systems will not result in severe requirements for landing site facilities except that pad selection must be carefully completed. The Apollo Lunar Module gear proved quite adequate for lunar landings on unprepared and uninspected sites.

### 3.1 ENGINE BLAST

The effects of rocket engine blast on both prepared and unprepared pads is probably the single most important and the most complex to analyze of any affecting pad designs. Blast from the lander rocket engine will present a broad range of issues affecting virtually every aspect of lunar base design.

The distance between the landing pads and surface facilities and equipment, especially the base itself, will depend on how far away blast damage can occur. The design and protection of equipment that must remain in the vicinity of the landing pad will be governed by how serious the damage from blast will be. Indeed, design and operation of all equipment that will be located around the lunar base must account for lander blast. When permanent reusable landing pads are needed, the stabilization of those pads will depend on the expected impingement of engine blast.

Blast effects can be summarized by a description of the damage to surfaces at various distances. In general the particles and grains ejected by blast will be at low velocities relative to typical meteoroid velocities. The maximum ejecta grain size is expected to be in the neighborhood of 5 millimeters with a velocity of around 10 meters per second. Smaller particles will have higher velocities and thus will travel farther.

- Metal objects within 50 meters of the lander will experience significant surface pitting damage after only one landing.

- Glass surfaces within 50 meters will experience severe pitting after one landing. Vision glass will be virtually unusable.

- Metal objects within 200 to 400 meters will experience significant, although not major, pitting damage after several landings but only minor pitting after one landing.

- Glass surfaces within 200 to 400 meters will experience significant pitting after one landing and be unusable after several landings.

- Metal objects over 2 kilometers away will sustain only very minor and probably unnoticeable pitting damage after numerous landings. Reflective surfaces should be protected.

- Glass objects over 2 kilometers away will sustain only very minor damage after numerous landings. The damage will eventually be unacceptable for optical quality glasses. Optical instruments should face away from landings.

After permanent landing pads are completed, the effects of blast will be limited. However, the possibility of particles small enough to be ejected still exists so the same sorts of precautions used for unprepared pads must be made.

The analysis presented here is a rough order of magnitude (ROM) calculation. Many assumptions and simplifications have been made. Where they were needed they were made as conservatively as possible. Detailed sensitivity analyses were not possible, but comparison to known data and effects are made where information is available. Calculations are broken into four sections:

- Lofted particle sizes
- Lofted particle trajectories
- Particle flux at a distance
- Particle damage

### 3.1.1 Ground Rules and Assumptions

As a starting point, the nature of the rocket plume must be quantified and the assumptions made must be described. Plume quantification was done using reference 13 and personal conversations with the author. This reference characterizes the exhaust plume of an RCS engine with respect to radial distance from the nozzle and angle away from the centerline. Distances are measured in nondimensional nozzle radii so the result can be roughly scaled to larger engines. The 1.5 meter diameter, 50,000 newton LM engine is the baseline for this study. The reference density and velocity presented in reference 13 are also assumed to be general. Finally the data presented in reference 13 are assumed to apply to the case of a lander which is close to the surface. In other words, the effects of backpressure and flow redirection due to proximity with the surface are ignored. The effects of backpressure will be to modify the exhaust flow at the nozzle exit. The effects of flow redirection due to impingement with the surface will be to increase horizontal flow rates in areas within a few meters of the nozzle. This should not affect the long distance ejecta a great deal. The effects of the assumptions and generalizations could be significant and any further study of lander blast effects should quantify the plume characteristics again. Resources for this work were too limited to allow detailed study of the effects of the surface on the plume.

Surface particles are assumed to be spherical with a density of 1,600 kilograms per cubic meter. The at-rest elevation of the nozzle plane is assumed to be about 1.5 meters.

Finally, all calculations are based on the assumption of steady-state conditions. In-plume times for particles are around 0.5 seconds indicating that this assumption is reasonable.

### 3.1.2 Lofted Particle Sizes

Lofting of surface particles is assumed to occur by stagnation of plume flow directly under the particle. The vertically upward force resulting from this pressure is balanced against the vertically downward gravity force and the angled drag force caused by direct impingement of the plume. Figure 3.1-1 shows the distribution of lofted particles as a function of distance from the centerline for several nozzle altitudes. Percent-finer-by-weight lines are shown on this chart to characterize the particle size distribution of the lunar soil. These were derived from reference 4. Maximum particle size for the landed configuration is 5 millimeters which is off-scale high on this chart. Particles in the 75 micron or less category which make up 50 percent of the soil can be lofted from an altitude of 15 to 20 meters. This is generally consistent with Apollo 17 data presented in Figure 3.1-2 (reference 6) showing first dust at 15 meters. Apollo 15 data indicate first dust at 45 meters due possibly to different soil compositions or the nearly vertical trajectory.

Variation of the maximum sizes with respect to thrust variations is nearly linear. A five-fold increase in thrust to 250,000 newtons shows that rocks of up to 25 millimeters may be lofted. This thrust is equivalent to 1.5 lunar gravity forces on a 100 metric ton vehicle. It can be shown that 25 millimeter ejecta will not travel over 20 meters in the plume.

### 3.1.3 Lofted Particle Trajectories

Ejection of particles is assumed to occur by direct drag acceleration of particles in the plume. The ejecta trajectory calculations from the baseline engine show the following maximum distances and velocities:

Table 3.1-1, Landing Blast Ejecta

| Particle Diameter (mm) | Impact Distance (m) | Impact Velocity (m/s) |
|---|---|---|
| 4.0 | 20 | 10 |
| 2.0 | 40 | 15 |
| 1.5 | 50 | 20 |
| 1.0 | 75 | 25 |
| 0.5 | 150 | 35 |
| 0.25 | 325 | 50 |
| 0.075 | 1,200 | 100 |
| 0.050 | 2,000 | 125 |

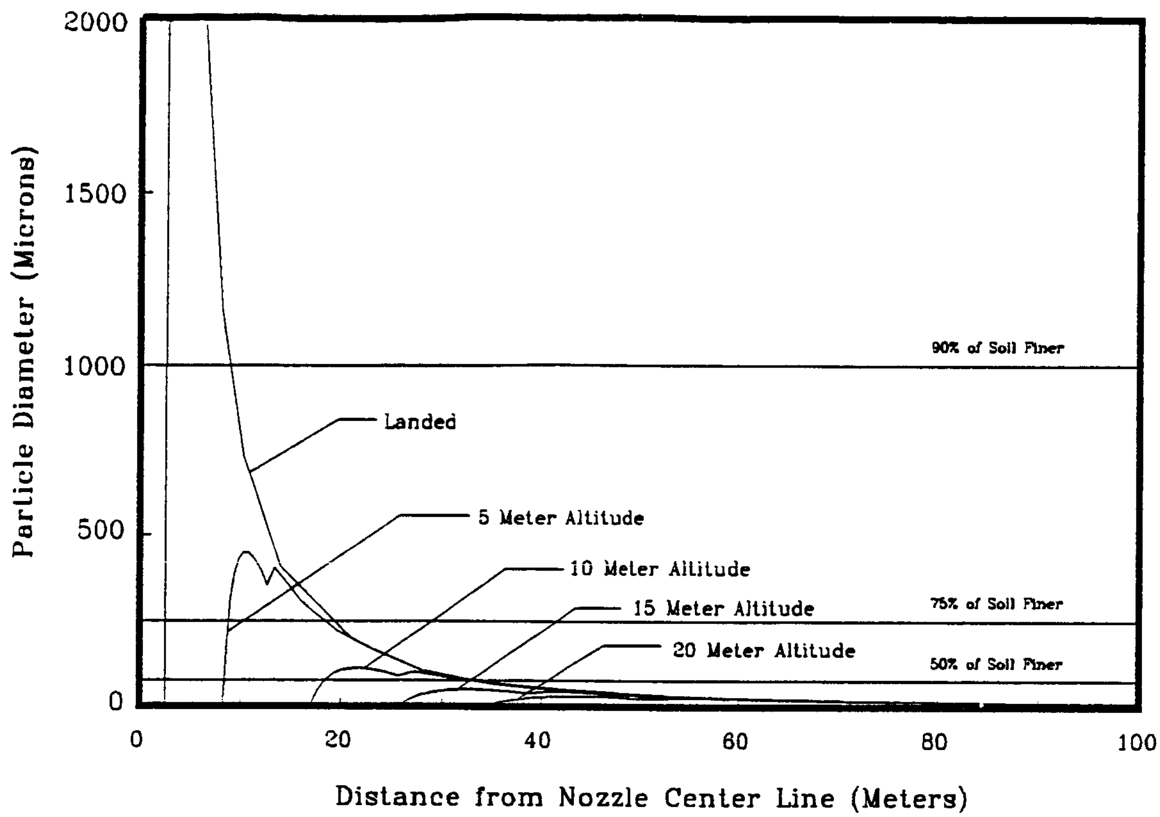



Figure 3.1-1, Lofted Particle Sizes

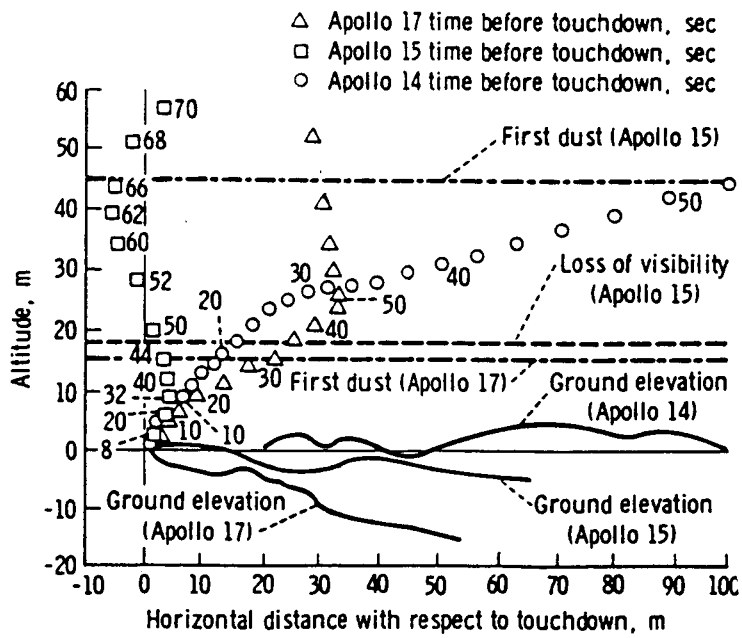



Figure 3.1-2, Apollo Dust Plumes

The trajectory data are generally consistent with reference 20 which, based on Apollo 12 and Surveyor interaction, indicates that particles with velocities in the neighborhood of 100 meters per second were ejected from the engine blast. Figure 3.1-3 shows graphically the ballistic trajectories of the particles after they leave the plume.

The effects of thrust increase on distance is roughly linear. Velocity increases with the square root of thrust increase. A fivefold increase in thrust results in 50 micron particles being ejected 12 kilometers. The impact velocity associated with this increased thrust is 300 meters per second.

### 3.1.4 Particle Flux at Distance

The flux of ejected particles will obviously vary with the square of the distance from the lander. The original flux was calculated assuming a percent surface obscuration due to particles and converting this to a number of some sized particles. The calculations were made using 50 micron particles and 50 percent obscuration. This should provide conservative estimates of the number of surface impacts due to ejecta flux. Results are shown in Figure 3.1-4. In general, at 50 meters over 30,000 particles per square centimeter per second can be expected. If larger particles are included, fewer impacts can be expected. At 200 meters the flux drops to around 2,000; at 2 kilometers the flux is below 50. Calculation of the power represented by the ejecta indicates that it accounts for about 10 percent of the engine power. This is not an unreasonable fraction of the plume energy converted to ejecta energy. The flux will vary with the square root of power increase so a fivefold increase in power will only roughly double the flux at a fixed distance.

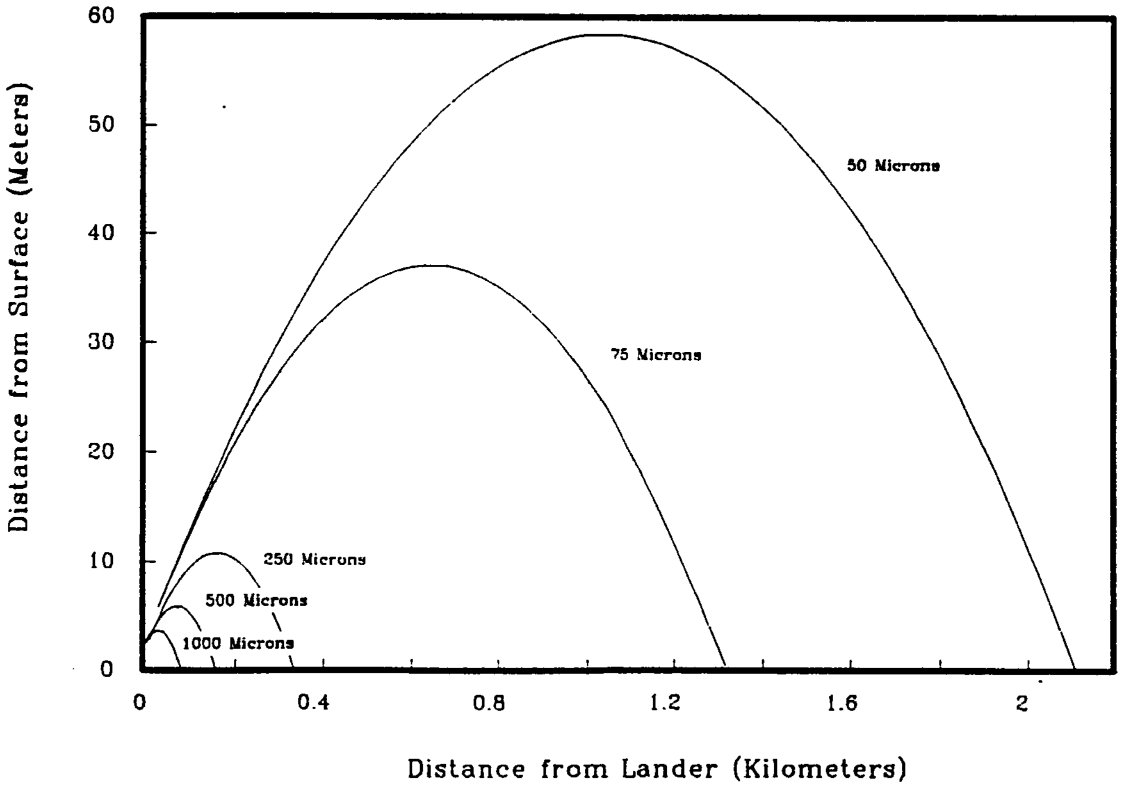



Figure 3.1-3, Lofted Particle Trajectories

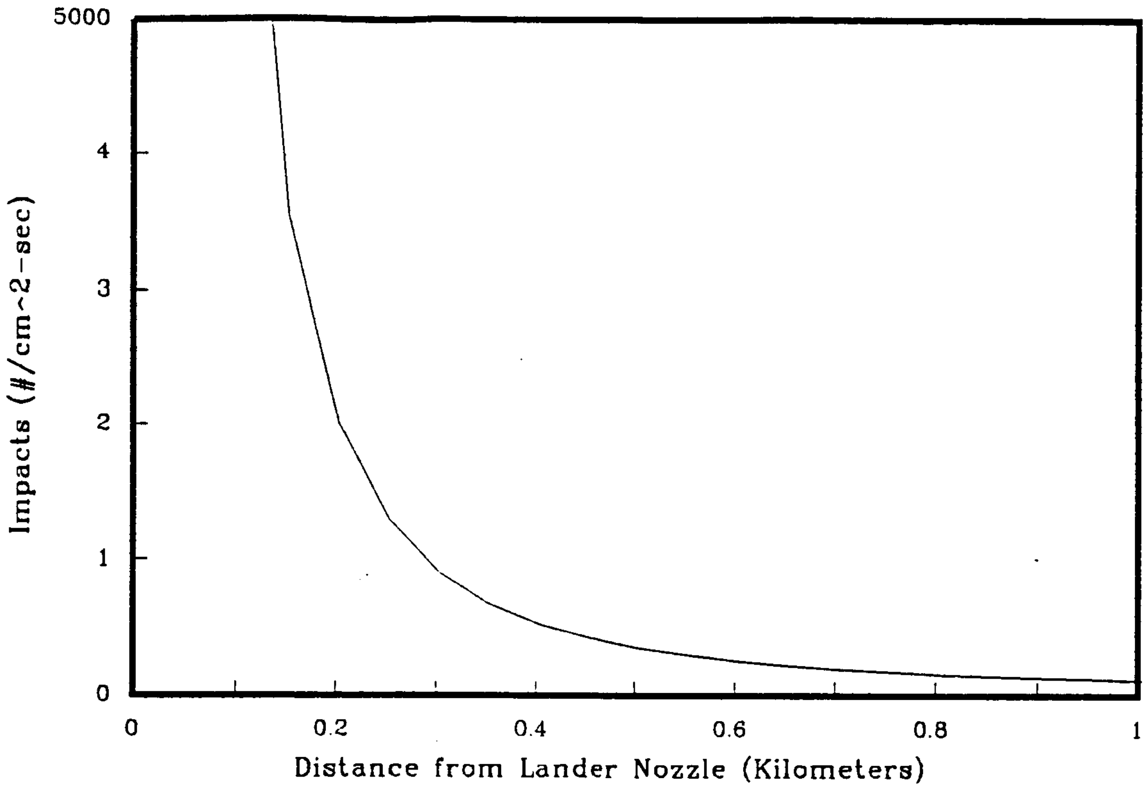



Figure 3.1-4, Particle Flux Distribution

### 3.1.5 Particle Damage

Finally, the net cumulative effects of the impact of particles on surface facilities and equipment must be assessed. Impacts such as these are considered low velocity impacts. Cratering by the low velocity impacts can be studied with known relationships such as those presented in reference 14. For the purposes of this study, cratering by ejecta on aluminum and glass surfaces is considered. Figure 3.1-5 shows the diameters of expected craters on these two surfaces. Ejecta particles at the velocities shown in Table 3.1-1 were used in each case. Note that craters in aluminum surfaces are relatively insensitive to particle size and stay generally below 20 microns. Craters in glass surfaces are very sensitive to particle size and exhibit significantly higher crater diameters for larger particles even though they have considerably lower velocities. To evaluate net effects of impacts on surfaces, the flux of 50 micron particles calculated above will be used. A typical final 10 meter descent should last approximately 5 seconds. Combining this with flux data, the number of impacts per landing can be found. From crater diameters, surface areas of each crater may be established and thus the percent of the surface area pitted by craters for each landing can be established. Figure 3.1-6 presents the effects for both surfaces with respect to distance from the landing event.

At 50 meters, an aluminum surface can be expected to have about 5 percent of its area covered by pits after one landing. This generally will not affect surface properties unless high reflectivity is needed. Glass at this same distance can be expected to have all of its surface pitted. Generally speaking, this will ruin optical quality glass surfaces.

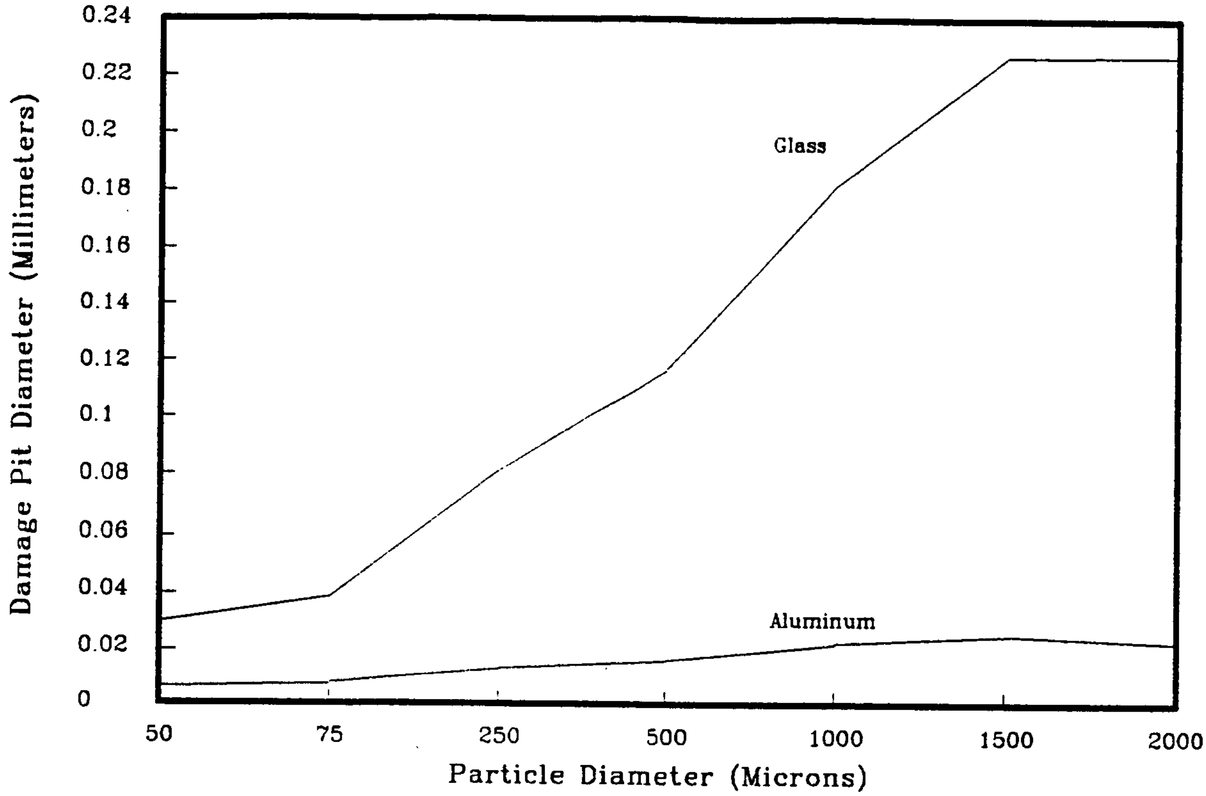



Figure 3.1-5, Damage Crater Diameters

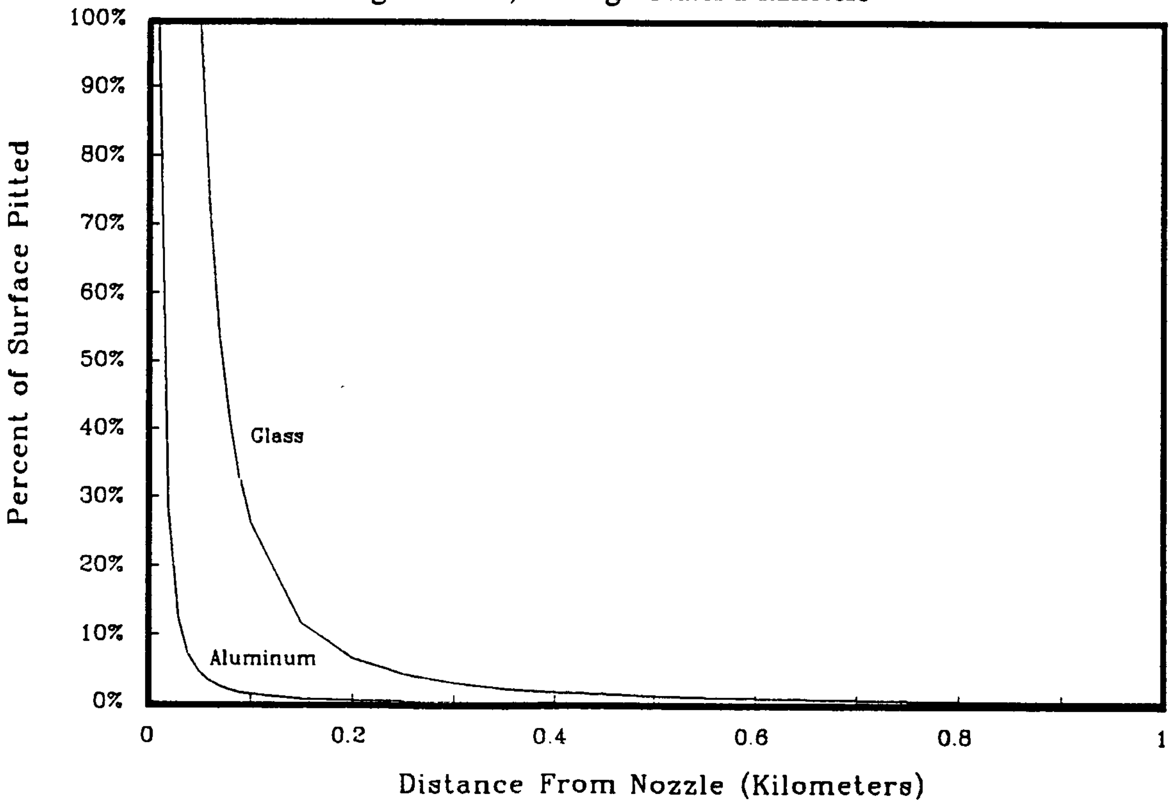



Figure 3.1-6, Single Event Surface Damage

Some pits resulting from bigger ejecta could achieve depths as high as 0.1 millimeter, easily visible to the naked eye.

At 200 meters, about 0.5 percent of an aluminum surface will be pitted. This is only minor damage. If degradation of the surface radiative properties is not at issue, aluminum surfaces should not present problems even after numerous landings. Glass, however, can have as much as 10 percent of its surface pitted after a single landing event. For serious optical instruments, this will be unacceptable. Pit depths of 0.03 millimeters are possible. This would not ruin vision glazing until several landing events had taken place.

At 2 kilometers, the aluminum surface will sustain virtually unnoticeable damage. Reflective surfaces will degrade after numerous landings and should be protected. Glass surfaces will sustain about 0.1 percent surface pitting. This will be unnoticeable in vision glasses after a single event but may show up a haze after several landings. Optical quality glasses should certainly be protected.

## 3.2 FLIGHT SYSTEMS

One of the primary purposes of the landing facilities and the equipment they encompass is to ease flight vehicle operations from surface to orbit and orbit to surface, ascent and descent. By far, the most involved of these operations is descent.

Flight vehicle navigation and guidance systems must be provided position updates and during final stages of landings must be able to find relative positions and velocities to within accuracies of meters. In particular, unpiloted cargo landers will require this level of accuracy to land on a specific site.

Because of this fact, a system of radar transponders is recommended near the site itself. The system should consist of one transponder uprange of the lunar base along the flight path and one crossrange. The separation should be large enough that the flight vehicle can begin triangulation calculations soon after the base comes over the horizon. Additional transponders may be required at the pad itself to provide redundancy and further accuracy.

### 3.2.1 Operations

The primary interaction between flight systems and surface landing facilities will be during descent operations. Flight systems must basically be able to identify their locations relative to the landing area. This must occur at times when the vehicle can either correct trajectory errors or sense that an abort mode must be entered. The main function of the system during ascent operations will be to provide navigation system updates prior to launches and during insertion operations. By far the most critical phase of interaction is during descent.

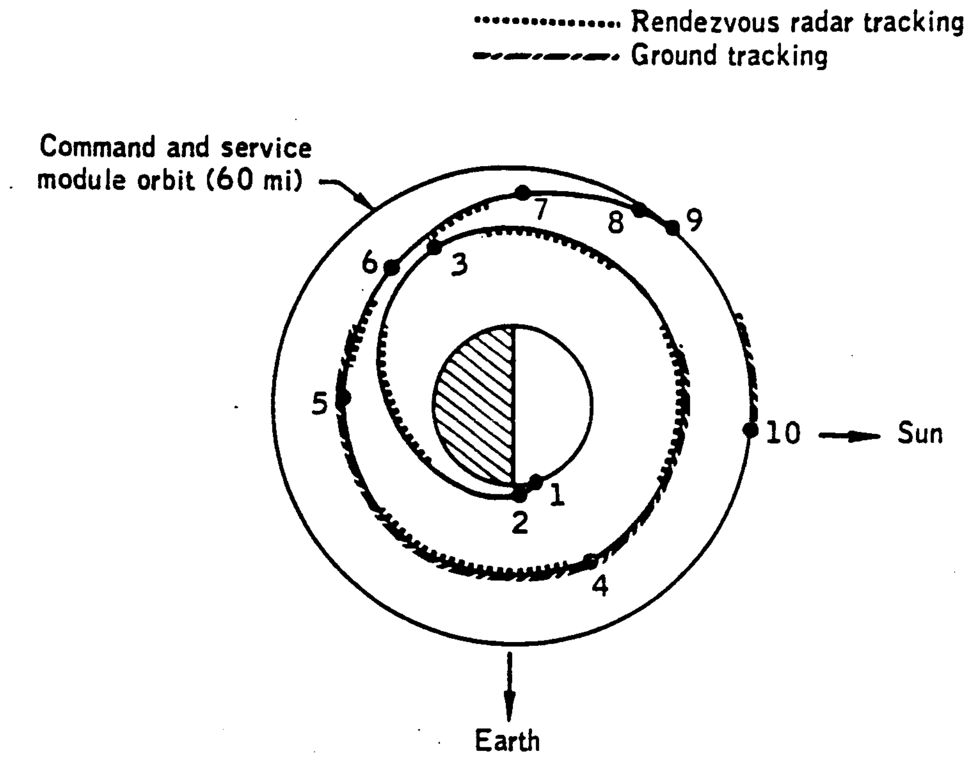
Ascent and descent trajectories similar to those used by the Apollo LM may be expected for the return to the Moon. The ascent phase of operations begins with a vertical rise for 10 seconds which represents an altitude of about 80 to 90 meters. After this, a pitchover maneuver begins and the vehicle is inserted into a 20 by 80 kilometer orbit for establishment of initial rendezvous conditions. Assuming the scenario requires rendezvous operations, rendezvous will take place in a 110 kilometer orbit. This was the Command and Service Module altitude for the Apollo missions. Navigation systems should provide inertial platform updates for both the ascent vehicle and its rendezvous target, whether it is an orbit platform or a trans-Earth stage. Figure 3.2-1 illustrates the Apollo 11 version of this trajectory taken from reference 11.

Descent operations begin from the 110 kilometer orbit. The descent stage inserts into a descent transfer orbit with a pericynthion of 15 kilometers. Upon reaching this position, a powered descent phase begins. During Apollo, this phase began when the landing site was 480 kilometers uprange and below the lunar horizon. Assuming no interfering features such as mountains, the base comes into view at just below 200 kilometers or about 8.4 minutes before landing. The first part of the powered descent will be called the approach phase. This phase ends about 8 to 10 kilometers uprange when the vehicle pitches over and, at least for piloted missions, the landing site comes into view. The vehicle will have an altitude of around 2 kilometers at this point and be at about 3.6 minutes before landing. The ensuing phase will be called the terminal phase. At about 100 meters uprange and 1 minute before landing, the final or landing phase begins. The vehicle will be almost vertical and at about 100 meters altitude. Figure 3.2-2 shows this trajectory again for the Apollo 11 mission (reference 11). The figures included as Figure 3.2-3 illustrate the views of the landing site from the vehicle. The terrain features for Lacus Veris, the primary site, have been included to show how they affect the view of the site during approach. The landing site should be able to provide updates to vehicle inertial platforms on the orbit before descent, and then continuously from the time of descent to landing.

Abort modes must be examined to determine if they place constraints on the landing facility. Range safety must be studied for the same reason. During ascent, abort modes are on-pad aborts which require immediate crew removal if possible, abort-to-orbit modes which will require the same platform updates from the base as will nominal modes, and abort-to-surface modes which will probably result in general mission failure. When the base is permanently occupied, an abort-to-surface should be tracked and some sort of rescue party mounted if the occurrence is far down range. Critical failures during the first 10 seconds will be difficult to manage without range safety.

This range safety will only be needed when humans remain at the base during an ascent event. For piloted missions, range safety in the form of thrust termination will probably be unacceptable. However, if a critical failure occurs during vertical lift-off, the crew can reasonably be expected to handle the abort to surface. A critical control system failure though could result in complete mission failure and also impact on base facilities. For piloted vehicle designs, reliability and range safety thrust termination must be traded to provide safety to base inhabitants. For unpiloted vehicles, lunar base range safety thrust termination should definitely be included. Understandably, after the insertion phase of ascent begins, whether for piloted or unpiloted cases, range safety thrust termination will be unneeded until downrange inhabited facilities are in place. This will certainly be out of scope for a Phase II lunar base.

During descent, credible aborts include abort-to-surface which will result in controlled landings in bad locations, abort-to-orbit which will involve returning to the original orbit, and bad landings which result in damaged vehicles. In combination with vehicle navigation systems and landing site navigation aids, the guidance system should always know whether the abort-to-surface or abort-to-orbit mode is appropriate. Bad landings are generally associated with failures during the final landing phase of operations. The primary response by the base will be emergency evacuation of crewmembers.




| | Event | Time |
|---|---|---|
| 1 | Lift-off | 124:22:00.8 |
| 2 | Lunar module insertion | 124:29:15.7 |
| 3 | Coelliptic sequence initiation | 125:19:35.0 |
| 4 | Constant differential height | 126:17:49.6 |
| 5 | Terminal phase initiation | 127:03:51.8 |
| 6 | First midcourse correction | 127:18:30.8 |
| 7 | Second midcourse correction | 127:33:30.8 |
| 8 | Begin braking | 127:36:57.3 |
| 9 | Begin stationkeeping | 127:52:05.3 |
| 10 | Docking | 128:03:00.0 |

Figure 3.2-1, Apollo 11 Ascent Trajectory

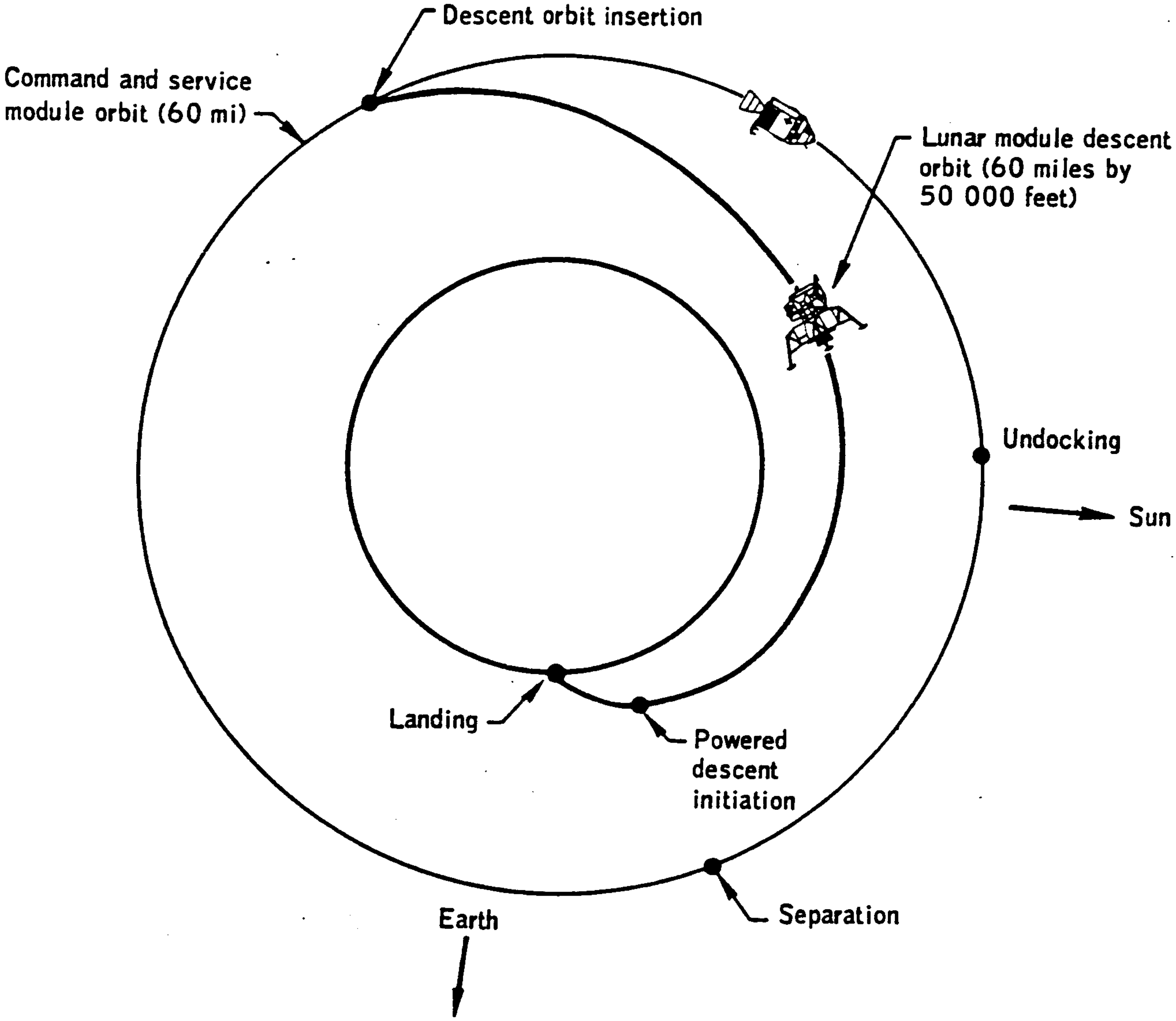



Figure 3.2-2, Apollo 11 Descent Trajectory

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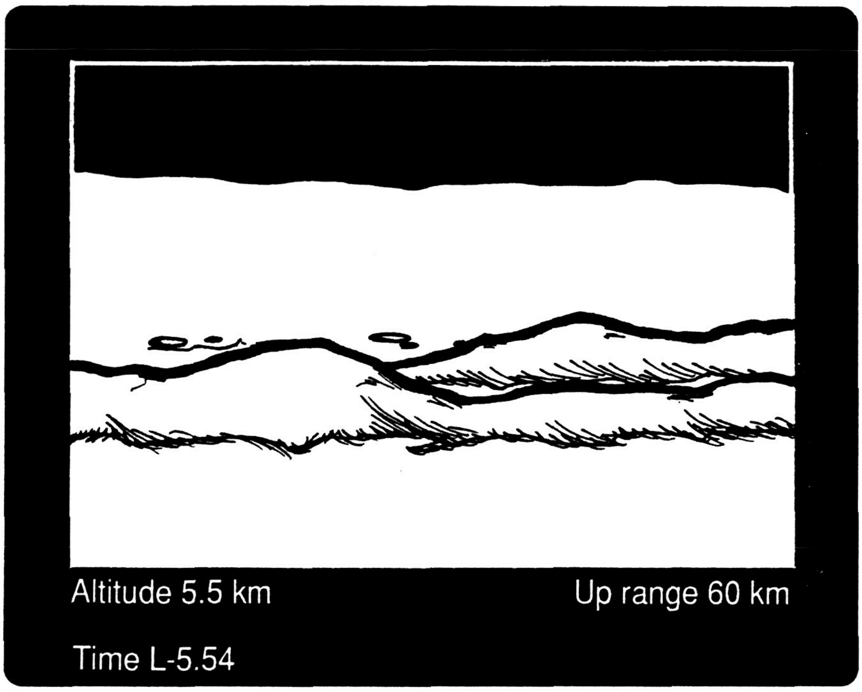


Figure 3.2-3, Landing Approach

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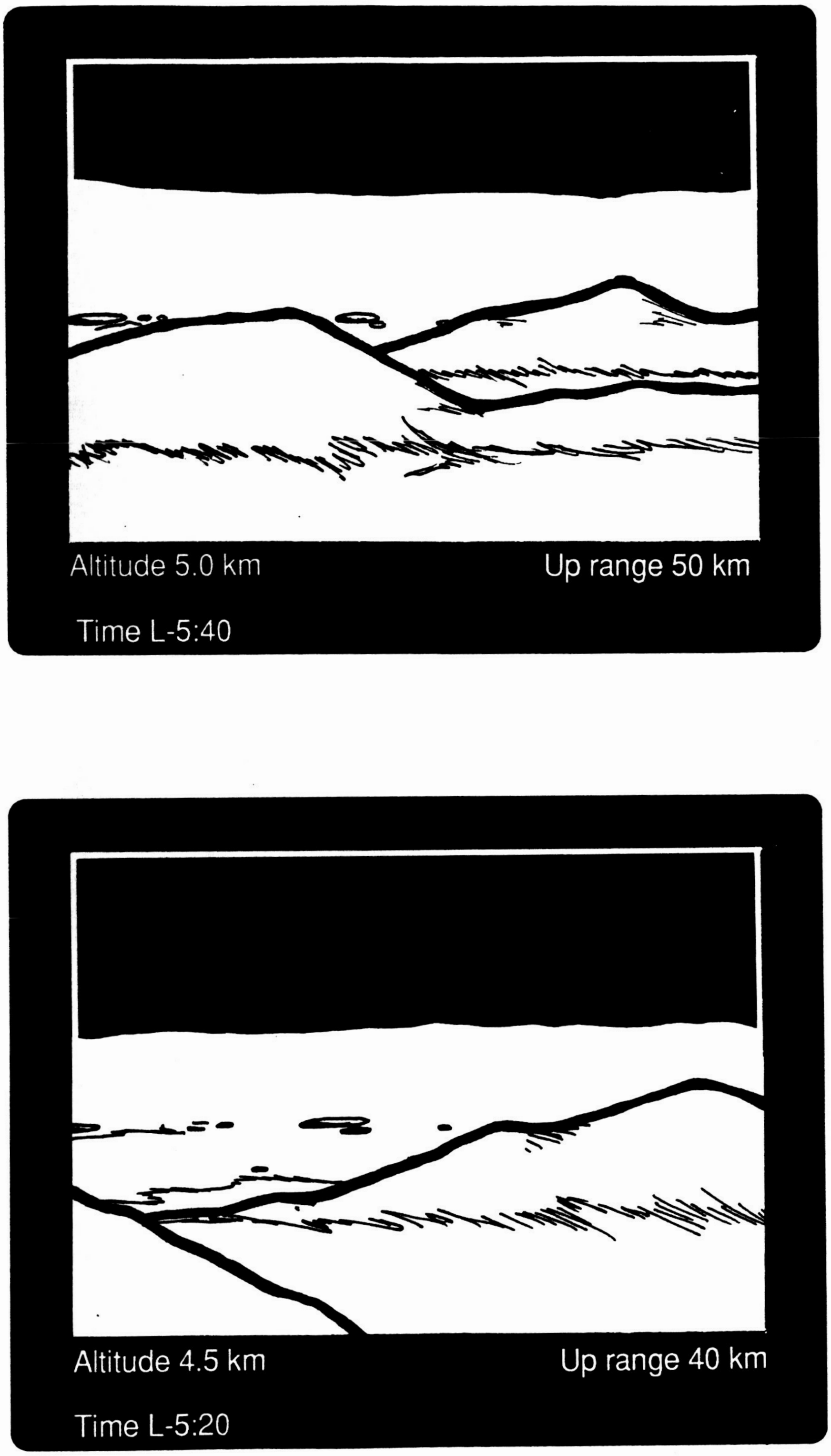
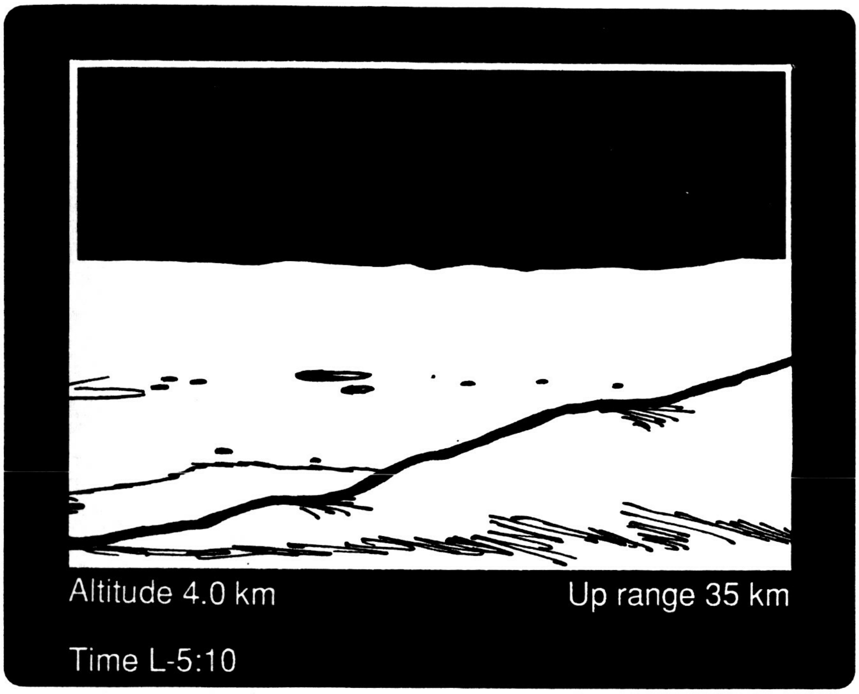



**Figure 3.2-4, Landing Approach, Continued**



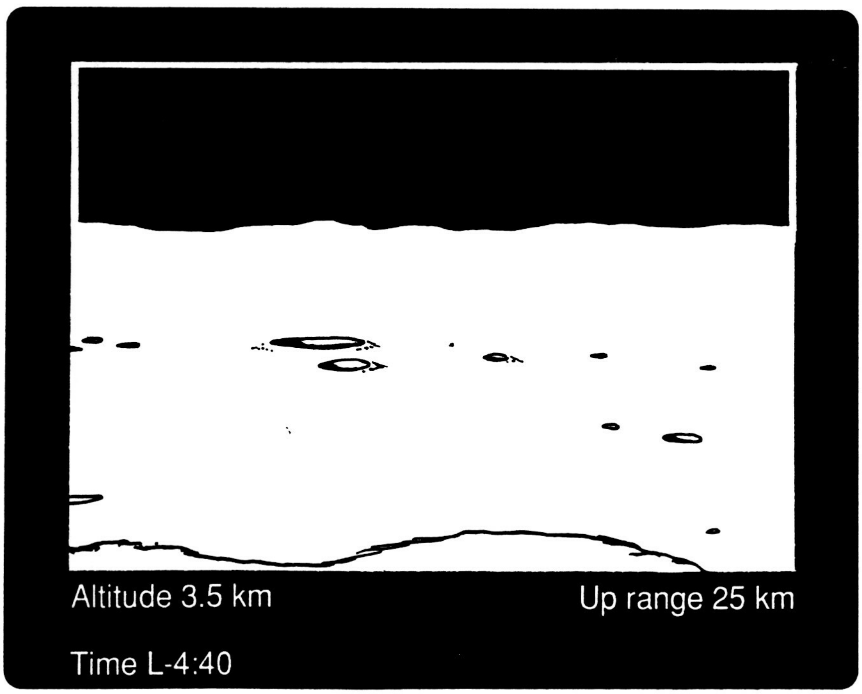




Figure 3.2-5, Landing Approach, Continued



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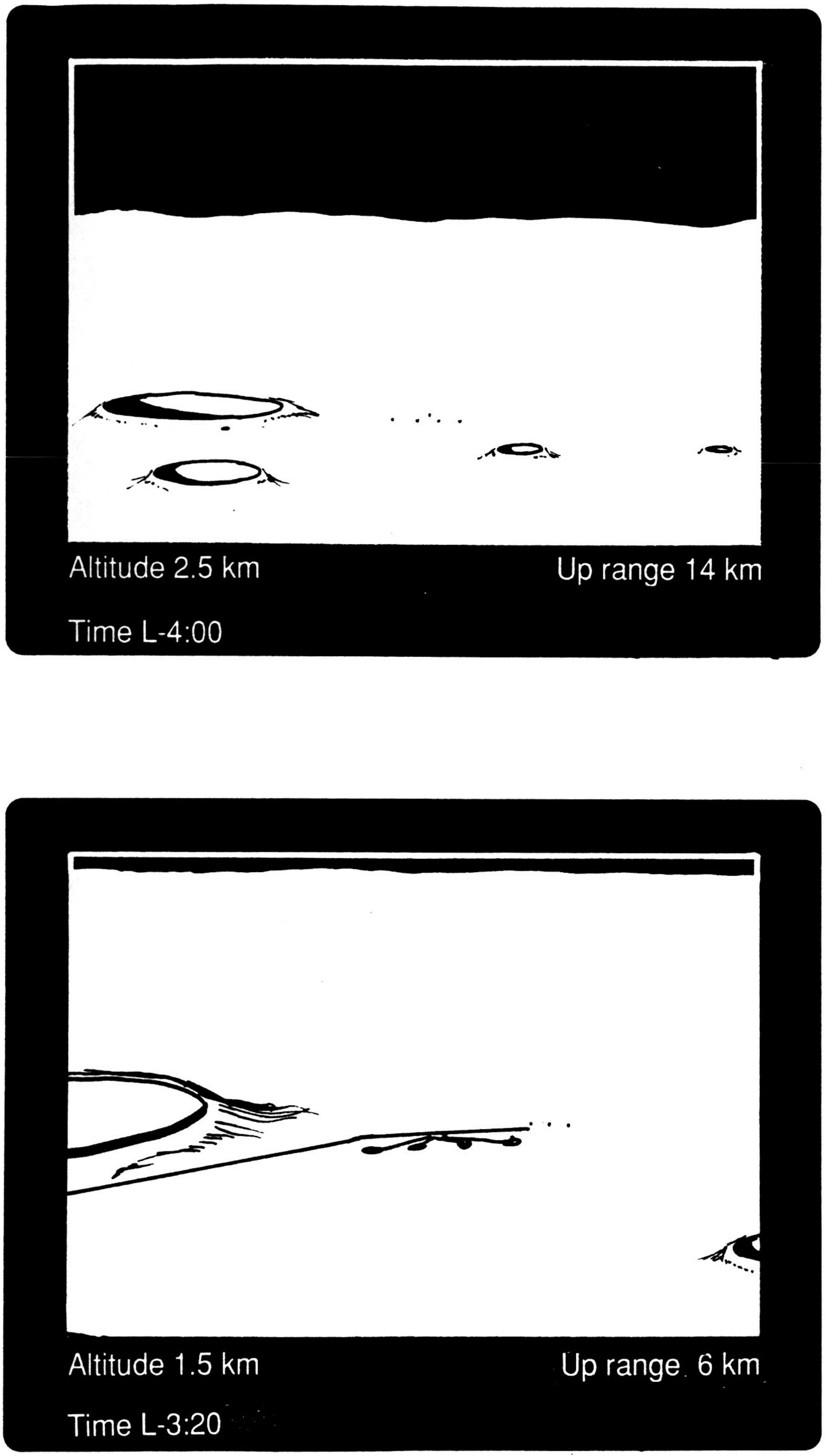


**Figure 3.2-6, Landing Approach, Continued**

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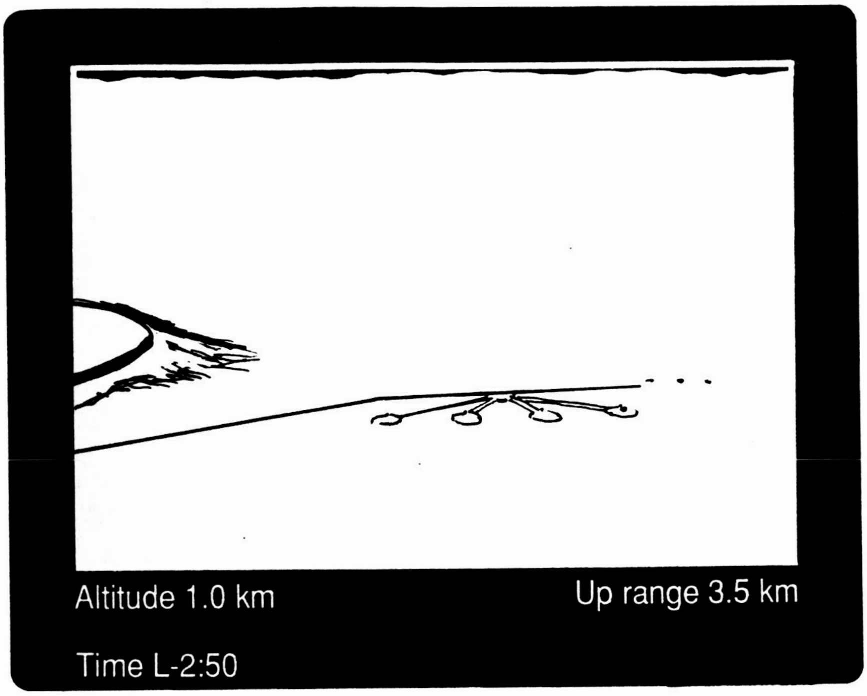


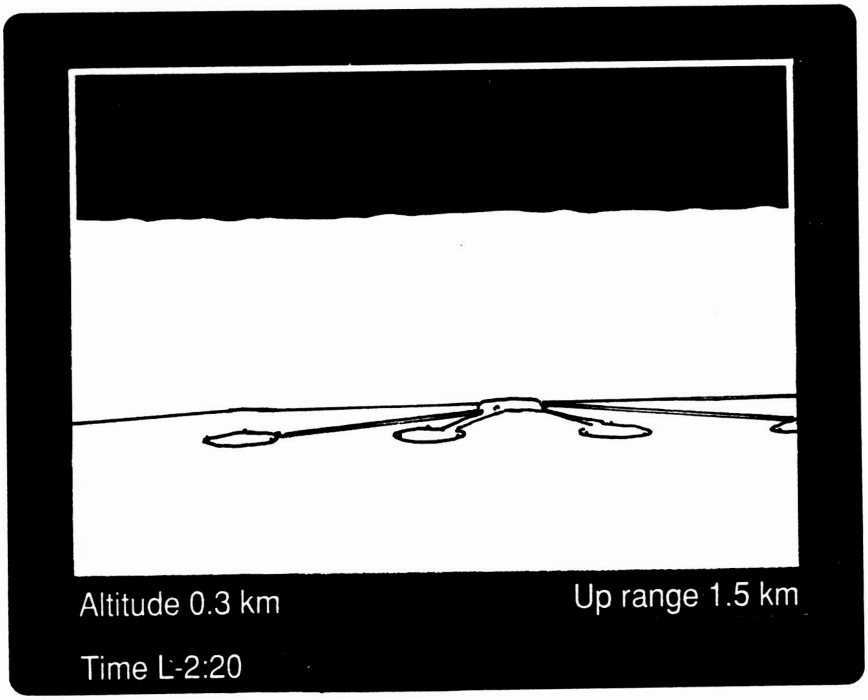


Figure 3.2-7, Landing Approach, Continued

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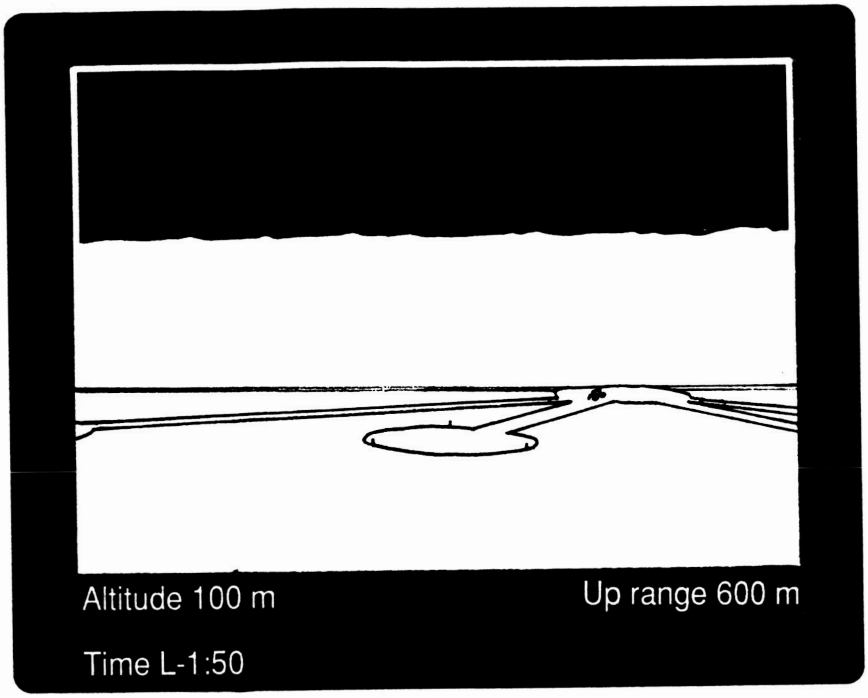


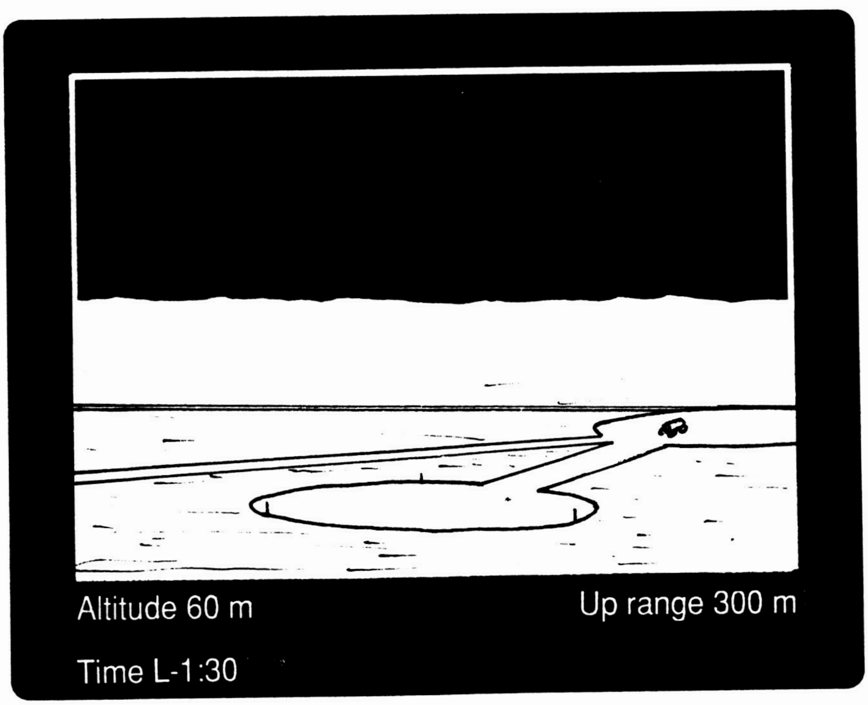


Figure 3.2-8, Landing Approach, Concluded

### 3.2.2 Navigation Systems

The navigation systems provided as part of the lunar base landing facility may be relatively simple systems of radar transponders with known locations. Onboard systems should utilize terrain and feature matching systems during periods when the base is out of view. In short, the navigation systems can use currently available terrestrial systems applied to the lunar surface to achieve high degrees of landing and positioning accuracies.

Lunar navigation requires more and more precision as the vehicle approaches the landing site. First, the orbital parameters and the location of the vehicle and the orbit relative to the landing site must be determined. The vehicle must transfer to an orbit that allows an optimum descent to the site. Once in the vicinity of the site, the vehicle must maneuver to end up roughly over the site with the relative velocity nulled. The vehicle must then descend to land on a location with no more than a few meters of error.

The lander will have an inertial platform to keep track its of location, but updates will be required. The inertial navigation will be inadequate for the terminal and landing phases. Given adequate orbital and approach navigation, the crew can handle the landing navigation in the right lighting conditions. The unpiloted cargo lander requires a good landing accuracy navigation system for all flights however.

The Apollo landers used a combination of Earth-based radar, crew recognition of local features, space sextant work, and inertial navigation to achieve an impressive accuracy. In addition the vehicles had radar altimeters and radars measured relative velocity. The radar altimeter was used to determine certain checkpoints later in the program. The crew always did the landing navigation visually. The missions were constrained to having the proper lighting conditions for visual landing.

Table 3.2-1 shows a variety of possible systems for updating the onboard inertial system and accomplishing landing navigation. The advantages and disadvantages of each are discussed. All of these systems are related to similar Earth-based systems. In order to better understand how Earth-based systems can be extrapolated, a number of them are described below.

The Rockwell designed Navstar Global Positioning System (GPS) will consist of 21 satellites in 20,000 km Earth orbits to be fully operational around 1991. Three satellites are on-orbit spares. The satellites mass in the range of 800 kg and are predicted to last 7 years in orbit. The system is designed such that the ground or flight receiver stations are passive. The power and cost are concentrated in the satellites and the receivers are small and low powered. The system provides extremely high accuracy navigation to within 16 meters vertically and horizontally. This will allow aircraft to do precision approaches to almost any spot on the surface of the Earth. If it works reliably, it will replace many current systems and provide high quality navigation to many countries without the funds or the traffic to justify big investments in surface transmitters. The entire system, ground and flight, will likely cost well over 10 billion dollars.

It has been suggested that the GPS system in orbit around the Earth could be used to navigate on the near side of the Moon. The GPS system can be used in space, as well as on or near the surface of the Earth.

Table 3.2-1, Navigation System Advantages and Disadvantages

| System | Advantages | Disadvantages |
|---|---|---|
| Lunar Orbit Global Positioning Satellite (GPS) type system. | Terminal, perhaps landing accuracy navigation over entire surface. | Many satellites required. Expensive to place.<br><br>Accuracy limited. Not adequate for touchdown navigation. |
| Earth orbit GPS system or Earth-based radar. | Nothing to place or power on lunar surface.<br><br>Good for orbit determination on the near side. | GPS accuracy unknown. May require large antenna. Earth side only. |
| Long and Medium Range Lunar Surface Transmitters: TACAN, LORAN, low frequency. | Several low frequency transmitters may provide low accuracy global coverage.<br><br>Can be placed and powered at base for local navigation and orbit updates. Terminal accuracy. | Heavy ground stations. Large antennae.<br><br>Accurate over a limited range only. Low frequency doesnotprovidehighaccuracy for any location.<br><br>Low frequency global coverage requires several transmitters at different places. |
| Instrument Landing System or Microwave Landing System at base | Can be placed and powered at base. Landing accuracy. | Terminal and landing navigation only for area close to transmitter. |
| Lunar Surface-Based Radar (located at base) | Enables range safety thrust termination. Can provide updates to vehicles in orbit. Low mass system. | Local area navigation only. |
| Cruise missile type onboard terrain matching radar on lander with transponders on surface if required. | Transponders only on surface in landing area. Very low mass. Landing accuracy navigation probable over entire surface. | Landing accuracy depends on accuracy of surface feature maps. |

An analysis beyond the scope of this study must be conducted to determine if the use of the GPS is truly feasible and what navigation accuracy would result. This analysis is valuable because, if the existing GPS will work, low cost navigation will be available on the near side at virtually no cost to the lunar program. On the other hand, given the accuracy on the surface of the Earth (16 m) and the probability that it will be significantly degraded on the Moon (100 m ?), this system will probably not be sufficiently accurate for precision landing navigation (need 1-2 m accuracy).

It has also been suggested that an equivalent of GPS be put in orbit around the Moon. All the satellites described above would not be required, but the cost of such a system would still be significant. The GPS system is designed to put the high cost part of the system in orbit in order to reduce the cost of the receivers such that they can be mass produced. This philosophy is not needed for the lunar case where, in the near future, there will be only a small number of receivers and all will be associated with very high cost vehicles anyway. GPS is also designed to keep the receivers passive for military reasons. The enemy cannot locate them from their transmissions. This feature is also unimportant on the Moon.

Some type of satellite navigation system may prove appropriate for lunar use in the future. The system can be less biased toward low cost receivers and military considerations. This deserves some study. Space vehicles require frequent updates, meaning one or more satellites must be in view at all times. A number of satellites are therefore needed and it is difficult to build a small, inexpensive system. Navigation systems designed for Earth using several geosynchronous communication satellites may prove to be more appropriate models.

The Navy Navigation Satellite System consists of a series of small satellites in low polar orbits (1,000 km). The original Transit satellites are being replaced by the improved Nova series. This inexpensive system provides approximate position updates (original system accuracy was 150 miles) at intervals of hours to days for ship and submarine navigation. An equivalent system, with much improved accuracy, could be installed in lunar orbit, but it would be of use chiefly to ground vehicles. The update rate is too slow for flight vehicles.

Earth-based radar uses a large radar (transmitter and receiver) on the surface of the Earth to hunt for a return from a vehicle in lunar orbit or on the lunar surface. The system works best when the vehicle in lunar orbit retransmits the received radar pulse to up its power and make itself appear "brighter" electromagnetically. The device that does this is commonly called a transponder. Apollo proved this system could work to update an inertial navigation system. Its major disadvantage is the large number of people and equipment at various locations on the Earth that must be maintained to track a limited number of vehicles. On the other hand, within the Deep Space Network and the U.S. military, the people and equipment may be largely in place already. It can only be used on the near side and is probably inadequate for precision landing navigation. Given a flight crew to avoid obstacles at the landing site, the system worked quite well for Apollo. Except for the landing phase, it may be adequate for landing large unmanned cargos and will undoubtedly be used at least early on in a return to the Moon.

TACAN and VOR/DME systems are ground-based transmitters that provide range and azimuth to passive on-board receivers. The transmitters and their antenna arrays are about the size of a small house trailer. The accuracies are high, but the frequencies require line-of-site, so the range is limited to on the order of a few hundred miles for vehicles in anything other than a high orbit. Originally designed for aircraft navigation, TACAN was tested on the Shuttle in orbit. Most of the developed world, including the U.S., is covered with these stations and they are the current mainstay of continental aircraft navigation. The transmissions provide only range and azimuth in the horizontal plane. Extensive navigation in the vicinity of the Moon would require a large number of these transmitters, spread over the surface of the Moon, which is impractical in the near term.

Low frequency, OMEGA, LORAN, and others types of transmitters are similar to VOR and TACAN except their low frequency allows them to be used out of line-of-site. A relatively small number of ground stations allows whole Earth coverage at a rate adequate for aircraft but, with low accuracy, inadequate for landing navigation on the Moon. Such a system might work on the Moon given several fixed bases where transmitters could be maintained and another way of doing landing navigation. The antennas are large.

Instrument or Microwave Landing Systems (ILS or MLS) use high frequency transmitters to provide landing accuracy navigation for aircraft at present. They are the major means of landing navigation in bad weather and are required for all aircraft auto-land systems. They consist of relatively small ground-based transmitters which, combined with a ranging device, could provide adequate navigation for lunar landing. They are short range however and of no use for general navigation.

A radar at the base is a line-of-sight system which will only be effective overhead and down to the horizon (which is rather close on the Moon). At low altitudes it is good for ranges in the 100s of miles due to this horizon constraint. It is accurate enough for precision landings. The unit on the ground and the antennae (1 m diameter) are not unreasonably large if the target has a transponder. General navigation with surface-based radar requires a number of radars at different locations which is impractical for an early base. The radar is complex and expensive when compared to other Earth-type navigation devices but not unreasonably so when compared to spacecraft systems in general. It must also be installed and tested on the surface before an unmanned precision landing can occur.

Terrain-following radar was used in a primitive manner during Apollo to determine when a mountain range or other large geographical feature was crossed. Apollo LM's carried radar altimeters and sensed horizontal velocity with radars. Terrain-following radar has now been refined to a practical device for use in unmanned cruise missiles carrying explosives for long distances at low altitudes on Earth. The radar maps the terrain and compares the map mathematically to an internal map held in a computer. Position can thus be determined. A radar altimeter determines altitude. Given an accurate map of lunar surface features, this system has many advantages for the lunar case. It can be used for general and terminal navigation anywhere on the surface, requires no large facility emplacement on the surface, can be used on the first landing, and if terrain features are well placed and known may be adequate for landing navigation at many points on the surface. Given a transponder on the surface marking the landing site, it should be able to perform precision navigation to meter accuracy until touchdown. The lunar surface must be well mapped however. A study is required to determine what is needed in terms of mapping accuracy and how to go about getting it if it does not already exist.

The preferred system is this terrain-following radar with surface-based transponders. The basic elements of this system will all be part of the landers anyway and, depending on the surface features and the accuracy of their positions, it is even possible that no surface elements at all may be required. As a baseline, transponders positioned to allow a high degree of triangulation resolution when the landing site comes into view will be needed. In addition, transponders located very near the landing pads may be needed for the very accurate positioning and for redundancy during the terminal and final landing phases. A small surface-based radar would be a low cost addition to provide for range safety once permanent occupation begins.

The first requirement for terrain-following type navigation is knowledge of location of the terrain features within a certain range of error. As the landing site is approached, this knowledge must become increasingly precise if surface transponders are to be avoided. In addition there must be terrain features with good echoes near the landing site.

There will be pressure to locate the site on a plain to improve safety so surface features may not be distinct. In any event, the general area of the site must be mapped well enough to allow good terminal navigation. If the first landings on the site are unmanned, a certain element of risk may exist in the absence of good landing navigation from visual or other sources. If the first landings on the site are manned, they must occur during lighting conditions allowing good visual landing navigation. The first landers can carry transponders and place them at appropriate locations. Transponders should be detectable by the lander radar system from 200 kilometers. Subsequent missions will then get position updates relative to these transponders.

Once there is a crew on the surface during cargo landings, the surface-based radar can be installed. This is anticipated to be a small unit with a dish less than a few feet in diameter. It will track the transponder on the incoming lander. The crew on the surface may be provided with the option of terminating the thrust on the incoming unmanned lander if prediction software indicates deviations that may lead to damage to surface equipment. The crew may also give relative position updates to the vehicles that pass overhead in orbit.

## 3.3 LANDING GEAR INTERACTIONS

Vehicle landing gear must be designed to accommodate the expected landing surface. Unprepared landing pads for which no leveling has been done will place more stringent requirements on landers than level and well prepared reusable pads. Landers, however, always have to be able to land on unprepared surfaces within a set of landing ellipses determined by failure of specific navigation system updates. With site selection activity similar to Apollo experience, an area with slopes no larger than 12 degrees should be located.

Thus landers must be capable of landing, with all systems functioning properly, on a 12 degree slope. Unpiloted landers should be capable of tolerance of slopes up to 16 degrees.

### 3.3.1 Apollo LM Landing Gear

The Apollo LM was designed to land on typical flat areas of the Moon. The design was fixed in July 1965 at the 167-inch radius four leg configuration with the estimated final loads as described in reference 7. The design was based on pre-Lunar Orbiter and pre-Surveyor data. These missions were between 1966 and 1968. As is obvious now, the Apollo landing gear proved adequate. There is some doubt about the lander's ability to clear localized surface roughness such as rocks. The design requirements allowed the engine bell to contact the surface. Future designs for vehicles which will reuse the descent engine should require more clearance.

The LM was designed assuming that the average lunar slope was 6 degrees and that the effective slope was less than 12 degrees including the effects of depressions and protuberances (rocks). It was assumed that the vertical distance between the highest and lowest foot pad would be 24 inches (61 cm) or less. The soil bearing strength was assumed to be such that a load of 1 pound per square inch (0.69 $N/cm^2$) would result in a penetration of 4 inches or less. A dynamic load of 12 pounds per square inch (8.3 $N/cm^2$) was assumed to result in a penetration of 24 inches (61 cm) or less. The coefficient of sliding friction was assumed to lie in the range of 0.4 to 1.0. The landing gear was designed to a touch-down velocity of 10 feet per second vertically and 4 feet per second horizontally. The LM was designed with a safety factor of 1.35 and 1.5 on fittings. In retrospect the LM landing gear system was designed for soil much weaker than necessary; the foot pads never penetrated more than a few centimeters into the lunar soil.

However, the LM did not have any tolerance for surface roughness to land in sloping or rock-covered terrain. The topographic variations encountered were at the upper limit of the design range, with the Apollo 15 vehicle coming to rest with its vertical axis inclined at about 11 degrees from vertical with the foot pads differing in elevation by nearly four feet. The crew was not able to observe and avoid the crater into which the rear leg came to rest because of the dust cloud thrown up by the decent stage exhaust. Only the back landing gear was in the crater, and thus the engine straddled the edge of the crater. The engine bell came to rest within a few inches of the ground. The crew noted and photographed the decent stage engine bell (reference 8) which had collapsed. Post-mission analysis suggested that the collapse was due to the ground effect backpressure on the engine rather than striking a rock. Nonetheless, the engine would not be suitable for reuse.

### 3.3.2 Lunar Base Lander Systems

All of the landers associated with the return to the lunar surface must be capable of landing safely on unimproved surfaces whether prepared landing pads are available or not. Apollo design criteria may generally be followed with some exceptions. Foot pad design criteria may be relaxed somewhat since the lunar soil bearing strength was higher that expected. Tolerance for surface roughness should be increased especially if reusable landers are to be used. Constraints for landings on unimproved sites must be used as long as any credible failure of guidance or propulsion systems indicates the possibility of landings on unleveled surface areas.

For vehicles designed for piloted terminal and landing guidance, all systems should be designed to operate normally with the vehicle coming to rest at an angle of up to 12 degrees. The maximum elevation difference between pads can be as great as 2.5 meters given gear 10 to 12 meters from each other. Obstructions, such as a break in slope at the edge of a crater or rocks as high as 1.5 meters above the plane containing the four foot pads should be manageable without degrading vehicle performance.

Vehicles designed for unpiloted terminal guidance should be designed to land with the vehicle coming to rest at an angle of up to 16 degrees. The maximum elevation difference between the highest and lowest foot pad is 3.5 meters. Obstructions such as rocks as high as 1.75 meters should be manageable without degrading vehicle performance.

The crater counting and slope data presented previously in this report indicate that the average slope over 25 meter distances is over 4 degrees. Only about 25% of the surface has a slope of less than 2 degrees even in the smooth young mare regions. Craters with a diameter of 10 meters and depths of about a meter cover virtually the entire surface of the highlands areas and about half the area of the youngest mare. Thus it is virtually impossible to find a natural lunar surface even a hundred meters across which lacks relief of at least a meter or slopes of at least 4 degrees. These values set the lower limit for relief and slope tolerance of any lander using unprepared landing sites no matter how good its landing navigation and guidance.

The Apollo LM had a landing ellipse of 1.5 km x 2.7 km at Apollo 17 (reference 3). In the event of a gross navigation system error, the landing ellipse was 6 km across cross-range and 14 km diameter downrange. The nominal landing site was selected so that the entire landing ellipse fell in a flat, hazard free area. In the case of Apollo 17 that area was the flat valley floor. For Apollo 17 the extreme downrange end of the landing ellipse crossed the Lincoln Scarp with about 50 meters of local relief and a 14 degrees average slope which was considered by the site selection board to be an acceptable risk. Unpiloted vehicles may not be able to avoid such a surface feature and should be designed to handle larger slopes than piloted landers.

The Apollo LM had a four point landing gear with a radius of about 4 meters. The radius of the gear for the next generation landers will vary but should be in the range of 6 to 10 meters. This dimension is used in all further analyses of the landing sites as the most constraining.

Based on a derivative of the Apollo design the lander landing system design static load on the pads should be less than 10 pounds per square inch (6.9 $N/cm^2$) and the dynamic load should be less than 120 pounds per square inch (82 $N/cm^2$) which would result in a penetration of less than 10 centimeters.

## 4.0 SURFACE OPERATIONS

Surface operations include the general activities surrounding the launch and landing facility which do not involve vehicles in flight. These operations will fall into four categories: site operations, crew accommodations, cargo accommodations, and vehicle accommodations. Site operations involve activities surrounding the development of the landing pads such as pad selection, preparation, and marking. Crew accommodations cover the activities surrounding removal of crewmembers from vehicles and transporting them to the base. Cargo accommodation activities are those that involve removal and loading of cargo onto and off of vehicles and transfer of cargos to other base areas. Finally, vehicle accommodations are those activities which support the vehicle itself such as support for long-term surface stays and overall maintenance and servicing.

The stages of base development within the Phase II lunar base period are early, temporary and permanent. The early stage is characterized by the incomplete nature of base facilities which will be unable to support life for any long period of time. When this capability is in place, temporary occupation and thus the temporary stage begins. In most scenarios for the lunar base, the facilities grow during the temporary stage until permanent occupation is feasible. When the base begins this permanent occupation, the permanent stage has begun. This typically marks the end or near-end of the Phase II Lunar Base depending on what milestone is used for this determination. While some overlap can be expected, the landing facility surface operations can be expected to follow these three base stages in their level of sophistication.

The following sections describe the operations beginning with a description of general operations. This is intended to provide a framework for the understanding of what sort of activities actually take place in support of landing and launching operations. In addition, by examining these operations, some operational considerations for design of landing facilities and equipment become evident.

### 4.1 GENERAL OPERATIONS

During early operations, landing facility activity will be coupled closely with overall base operations. Lunar surface operations will use the lander/ascent vehicle as a hub and crews will live in the vehicle. The first crews will arrive on the lunar surface select or verify a base site with an area suitable for landings nearby. They will place remote navigational aids and lay out the additional pads needed. The number of pads will actually depend on the scenario but it should be sufficient to handle all landings up to, and including, the next piloted mission. Subsequent crews will do the same except they will not need to place the remote navigation aids. Vehicle off-loading will take place when appropriate according to mission plans. When each crew leaves, sensitive surfaces and equipment installed at the base will be protected from the blast of the next landings as appropriate for each case.

The general area of the temporary pads will be selected by crews near the end of the early landing site development stage. They will move the remote markers at the same time to accommodate the new landing location. Each crew will lay out at least a sufficient number of landing pads to accommodate all the missions up to and including the next piloted mission. Mission planning may indicate that all temporary pads may need to be marked during one mission. Crews will move to the base after arrival on the surface. Until pressurized transfer from vehicle to base is available, EVA will be needed to get crews into the base. This will necessitate careful mission planning to ensure that every

EVA hour is used appropriately. Crews will unload cargo vehicles as indicated by the mission plans. When each crew leaves, they will protect the equipment left behind near the pads, such as surface transportation vehicles, from the blast of the next landers. In addition, some of the equipment, instruments, and facilities left at the base may need protection as described in the Facilities Conceptual Design section.

At the end of the temporary stage, the best site will be picked by the crews and the pads will be leveled and finished according to the surface stabilization methods described under Facilities Conceptual Design. These pads will be marked using the standard markers. The remote markers may be left where they are since the temporary and permanent pads will be close together. Depending on the availability of pressurized transfer, the crew may or may not need EVA to get into the base itself. In addition to off-loading vehicles, the reusable pads will need to be cleared of empty cargo vehicles and expendable lander platforms. Some vehicles may require loading and servicing. The activity of the crew as they leave the lunar surface will depend on whether the base is permanently occupied or not. Temporary occupation will indicate the same preparation as needed for the temporary stage. Permanent occupation indicates the same sort of preparation but may also require suspension of some ongoing activity such as EVA operations.

## 4.2 SITE OPERATIONS

### 4.2.1 Landing Site Selection

Landing site selection involves actually going out and picking the optimum locations for landings. The selection of the first landing site will simply require the location, either by teleoperated surveyors or from orbital observation, of a relatively flat area which is suitable for the first piloted landing. Since the first landing site will be very near the site selected for the base, site selection will be coupled with the base site selection.

Early site selection will take place during the first piloted mission. This activity will simply require the location of relatively flat areas near the base which are suitable for piloted and unpiloted landings. The actual criteria used to select these sites are described under Facilities Conceptual Design.

Selection of temporary sites occurs when installed base facilities can be used for habitation. This activity includes the location, by crewmembers, of multiple flat areas suitable for landings without site preparation. A sufficient number of these areas must be located to support the planned landings before permanent prepared sites are used. The crew will travel in a surface rover to a previously defined landing zone. They will then select and mark the appropriate number of landing areas.

Permanent landing sites will be selected when operations surrounding landed vehicles become sufficiently involved that temporary sites are unacceptable. This could occur when significant vehicle servicing and fueling begin or when the frequency and complexity of cargo loading and unloading require a flat, fixed pad. The actual selection will be much the same as for the temporary sites except that the very best of landing areas will be chosen. The landing sites should require the least amount of flattening and be the most easily accessible, in addition to being near an area where vehicles may be moved and stored when they are cleared from the prepared pads. In fact, the permanent sites may be selected at the time the temporary sites are selected and could be expected to be very near the temporary sites since the temporary sites will already be a vehicle disposal area.

### 4.2.2 Landing Site Preparation and Marking

These operations are the activities necessary to get the landing sites ready to accommodate the relevant descent stages. The first landing site will be selected only by teleoperated or remote activity so site preparation will be minimal. If teleoperated surveyors are used, some sort of marking may be done. The surveyor could carry a transponder device or be driven around in a circle to disturb the soil and provide visual markings. The Apollo program accomplished fairly accurate landings with no site preparation or marking and it is likely that even minimal marking will allow even more accurate landings.

Site preparation for the early and temporary landing areas will be rudimentary, consisting mainly of marking with visual landing aids or transponder devices. Some sites may be selected that are flat enough for landing sites but have rocks which must be removed. Site preparation, then, must allow for the removal of large boulders that exceed the maximum criteria described under Facilities Conceptual Design. Depending on mission planning and the number of boulders found, all anticipated sites may be prepared during one operation or sites may be prepared piecemeal during several missions. Landing sites must be marked in sufficient numbers during each mission to accommodate the next few landings. Subsequent piloted missions will mark more sites by relocation of markers and transponders.

When landing pads are marked, their distance from remotely located transponders or at least two prominent surface features must be determined. These measurements will be provided to vehicle navigation systems so they can locate the landing pads during future landing events. A hand-held laser range finder accurate to within meters should be adequate as long as reflectors on the remote transponders appear above the horizon to a crewmember standing at the pad.

Preparation of permanent reusable landing pads will be the first active preparation of landing pads. The primary and most obvious operation is grading of the pad surface. This allows for level and thus easier interaction with the lander to simplify the more complex activities which necessitated the permanent pad. Detailed alignment between vehicle servicing and cargo loading equipment and vehicle systems will be difficult or impractical on uneven surfaces. The freshly graded surface must be stabilized according to planned methods described under Facilities Conceptual Design. Remote navigation devices may be permanently installed by fixing them to the lunar surface if necessary. The markings of the reusable pads may be permanently fixed and may be enhanced if needed. The distances between transponders and the desired landing targets must be measured and recorded as they were for early and temporary pads. As the base develops further, permanent power, cooling, and data support connections may be installed.

### 4.2.3 Refurbish Landing Pad

Refurbishment of the landing sites is the activity necessary for readying a landing pad for reuse. Early and temporary pads will be reused only if a single stage lander/ascent vehicle is in place. Since no surface preparation was needed for these facilities originally, refurbishment should only consist of the checkout and fixing of pad markers and transponders. These devices must be checked after each landing in any case if they are to be reused, and may need replacement or refurbishment due to the effects of repeated impacts from lander blast ejecta. Cargo vehicles and two-stage piloted vehicles will leave equipment on the pad and the pad itself will not be reused.

Refurbishment of the permanent landing pads will be a significant activity. Operations will include clearing the pad of vehicles that will not be relaunched before the pad is needed for another landing. The landers will be transported to an area where they may be stored safely until needed. Pad surfaces must be inspected for degradation and, depending on the stabilization method used, may be resurfaced. Pad markings and transponders will be checked and refurbished or replaced as needed. Any other permanently installed equipment must be checked for blast damage and refurbished if necessary. These operations are involved and may be quite time consuming. This indicates that permanent pads should not be used until it is clear that reuse will be well justified.

## 4.3 CREW ACCOMMODATION

### 4.3.1 Crew Egress and Ingress

These activities cover the methods for getting the crew in and out of the landing vehicle. Early crew egress and ingress will be by Extravehicular Activity (EVA). Crewmembers will exit and enter the vehicle via an airlock. This EVA will be the only method available until systems of transporting the crew to and from the base in pressurized vehicles are in place. When these early EVA activities are necessary, careful mission planning must be executed. For example, if a mission has four crewmembers who must transfer to the base, four EVA's will be consumed on the first day of the mission and four will be needed for the last day. In order not to waste these EVA's, activities must be accomplished other than simply leaving the vehicle and going to the base and vice versa. Assuming only two crewmembers can be EVA at one time, the first and last days on the surface will be long and hectic for the crew.

Intravehicular activity (IVA) access will be used for the permanent method of ingress and egress. At this stage, mission planning for EVA will be simplified since landing and launching events and EVA operations will be uncoupled. The operation will consist of a pressurized vehicle driving up to the lander and connecting a crew transfer device, such as a tunnel, between the vehicles. The crewmembers will transfer from the lander to the surface vehicle through this device. Finally, the crew will disconnect the vehicle from the transfer device and drive to the base site. Since there are really only EVA and IVA methods, the temporary stage of these operations is not relevant. To be sure, several types of devices may be needed so that one may be considered more permanent than another, but the basic operations will be the same. At some point, a device permanently coupled to a transfer vehicle may be appropriate, but such a dedicated device will have limited other use at the base and will probably not be seen in a Phase II Lunar Base.

### 4.3.2 Crew Transport

Crew transport is simply the operations surrounding moving the crew from the landing area to the base. The first method of moving the crew from the landing area to the base will simply be walking. The early landing facility will be very close to the base and egress and ingress will be by EVA; therefore, no provisions for transfer are needed.

Lunar base operations will be enhanced by an unpressurized rover-type vehicle to transfer crew back and forth to the base. As a result the temporary stage of transfer operations which involves the use of an unpressurized rover vehicle will begin as soon as this device is available at the base. Crewmembers will leave the lander, locate the vehicle which should be close by, activate it and use it for transportation for the duration of the mission.

Permanent transport operations take place when the first pressurized personnel surface vehicle is available. When the crew enters the vehicle, they are simply transferred to the base. A connection is made to the base proper and they then enter the base. For safety reasons, it is anticipated that crewmembers will be suited during the first several attempts at this type of transfer. After sufficient reliability has been established, the operation may take place in a shirtsleeve environment.

## 4.4 CARGO ACCOMMODATION

### 4.4.1 Small Cargo Handling

This involves removing individual pieces of cargo from an unmanned or manned lander. Small cargo is defined as cargo which is attached to the unpressurized exterior of vehicles and is light enough to be handled on the surface by one or more unaided EVA crewmembers. Small cargo may include individual experiment packages and small equipment items or samples for return to Earth. Cargo small and light enough to be carried into pressurized volumes is considered trivial from operational aspects and will not be studied here.

Early unloading and loading of small cargo items from landers is accomplished by manual operations. Crewmembers performing EVA will disconnect and lower items from the landers to the surface during unloading or hoist them to the appropriate position and connect them during loading activities. This will necessitate equipment to allow the astronaut to climb aboard the vehicle and a method for lowering equipment to the surface. Temporary stages of these operations may be handled using remotely operated systems. Assuming this capability is available, and has the dexterity to disconnect small cargos from the lander, EVA may be eliminated.

Small cargo handling operations should not apply to permanent stages of cargo accommodation. As operations progress, small payloads can be loaded collectively onto pallets or into logistics modules. These payloads will be large and thus will be handled as large payloads.

### 4.4.2 Large Cargo Handling

This involves loading and removing large payloads from landers. Large cargo is defined as cargo which is attached to the unpressurized exterior of vehicles and is too heavy to be handled on the surface by EVA crewmembers without aids. Among items which are classified as large cargo are major surface equipment items such as construction equipment and rover vehicles, palletized collections of small cargos, logistics modules, base modules, and cryogenic fluid tanks. It is assumed that these large cargos will be configured with loading aids such as harnesses, rings, or trunnions, so that they can be easily connected to whatever handling device is planned. In addition, it is assumed that alignment aids will be employed to ease the mounting of payloads to vehicles during loading operations.

There are many concepts for cargo handling devices including erectable hoists, cranes, forklift devices, and off-loading ramps. While the specific operations for each of these concepts will vary widely, they all follow the same general procedures.

Early handling of large cargos takes place before the handling equipment is in place. In fact the first large cargo will probably be the handling device itself. This condition will mean that these early operations involve only unloading and will only happen once. Generally, the operation will be EVA intensive. The crew will board the landed vehicle, make whatever arrangements are needed, unload the cargo handler, disconnect the handler from the vehicle, and unload it. Since cargo handling aids will not be in place for large cargos, it is likely that the cargo handler will have to be capable of unloading itself or at least assisting in the unloading. After the handler is set up on the surface, it can be used for the temporary stage of large cargo handling.

Temporary cargo handling operations will be characterized by the use of the cargo handler with assistance from EVA astronauts. When the crew begins unloading operations, they will connect the cargo handler to the cargo. Specifically, this could include attachment of crane or hoist hooks to a cargo harness, attachment of lifting rigs to trunnion pins, or alignment and positioning of forklifts under the cargo. The crew will disconnect the cargo from the lander attachments; the cargo will be removed from the vehicle and be placed on whatever transport system will be used.

For temporary cargo loading, these operations are basically reversed. The crew connects the cargo to the handler, removes it from the transporter, and lifts it to the vehicle. The cargo is aligned with ascent vehicle attach points, placed in the attachment fittings and the crew makes all connections. Depending on the orientation of the lander and the handler configuration, alignment of cargos with ascent vehicle attach points may be difficult or not. If the vehicle is listing because of landing on an unlevel surface or the handler does not allow alignment flexibility, mounting cargo on the vehicle may be very complex, time consuming, and perhaps even dangerous. This is an indication that the most level surface possible should be provided when cargos must be loaded onto ascent vehicles. Concepts for accommodating alignment problems may be available but the use of a level surface will provide maximum latitude in cargo handler design.

Permanent stages of cargo handling may be characterized by the elimination of EVA from large cargo handling activities. Different cargo handling systems may be used but basic operations will be the same. For these operations, the crew may use remote manipulator systems to perform the attachments of handler to cargo and connections and disconnections between cargo and vehicle. Otherwise, these operations are analogous to temporary cargo handling.

### 4.4.3 Cryogenic Cargo Handling

Cryogenic cargo handling involves actually draining or filling cryogenic liquid tanks fixed to vehicles. Cryogenic cargos which are loaded into removable tank sets will be handled as large cargo items since they do not involve the actual handling of liquids at cryogenic temperatures. Cryogenic handling operations are required for special dedicated tanker vehicles used to transport cargo to and from lunar orbit, as well as for fueling ascent vehicles on the launch pad. Another activity surrounding cryogen handling is scavenging unused propellants from vehicles after a landing event.

Handling of cryogenic liquids is generally not anticipated during early and temporary base development stages. Because of this fact, the operations will only apply to one stage of landing and launch facility operations. It is anticipated that a vehicle will be used to move cryogens between the vehicles and a central storage facility.

Cryogenic cargo handling will usually require intervention by EVA crew. At the landing pad, the crew will first align the transfer vehicle with the lander and fluid interfaces will be mated. Next the lines and connections between the two systems must be chilled down to the appropriate temperatures so that flash vaporization will not occur when cryogenic fluids are introduced. Once this process is complete, the transfer of fluids may take place. Fluids may be transferred in either direction and may be pumped or transferred by differential pressures between tanks. In any of these cases the general transfer operations will be the same. Once the fluids have been transferred, the lines between will be disconnected and allowed to warm up so flexible lines will not be brittle and may be stowed. The transfer is now complete and the transfer vehicle may leave the pad. It will return to the central cryogenic storage facility to unload, depending on its mode of operation, loading fluids or unloading fluids on flight vehicles.

Since these operations involve extremely low temperatures, any heat input will affect the operation. Because of this fact, the ideal time to perform cryogenic transfers will be during the lunar night. Cargo delivery landings should take place early in the night so off-loading operations can be done throughout the dark period. Launches of refueled vehicles or export tankers should be done early in the morning or just before dawn so loading can be performed without solar heat input. Fuel remaining in the tanks of piloted landers can be scavenged for use at the base. In fact this scavenging can become a standard way to deliver small amounts of fuel to the base. The ideal time for piloted landings will be early in the lunar morning so surface features will have good definition from shadows, but the shadows will not hide important features. Fuel scavenging operations on piloted landers will have to be performed in daylight if morning landings occur.

### 4.4.4 Cargo Transport

Transportation of cargo from the landing site to the base is an uncomplicated process. Most concepts for this transport involve the use of a powered flatbed truck/trailer that is strong enough to carry the anticipated cargos. Once cargo is loaded, the vehicle simply travels to the base site.

During early versions of this activity, the path between the pad and base may not be well defined. The crew will be required to drive it by EVA.

Permanent versions of these operations will begin when permanent reusable landing pads are in place. The paths between the various base locations and landing pad will be well defined and marked roads.

## 4.5 VEHICLE ACCOMMODATION

### 4.5.1 Vehicle Survival Support

These operations cover the activities needed to allow the ascent stages and reusable vehicles to survive and maintain flight readiness while on the lunar surface. Survival support consists of providing utilities for long stay times, protection against meteoroid and lander blast impacts, and monitoring of vehicle systems.

During early operations, surface stay times will be short. It is assumed that this time will range from 8 to 10 days and the crew will live in the ascent vehicle itself. During surface stays, supplemental power and cooling may or may not be required depending on ascent vehicle design. If these supplemental systems are needed, the crew will connect them to the vehicle as part of their first EVA. The systems needed to supply these utilities will be located at the base or near the site of a previous landing so the crew will have to make some sort of traverse to get them. The monitoring of vehicle health will be handled in the normal course of activities since the crew will be living close at hand. The vehicle automated systems must have health status systems onboard to support flight activities and simple changes in software system operating modes should accommodate the landed configuration.

Temporary operations are characterized by longer stay times of 1 to 2 lunar days and by the crew living at the base. Because the stay times are as long as they are, and surface conditions will vary from hot to cold, supplemental utilities will almost surely be needed. The activity surrounding the connection of these utilities will be virtually the same as for the early operations. Since the crew moves to the base as soon as they arrive on the surface, they must provide some communication link between the vehicle and the base. It is assumed that the vehicle will perform much of its own monitoring but enunciation of fault conditions must be made at the base to allow the crew to take corrective action. If alternate ascent vehicles are left on the surface to provide complete vehicle redundancy, they will require monitoring from Earth while the base is unoccupied. This monitoring can be done by a "bent pipe" communications link so no additional reorientation of vehicle antennas is needed.

Permanent survival support operations will be needed when vehicle stay times reach 6 lunar days or 170 to 180 Earth days. All the basic operations will be the same as for the temporary stage except that some sort of protection from meteoroids and thermal loads must be provided. Operations needed to provide this protection will depend very heavily on the type of protection needed. For example, if a blanket style bumper and reflective thermal blanket is used, the crew will first lay the blanket out around the base of the vehicle. Next, using a crane or hoist, they will raise the blanket to the top of the vehicle. Finally, the protection is completed by pulling the blanket down.

Throughout these activities the crew must be careful to avoid damaging protruding equipment such as radar and communications antennas. If the blanket is not transparent to the base-to-vehicle radio signal, some other accommodation may be needed. As the landing facilities are developed, hard line data connections may be feasible. This will provide cleaner data connections and will reduce radio noise in the vicinity of the base.

### 4.5.2 Vehicle Servicing

These are the operations needed to ready a vehicle for reuse. At this time, the extent of surface-based servicing operations is undefined. To a certain extent, the method of accomplishing expected operations may be described, but specific examples will be difficult to analyze.

During temporarily-occupied operations of the Phase II lunar base, exterior vehicle servicing will be minor and will be handled EVA efforts. Line replaceable units (LRU's) will be removed and replaced. Efforts should be made to make as many LRU's as possible accessible in a pressurized environment. When vehicle fueling and propellant scavenging begins, operations will be the same as for cryogenic cargo handling.

As the base develops and vehicle servicing increases, certain exterior tasks can be done by shirtsleeve crewmembers in a pressurizable facility attached to the vehicle. In these cases, the facility will be connected to a corresponding interface on the exterior of the vehicle and will be pressurized. The crew can then work in the shirtsleeve environment. Engine changeout on a reusable lander is a prime candidate for this kind of activity. Significant servicing on the surface will require a large infrastructure and parts supply unlikely to be available until permanent habitation has been going on for some time.

## 5.0 FACILITIES CONCEPTUAL DESIGN

The following sections are intended to describe the various elements that comprise the lunar base landing facilities. In some cases, the facilities will not be unique to landing and launching activities. The landing facility will often use equipment and capabilities that are already present on the lunar surface. When this is the case, the equipment will be described and the requirements placed on it by landing operations will be discussed.

Like surface operations, landing site facilities can be broken into site, crew, cargo, and vehicle facilities. Primary emphasis is on site related facilities. In general, facilities associated with surface transportation of crew, cargo, or vehicles will be treated on a concept and requirements basis only. Surface transportation issues will be covered in other portions of the Lunar Base Surface Systems study.

### 5.1 SITE FACILITIES

Site facilities are those associated with the actual treatment of the lunar surfaces. This includes landing pads, surface stabilization methods, marking devices, roads and servicing areas, and others. Site facilities lend themselves to the highest levels of definition in this particular study since they are the only facilities truly unique to the landing and launching activities.

#### 5.1.1 Landing Pad

The most obvious and indeed most important of the site facilities is the landing pad itself. Two basic types of pads must be designed: permanent reusable pads for later base development stages and non-reusable unprepared pads for early use. Figures 5.1-1 and 5.1-2 show the conceptual designs of these two types of pads respectively.

A reusable pad will have a flat, leveled and stabilized surface inside a 50-meter radius. Surface stabilization techniques will be described later in this report. The pad will be marked by three markers on the 50-meter circle. The slopes within this area should be as close to 0 degrees as is practical and certainly not over 1 degree. These slopes will allow easy alignment between surface and flight vehicle systems so complex surface support activities can take place. An area 100 meters in radius should have slopes not greater than 4 degrees so that small dispersions can be accommodated with little off-nominal surface support efforts. Usable items should be outside a 250-meter radius to prevent damage from stray ejecta that may break away from the pad. The pad should be located 3 kilometers from the base to accommodate $3\sigma$ landing dispersions determined for gross navigation update failures, for crew safety during permanently-occupied operations, and to minimize blast effects on the base.

An unprepared pad will be of the same dimensions and markings as the reusable pad. Slopes of 6 degrees over 20-meter distances, and 1-meter humps and depressions are acceptable. Boulders over about 0.5 meters should be eliminated or avoided to provide footpad stability and clearance for descent engines. The 100-meter area should have no slopes over 12 degrees and no humps or depressions over 2 meters in relief. Slope restrictions are based primarily on landing stability limits in this case instead of surface support interface requirements. Pads may be located as close as 250 to 400 meters from the base and each other as long as the lander is used for surface dwelling. However, at these distances, precautions must be taken to protect reflective and optical surfaces on base equipment.

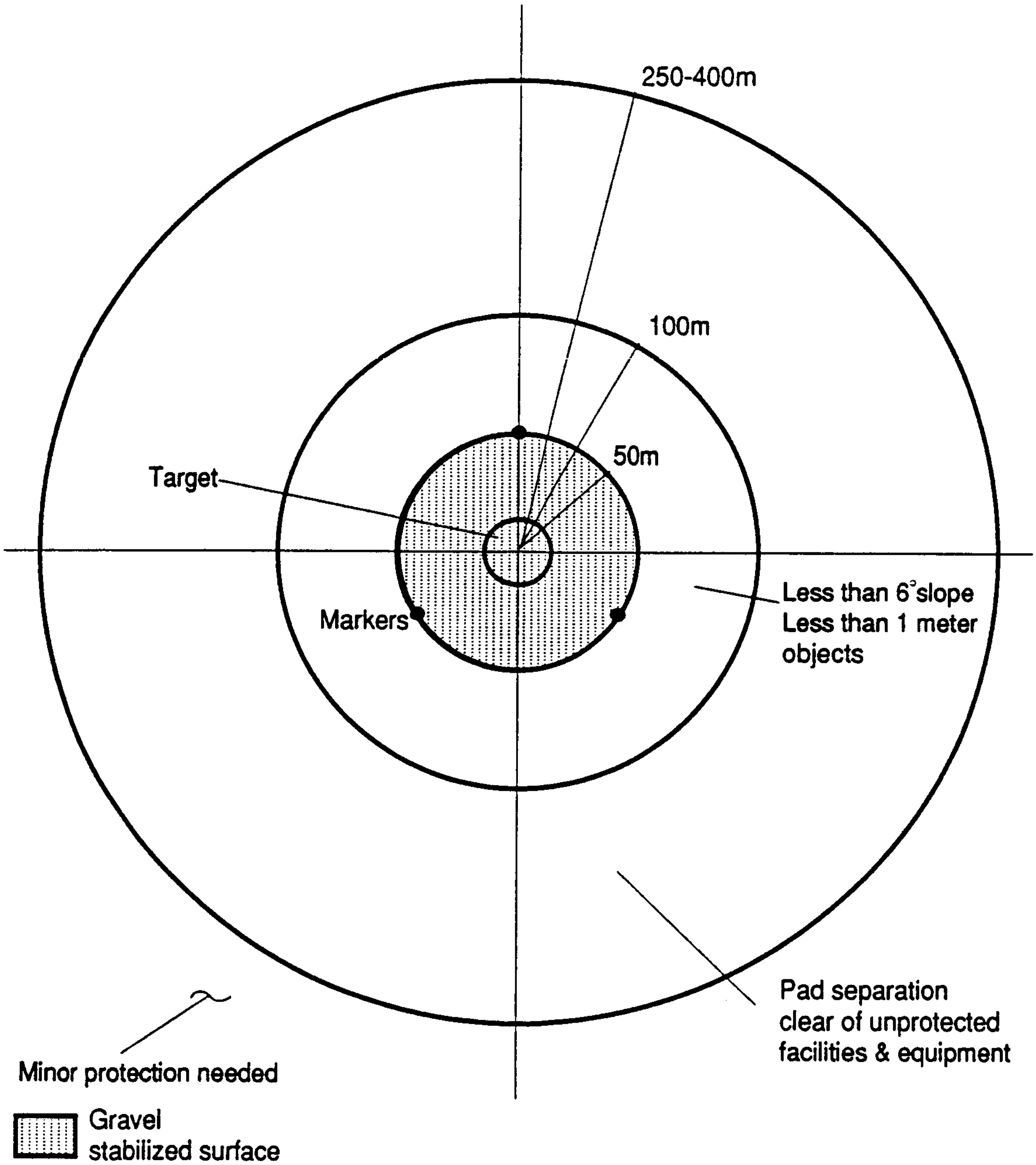


Figure 5.1-1, Permanent Landing Pad

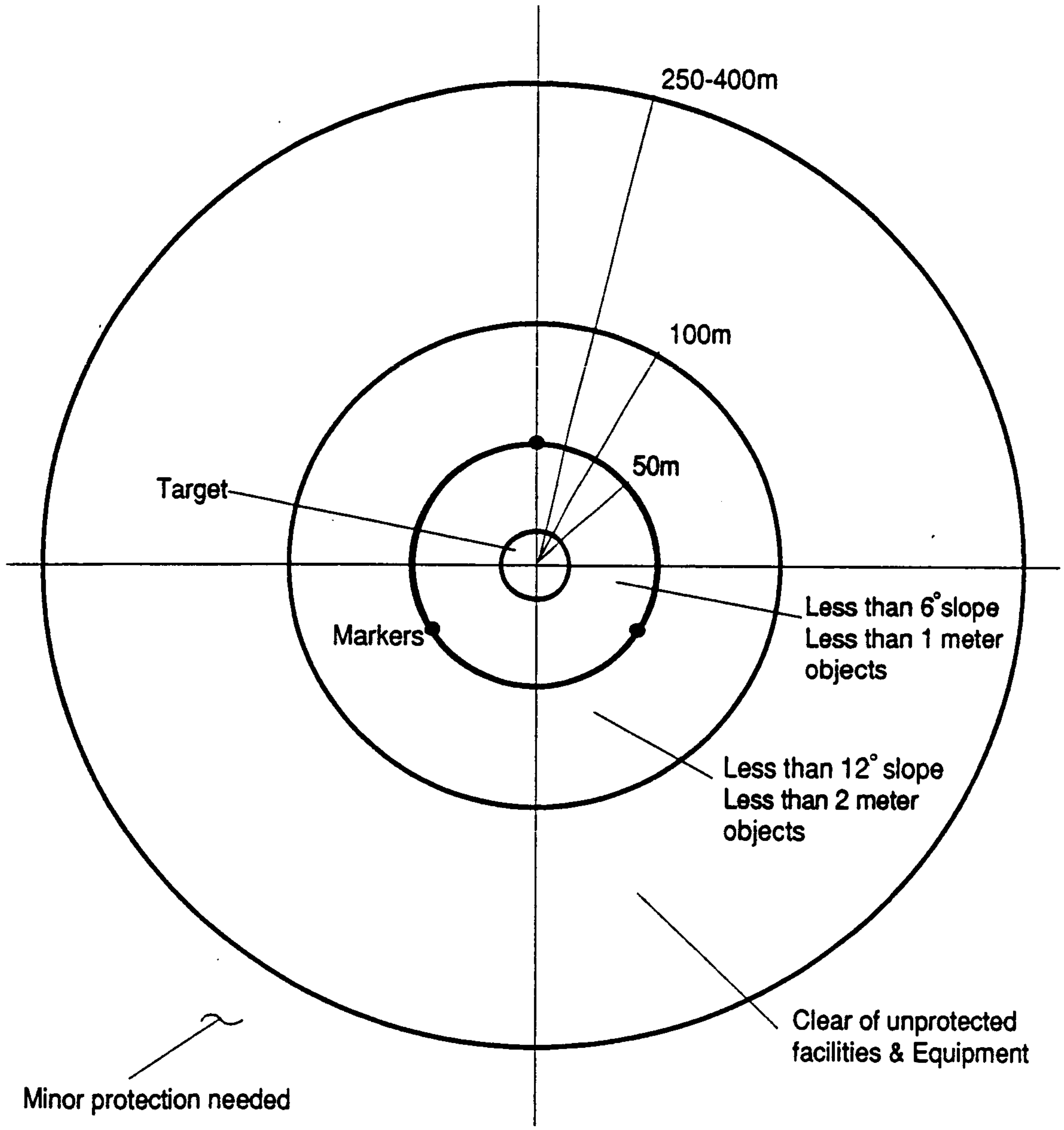


**Figure 5.1-2, Unprepared Landing Pad**

Once dwelling is established at the base, the pads should be 3 kilometers from the base. In addition to accommodating safety and navigation errors, this distance relieves some of the facility and equipment surface protection precautions. Consecutive landings should be on pads no closer than 250 meters. Reflective and optical surfaces on cargo landings and emergency ascent vehicles must be protected from subsequent landings.

The following issues combine to define the degree of surface preparation and refurbishment needed, the size and configuration of the landing pad, and the distances at which other base elements must be kept.

- Stage of lunar base development
- Surface slope and obstacle characteristics
- Landing error effects
- Lander and pilot visual and radar resolution
- Blast effects

Each issue will be discussed in regards to how it affects the pad designs.

Lunar Base Development Stage- The stage of lunar base development affects two aspects of landing pad design -- pad preparation and pad location. The effects can be summarized as follows:

- Unprepared nonreusable pads are appropriate during early stages of base development when surface crew time is at a premium.

- Prepared reusable pads are not desirable until vehicle servicing and cargo loading are needed.

- 250 to 400 meters is the maximum distance between the base and landing pad before base habitation is possible. Crews must be able to walk between the vehicle and base site.

- 3 to 5 kilometers is the maximum distance between base and landing pads until highly reliable surface transportation is available.

During early stages, depending on the major emphasis of the base, surface stay times will be short and primary crew duties will be completing science, astronomy, technology development and base construction objectives. Non-reusable pads with unprepared surfaces require only simple operations. Pad preparation may include selection and marking and some removal or destruction of larger obstacles. Unprepared pads are advantageous operationally during early stages because they affect mission planning less than reusable pads.

Once the base has become well established, crew time required for pad preparation will represent lower percentages of overall time available. However, recurring operations in support of clearing and refurbishing the pads will be extensive as described previously. This increased pad-associated activity must be justified by the need for more complex on-pad activities. Complex on-pad activities will be associated with putting things onto or into the vehicle instead of taking things off. Cargo unloading will already be an established activity. Permanent reusable pads will be necessary when the landers become reusable and require servicing or when cargo is taken away from the base on the ascent vehicles. This is an important point in the formulation of landing site development plans. Permanent reusable landing pads require considerable recurring activity in addition to the high initial setup operations. Because of this fact they are not desirable until launch and landing vehicles require loading and servicing on the lunar surface.

In examining the effects of base development stage on the distances between the base and pad, the location of work areas and living areas and the desired travel times must be considered. Before the base itself is capable of supporting habitation activity, the crew must live in the lander/ascent vehicle. Since the lander will be the hub of all surface activities, especially those relating to base construction, the landing pad must be relatively close to the base. The minimum allowable distance between the pad and the base will be dictated by the resolution of other issues such as landing errors and accuracies and blast effects. The maximum acceptable distances can be established by examination of base to vehicle operational limitations. It is assumed that an unpressurized surface vehicle similar to the Lunar Rover Vehicle will be available. The trip between base and vehicle should take about a minute. This will allow for relatively easy, although infrequent, traverses. At a speed of approximately 10 to 15 kilometers per hour, this is 200 to 500 meters. In addition, a walking trip should not take more than a few minutes. Surface activity would not be crippled in the event of vehicle failure although it would be slowed considerably. At typical walking speeds of 3 to 5 kilometers per hour, the distances are 250 to 400 meters. As a result, during early lunar base development, the desired distance is under 250 meters and the maximum distance should not be farther than 400 meters.

Once the base can support habitation, the lander/ascent vehicles will no longer be the hub of surface activity. The crew will move into the base immediately upon arrival and will live there until the surface stay is over. The landing pad can therefore be farther away from the base if other issues indicate the need. To be sure, some activity at the lander/ascent vehicle will be required and trips back and forth should not last too long. In addition, the possibility of vehicle failure will require the capability to walk to the landing areas until sufficient reliability can be established. A walking trip between lander/ascent vehicle and base should not last more than one hour. At the 3 to 5 kilometer per hour rate the distances are 3 to 5 kilometers. This is within the 10 kilometers considered to be the maximum distance an EVA crewmember could walk during the Apollo missions. Of course the limit decreased as the EVA progressed since less time was available for the walk back to the lander. The 3 to 5 kilometer distance can be traversed by the surface vehicle in 15 to 30 minutes depending on the speed. In summary, if other issues indicate, the landing area can be located 3 to 5 kilometers away from the base once the base can support habitation.

<u>Surface Slope and Obstacle Characteristics</u>- The expected surface characteristics affect the degree of landing pad preparation required. Landing area selection efforts, the degree of pad preparation, and lander capabilities can all be traded against each other. As a first order discussion of these trades, the nominal lander capabilities discussed previously in this report will be assumed. The effects can be summarized as follows:

- Lunar base site selection must be done for an area at least large enough to handle all planned landing and gross navigation errors. This area may be as large as an ellipse 13 by 6 kilometers or greater.

- Unprepared landing pads can be located with only modest amounts of insitu inspection by crewmembers.

- Prepared, level landing pads are indicated when precise alignment of surface systems with vehicle systems is required.

The landers in general must be capable of landing on a 12-degree slope, or on humps or slope breaks of 2.5 to 3.5 meters without degradation of system activity. Nominal operation should be expected with average vehicle slopes of 6 degrees or 1 meter protuberances. The requirement for these capabilities has been presented previously in this report.

The ease of finding multiple areas meeting slope and protuberance requirements must be reviewed. Since the average slopes of lunar surfaces over 25-meter distances are in the neighborhood of 4 to 6 degrees, location of adequate landing surfaces by surface-based crewmembers should be relatively simple.

The area meeting the 12-degree slope restriction should cover all expected landings and cover navigation errors. For Apollo, this area varied depending on the landing site due to the expected trajectories. At the Apollo 17 site, the effects of failures of navigation update systems resulted in landing ellipses with maximums of 13 kilometers along the flight path and 6 kilometers crossrange. This a large area. The probability of encountering high local slopes such as the 20 to 30 degrees on the North and South Massifs, and the 14 degree Lee-Lincoln Scarp at Taurus-Littrow will be large. Careful selection of a lunar base site will be required to ensure that no slope criteria are exceeded over the whole area. This was done during Apollo site selection so lunar base site selection teams should be able to find appropriate base sites if good photographic and mapping data are available.

The Apollo missions, with the exception of Apollo 15, were able to land well within the 6-degree nominal constraints and did not have the advantage of any prior local site inspection. Surface based crewmembers should have little difficulty locating areas in the neighborhood of 100 meters across with slopes not exceeding 6 degrees. The 100-meter area represents about 5 lander diameters and should allow for minor landing inaccuracies and some further growth in lander diameter. The panoramic view of the Apollo 17 site shows large low slope areas clear of boulders. The Apollo 17 pilot's report (reference 10) indicates that the crew was able to find good landing area clear of boulders and with appropriate slopes within several minutes of the landing and from a distance of some 10 kilometers. With only a modest amount of insitu inspection, unprepared landing pads should be easy to find.

Operations surrounding landed vehicles with 6 to 12 degree off-horizontal lists should not be extraordinarily difficult as long as no alignment of cargo with lander features will be required. However, servicing and cargo loading will require alignment of surface systems and cargos with lander attachment systems. For example, placing a large cargo in a set of trunnion attachments will require significant alignments. If the series of fittings is not near horizontal, proper attachments to all fittings at one time will be difficult, time consuming and dangerous due to cargos coming loose. Significantly off-horizontal landing configurations may present unacceptable requirements for cargo loading and vehicle servicing equipment. Consequently, for landing pads at which vehicle servicing and loading will occur, level surfaces are indicated and prepared landing pads are desired.

Landing Errors- Landing errors affect the size of the landing pad and the distance between the pads and base. These effects are summarized as follows:

- Landing pad size should be about 100 meters across.

- The landing pads may be within 200 to 250 meters of the base during early base construction.

- The landing pads should be at least 3 kilometers away from the base during later stages.

The effects of errors on the selected landing pad size will be those of the minor inaccuracies only. Considering the state-of-the-art guidance system during Apollo and current state-of-the-art coupled with expected navigational aids, a nominal size of 5 lander diameters will be adequate for near nominal operations.

The Apollo nominal $3\sigma$ landing areas were about 2,000 meters across assuming good navigation system updates from landmark recognition and Earth-based tracking. The crew reported that they were able to redesignate the landing site by several hundred meters within this area while at only 8 to 10 kilometers from the site (reference 10). The additional aid of site-originated, precise, and continuous navigation system updates will be available for lunar base landings. This precise position data coupled with the maneuvering capability experienced in Apollo 17 should easily allow the $3\sigma$ landing area to be reduced by an order of magnitude to 100 meters.

Using this criteria, there is a risk of the vehicle landing in an area 100 meters from the target landing spot. Consequently, equipment and facilities located within 150 to 200 meters of the target are at risk of the same damage they would experience if they were located on the pad itself. The risk to equipment located just outside this area, while existent, may be acceptable depending on the sensitivity of the equipment to lander blast.

The risk to permanent inhabitants of any facilities will most likely be unacceptable in the 200-meter range due to possible failures of navigation systems. Consequently a permanently occupied lunar base will be considerably further away. The landing ellipses should cover the maximum credible failures of navigation systems. The maximum credible failure during the Apollo missions was considered to be failure of either the Landmark system or failure of the N69 Earth tracking system. The resulting landing ellipses for Apollo 17 were 6 kilometers crossrange by 3 kilometers on the flightpath, and 3 by 13 kilometers respectively for these failures. These two types of systems should be available along with the additional transponder aids at the base. The use of the same ellipses as for Apollo 17 should be conservative since two systems would have to fail. The minimum distance from the target landing site to the edge of a landing ellipse is about 3 kilometers crossrange. To handle navigation update failures, permanently occupied bases and sensitive surface facilities should be about 3 kilometers crossrange from the base.

Visual and Radar Resolution- Resolution will mainly affect the distribution of pad markings. Resolution will also affect the placement and sizes of other navigation aids which have been previously discussed and are part of the design of the landing pad itself.

- Markings may be placed at the apexes of a triangle inscribed within a 100 meter diameter circle.

Placement of three pad markings at a 50-meter radius from the target in a triangular pattern will result in about 90-meter separations. This presents a 1-degree separation at 5 kilometers. This should provide adequate resolution for final approach and landing sequences. Apollo landing operations only allowed direct line-of-site viewing at 8 kilometers. This should be sufficient for piloted landings and present little or no problems for radar guidance assuming transponders are provided.

Blast Effects- Blast from the lander rocket engine will affect the distance between the landing pads and surface facilities and equipment, especially the base. The interaction of the blast with the lunar soil was described under the Flight Vehicle Interaction section above. The effects are summarized again here for the sake completeness.

From 0 to 50 meters:

> Metal objects will experience significant surface damage after only one landing and glass surfaces will experience severe damage after one landing. Vision glass will be virtually unusable after one landing.

From 50 through 200 to 400 meters:

> Metal objects will experience significant pitting damage after several landings but only minor pitting after one landing. Glass surfaces on the other hand will experience significant damage after one landing and be unusable after several landings.

From 400 meters past 2 kilometers:

> Metal objects will sustain only very minor and probably unnoticeable pitting damage after numerous landings. Reflective surfaces should be protected. Glass objects will sustain minor damage after numerous landings. The damage will eventually be unacceptable for optical quality glasses. Optical instruments should face away from landings.

### 5.1.2 Surface Stabilization

Surface stabilization will be required once the conditions for the establishment of reusable landing pads occur and area grading has been accomplished. This stabilization reduces the amount of pad refurbishment required between landings, reduces or eliminates ejecta, and provides for easier surface transportation and more consistent roadway surfaces. In addition, dust that would be kicked up during surface traverses and other EVA operations is eliminated.

There are several methods for stabilizing the lunar surface. Paving tiles, depositing gravel, and simple compaction represent three methods of various degrees of complexity. The trade-offs between these three involve the quality of the surface finish, the complexity of the setup equipment and operations, and the extent of maintenance operations. The results of these trade-offs indicate that deposition of either natural gravel or man-made gravel is the best surface stabilization method. Figure 5.1-3 shows the three types of stabilization.

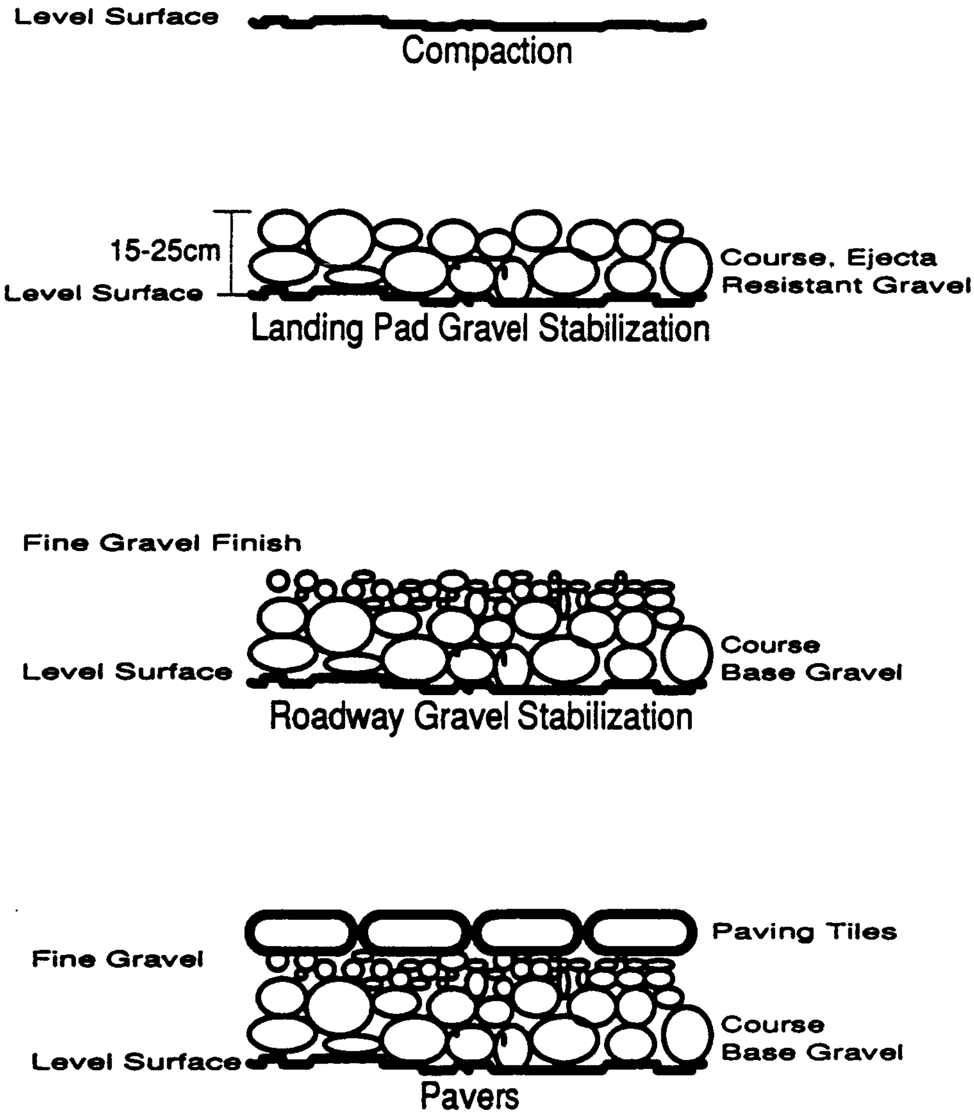


Figure 5.1-3, Surface Stabilization

Paving tiles, depending on the tile design, offer the best overall surface. In addition, maintenance of the surface is virtually not required. As a terrestrial analogy, cobblestone streets have been used successfully for many years. However, paving tiles are very difficult to set up. Significant installation and tile fabrication equipment will be required which are unique to paving operations. In addition, even automated tile layers will consume a large amount of crew time for monitoring and maintenance. Without examining the concept in detail, it is plain that major paving efforts or fairly flexible insitu resource based construction and fabrication activities are needed to justify paving-tile surface stabilization. The surface characteristics of paving tiles may well be required and justified when extensive cargo and servicing traffic is present. This traffic, however, is generally not considered part of any Phase II lunar base scenario. For the purpose of this study, further investigation of paving tile surface stabilization is considered out of scope.

Simple compaction, at the other end of the spectrum, offers the lowest quality surface. Even though soil cohesion is high, fine particles are still exposed to lander blast and to wheeled and foot traffic. This will eventually result in blast ejecta and dust problems. In addition, maintenance of surfaces will be the same as initial setup operations since the surface will require releveling and recompaction after exposure to traffic. Setup operations in addition to leveling will involve compression by some sort of heavy roller device. This type of device could easily be an attachment to an existing surface vehicle and have most of its weight provided by insitu resources such as lunar soil. The roller would not necessarily be a major cargo item. Operation of this device will be fairly intensive, time consuming, and tedious since the roller would require repeated passes over the surface to be compressed. The setup process is not considered restrictive, though, because it should lend itself to automation fairly well. Because of the inferior characteristics of a compacted surface in relation to time required for setup, compaction surface stabilization is not considered desirable.

Finally, gravel provides a good, although not superior, surface. The surface is not as stable or easy to travel on as paving tiles, but fine soil particles are not exposed to lander blast or surface traffic. Proper selection of gravel sizes should provide for roads and pads that are well within acceptable specifications. As will be discussed below, gravel is readily available from natural screening or as a by-product of the resource utilization processes which will just precede the need for stabilized surfaces. Equipment for screening or breaking and for transporting gravel will already be present even for modest resource utilization schemes. Leveling and spreading of gravel surfaces can be accomplished easily by the same operations used for leveling the surfaces below them. Maintenance may involve periodic leveling of gravel surfaces, but these operations should be minimal if gravel sizes are selected appropriately. In short, gravel deposition surface stabilization was selected because it provides adequate surface characteristics without the need of any significant unique equipment and without the need for exotic operational activity.

One final advantage of gravel surfaces is that they provide a first step for future installation of paved surfaces. Gravel surface will probably be needed as a base for paving tiles. Thus, when the paving tiles become justified, the subsurface needed will already be present. Thus roadwork can be done easily and incrementally as needed without removal of old roads and without extensive surface preparation.

The size gravel needed for surfaces is subject to several considerations. These considerations include maximum particle sizes ejected by lander blast, ease of travel, and availability of various sizes of gravel.

For landing pads, the blast calculations described above indicate that particles as large as 5 millimeters may be lofted by an Apollo LM engine. A fivefold increase in thrust level will result in 25 millimeter rocks being ejected even if for only very short distances. Because of this, gravel size will depend on the expected thrust levels of lunar landing vehicles. The minimum size for a 50,000 newton LM sized engine should be 5 millimeters. A 250,000 newton engine, consistent with a 100 metric ton lander, will indicate 25 millimeter minimum size. Gravel size will vary linearly with thrust. For the purpose of this study, the natural availability of 5 millimeter sizes will be considered. The need to accommodate landers as large as 100 metric tons will probably be accompanied by the additional need for paved surfaces. The need for 25-millimeter gravel will probably not arise when this is taken into consideration.

Ease of travel will indicate the need for a base of large gravel with smaller gravel on the surface. The larger gravel will provide a stable base for the finer gravel so wheeled vehicles do not sink too deep and consume energy in spreading and bulldozing gravel. The finer gravel will in turn provide a smoother surface for the vehicle so that energy is not consumed in the compression of vehicle suspension systems and vehicle occupants do not experience discomfort. Since vehicle energy usage and passenger comfort on the landing pad is not a consideration, the gravel configuration described above is considered only for roadways. Quantification of gravel sizes for roads has been the subject of considerable attention by civil engineers over the years. Sizes depend heavily on vehicle sizes and weights. Since the primary purpose of this study is landing facility design and not roadway design, roadway gravel sizes are not investigated here.

Two general approaches are possible for the acquisition of gravel. The first is to sieve large amounts of lunar soil and thereby extract the 1-2% of mature soils and up to 5% of immature soils which is coarser than 4 millimeters. The second possibility is the use of the sintered clinker. Clinker is produced by heating lunar soil as a part of processes to utilize insitu resources such as the extraction of hydrogen or oxygen. Either method provides large amounts of gravel although the man-made product comes in more tailored sizes and in much greater quantities.

Any attempt to extract volatiles from the lunar soil will require sieving large amounts of soil in the first place. For example, a pilot plant to produce 2 metric tons of oxygen a month will process about 12 tons of soil an hour for 13 days each month. Part of that processing involves sieving to a size of 80 microns. If gravel is desired, a second sieve which removes coarser material could be attached for a few hundred pounds including material handling equipment. Such a unit could provide from 40 up to 200 tons of natural gravel per month. At about 2 tons per cubic meter and coverage of 0.25 meters, this rate could allow coverage of up to 400 square meters per month. The gravel necessary to cover one landing pad could be produced by such an operation in less than a year.

Most of the processes which heat lunar soil will produce a sintered clinker. The sintered material can be broken up to yield the necessary gravel. The equipment to break up the clinker will be a standard part of the process equipment and designing it to provide the appropriate gravel sizes should be simple. As an example, the 2 metric ton oxygen extraction equipment cited above can produce about 6 tons of sintered material an hour while operating, amounting to about 2,000 tons of gravel per month. This rate would cover up to 4,000 square meters per month, enough to finish an 8,000 square meter pad or 1 kilometer of an 8 meter wide road in two months.

The structural properties of clinker gravel will need further study to verify that it meets design requirements. These requirements will vary depending upon the intended use of the surface. They will be related to the size of the gravel and the expected pressures on the surface.

### 5.1.3 Blast Barriers

Blast barriers are used to protect equipment from the effects of the ejecta from the landing events. There are two primary philosophies for the design of these barriers. First, blast barriers can be erected as permanent structures close to the landing pads. Second, smaller, temporary, or permanent structures can be erected at individual equipment locations to shield small areas from the effects of the ejecta. Examination of the nature of the blast and the effects of small off-nominal landing conditions indicate that the second philosophy of protecting equipment and facilities is the most desirable.

Close barriers must be tall enough to block the bulk of the particles and yet must be far enough away so as not to present hazards for off-nominal landings. Blast calculations above indicate that at 50 meters maximum particle altitude is 7 meters and at 100 meters particle altitude is 12 meters. Barriers 7 to 12 meters high are major items. With these heights, it is safe to assume that the barriers must be made from local resources such as piles of soil or gravel. A soil barrier 12 meters high beginning at 50 meters and peaking at 100 meters will have a slope of 13 degrees, only marginally acceptable, and will be a considerable construction project. Natural surface features such as craters may be available for use as landing pads. A crater larger than about 150 meters should suffice for a single pad with some preparation of the rim. The distribution of these craters should be in the neighborhood of 3 to 10 per square kilometer. However, the suitability of craters cannot be verified without inspection. For the purposes of this study, close barriers are considered inadequate.

Local equipment and facility barriers appear to provide easy forms of surface protection for modest efforts and minimal weight penalties. Several methods are available depending on the particular application. First and most simple is careful orientation of equipment so that sensitive surfaces face away from the landing. If this proves unfeasible because equipment cannot be moved, installation of a barrier will be needed. Figure 5.1-4 shows some of the methods of local blast protection.

For glass surfaces two methods may be considered. If the surface must be used to view the landing event, double glazing should be used such that the outer layer is easily replaced once surface erosion has progressed too much. If the viewing is not needed during the event, a movable opaque shield can be installed. This could consist of thin plastic or aluminum sheets.

For equipment with complicated geometries and extensive sensitive surfaces, covering by a blanket or erection of a vertical barrier may be used. Blankets of mylar or lightweight fabrics provide the simplest method of protecting sensitive equipment that is not used without crewmembers. A shield such as metal plate or fabric stretched on a frame of suitable size can be easily leaned against or propped next to equipment that must remain active during the absence of crew.

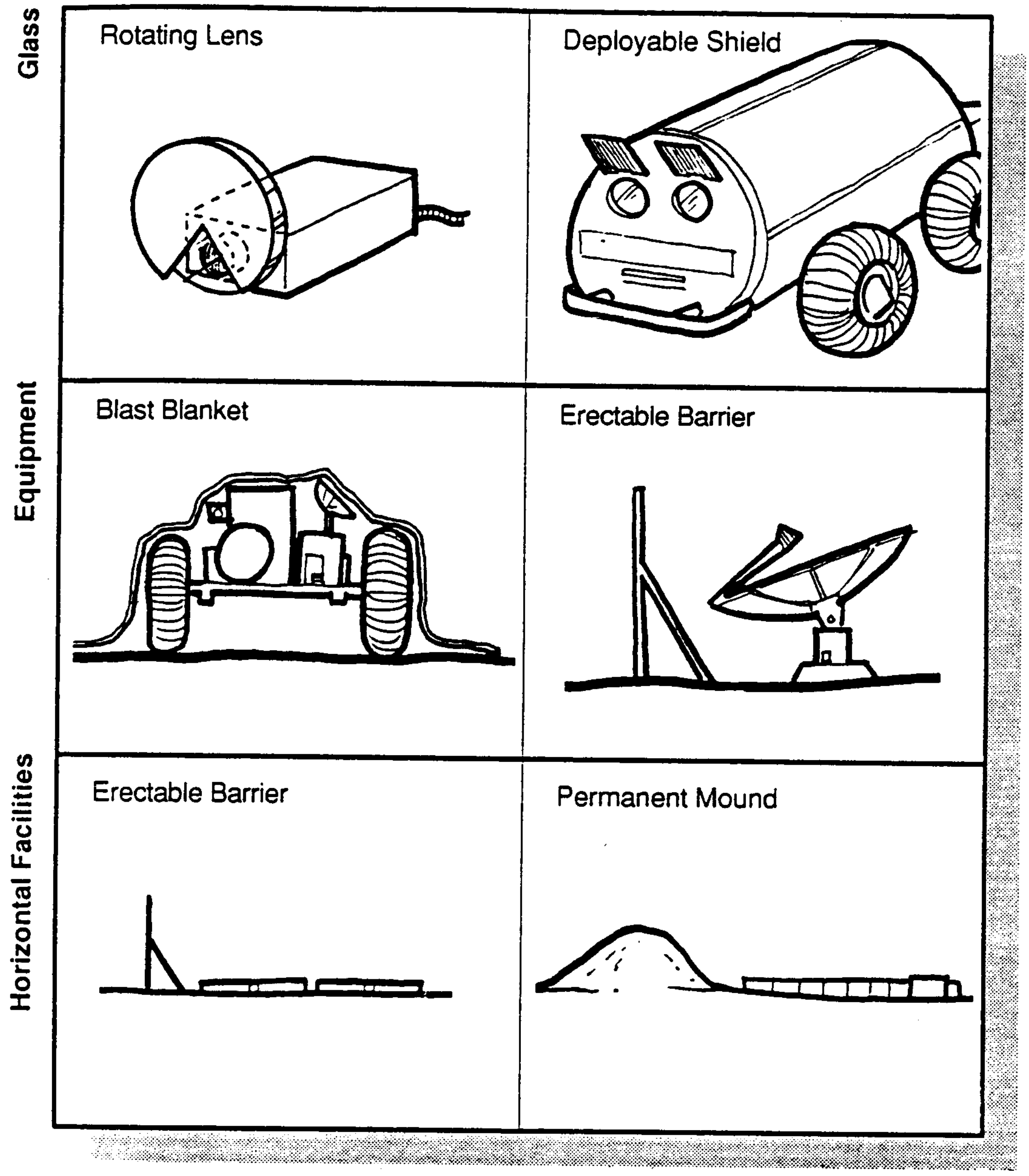


Figure 5.1-4, Blast Barriers

Equipment mounted horizontally such as solar panels will require protection from the glancing blows of ejecta. The maximum anticipated angle of descent of ejecta is less than 5 degrees. Each meter of barrier height should protect 10 meters of sensitive surface behind. This is easily accomplished with mounds of soil or the vertical barriers discussed above for sensitive equipment.

Design criteria for blast barriers in general are not stringent. The primary effect of blast, as noted above, is erosion of surfaces. The dynamic pressure of the blast drops off very quickly with the distance from the lander. This means that structural design requirements of a blast barrier are primarily for support of the intrinsic weight of the barrier itself. Surface properties are not important since the barrier is intended to be inert and an eroded surface is inconsequential. Thickness is important only for thin sheets such as mylar barriers. The effects of blast on mylar were not investigated directly but can be extrapolated from the data available. The maximum depth of penetration in glass was about 0.1 millimeter for large particles close to the pad. At greater distances only smaller particles are found and penetration depth drops off. Extrapolating these effects to softer mylar surfaces, it is feasible that thin mylar barriers on the order of 0.01 millimeters could be penetrated even at distances of 200 to 2,000 meters. Fabrics such as woven nylon or kevlar may prove to be the best for application as blast blankets.

### 5.1.4 Pad Markers and Navigation Aids

Pad markings and navigation aids are present to assist flight crews and automated landers in locating the landing pads and in adjustment of trajectories to insure precision landings. Pad marking is intended to provide visual identification of the pad to the crew for piloted missions. Navigation aids are intended to provide visibility to automated guidance systems.

Figure 5.1-5 shows one possible device to serve as a pad marker with a transponder. The marker should have stowed dimensions of 50 cm x 50 cm x 10 cm and a mass no greater than 10 kilograms. These markers are placed at three positions on the 100 meter diameter of the landing pad as discussed for the landing pad design. In addition, two of these markers are placed at about 1.5 kilometers downrange and 1.5 kilometers cross-range from the landing site. The two will be visible above the horizon both from each other and from the landing pad. These long-range transponders provide detailed navigation data to the lander guidance system. They will show 1 degree separation at 90 kilometers at which point the base will just be over the lunar horizon assuming no obstacles exist such as mountains. Three markers are needed for each pad along with two downrange and crossrange. Each crew will generally set at least two pads for a subsequent cargo and piloted landing. As a result, the first crew will need eight markers. The two long-range transponders will be set once and left in place. The three pad markers will be set each time a pad is selected whether for unprepared pads or reusable pads.

The device contains a transponder, a visual marker, and a light. In addition, the top of the marker has a retroreflector to allow ranging by a laser range finder. Since transponders are relatively small in terrestrial applications, and little or no noise can be expected, the ones baselined for this study are small. The size chosen is about the same as a hand-held radio. Power requirements should be minimal even when the transponders are broadcasting. The transponder will only have to broadcast for 5 to 10 minutes during landings not likely to occur more often than monthly.

Visual marking can be done by use of large disks mounted on a tripod on the marker itself or by stretching some sort of ribbon between the markers. Since the ribbon will have to be nearly 300 meters long and probably at least 0.5 meters wide to be of use, it can be expected to be heavy and difficult to deploy, stow, and redeploy. For this reason, the tripod mounted disks have been chosen for use on the marker.

The visibility of the marker depends on four factors: size, luminance, contrast with the background, and time. Luminance and contrast with the background are easily maximized by a high-reflectance surface that is also highly chromatic. Yellow-green or bright orange will probably be adequate. The yellow-green provides the most efficient response by the human eye while the orange probably will provide the best contrast with the lunar background. Durable, high-reflectance surfaces are currently provided regularly for road signs and thus should be fairly easy to duplicate for lunar application. A reflectance of 75 percent which is about the same as white paint should be sufficient against the lunar background which has an albedo of around 11 percent. Time in view will be maximized since the crew will have general knowledge of pad location from sightings of known local lunar features. Size will be difficult to maximize. A disk in the neighborhood of 2 meters in diameter should be about the limit for easy handling by crewmembers in EVA.

Lights are of questionable importance for daytime landings. Night landings are not likely during Phase II, but the lighting fixture has been added for completeness since they will be needed late in the lunar day when the sunlight does not reflect on the passive marker. The fixture is assumed to be 15 centimeters in diameter. The lunar surface can provide about 150 watts per square meter at 11 percent albedo and 1,350 watts per square meter solar flux. The light should provide about five times this amount to provide adequate contrast against the background for dusk landings. This is 750 watts per square meter or a total of 15 watts of visible light for the 15 centimeter fixture. At an efficiency of 10 percent, a 150 watt lamp will be needed.

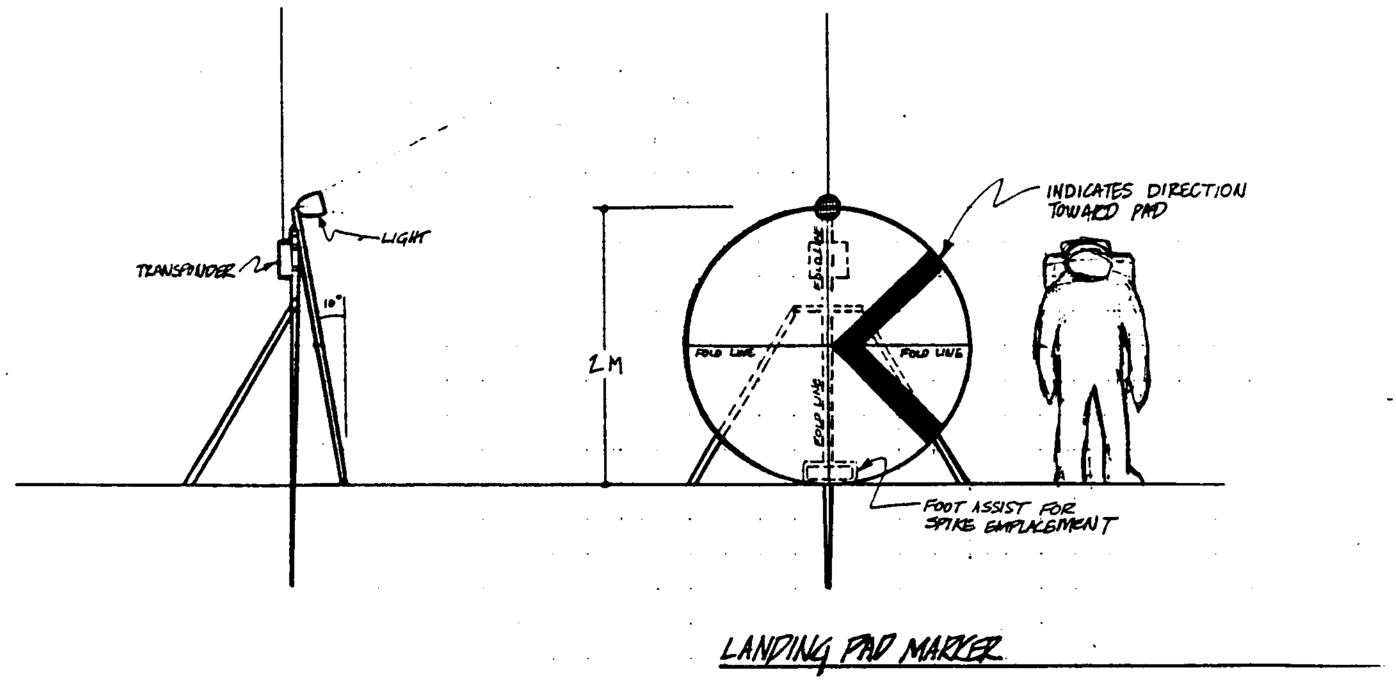


Figure 5.1-5, Landing Pad Marker

Finally, the power supply for the marker must be sized. Since we have added lighting for night landings, the system will consist of a battery with a solar cell for recharge. The requirement for the lighting fixture will be 150 watts. While the power for the transponder should be minimal, 50 watts will be allotted. This is a total of 200 watts. At standard spacecraft voltages of 28 volts DC, 7 amperes are needed. Assuming the system is activated for about 10 minutes for each landing event, a battery capacity of 1 to 2 amp-hours is needed. Current nickel-cadmium batteries of this capacity are about 20 cm x 20 cm x 10 cm and have masses in the neighborhood of around 5 kilograms. A solar cell on the top of this system should be able to charge it over a long period.

### 5.1.5 Roadways and Service Surfaces

Roads and service areas are included here because as the landing facilities evolve transportation and staging surfaces will be necessary to landing facility operations. The actual construction of these facilities has been discussed briefly under the Surface Stabilization section above. The primary design criteria will be ease of travel and structural strength. The actual landing events will not affect the surfaces so blast criteria can be ignored.

### 5.1.6 Grading Device

A grading device is required when reusable pads become necessary. This device may be attached to a multipurpose surface vehicle or be a dedicated construction device. Since the development of the base itself will almost certainly need a grading device, this equipment should already be available. Other reports in the Lunar Base Systems Study will consider the grader.

## 5.2 CREW FACILITIES

### 5.2.1 Vehicle Egress and Ingress

Methods for transferring crewmembers to and from vehicles can be extremely simple. The initial method will be via Extravehicular Mobility Units (EMU's) already carried by crews for other purposes. This method will be considered the trivial case since only a ladder on the lander leg will be needed. Of primary interest is transfer between two pressurized spaces. As discussed previously, the employment of IVA transfers will relieve operational issues such as mission planning for EVA on the first and last days of the surface stay.

Several concepts are available for accomplishing pressurized transfers, including rigid and flexible tunnels, systems fixed to either the lander or the pressurized surface vehicle, and independent systems. One concept involves a dedicated ramp vehicle similar to the mobile stairways used for airline passengers. The difference is that the lunar version would be pressurized. After the landing, the ramp, which can be teleoperated or used as a trailer, approaches and connects to the landed vehicle. Soon afterwards the rover vehicle attaches to the other end of the ramp. Crewmembers then pass from the lander to the rover, reseal the ramp, and depart for the base.

The general requirements for the transfer tunnel fall into three categories; transfer, interface, and mobility and control. First, transfer needs will dictate that the tunnel must be capable of pressurized crew transfers and must be able to pass light equipment and supplies with physical dimensions equal to a standard rack about 1.5 by 0.5 meters.

To accommodate this, the tunnel and hatch diameter must be varied. Interface requirements affect the design of the transfer system a great deal. The transfer tunnel should be able to mate with lander vehicles in a variety of landing configurations. Piloted vehicles may come to rest listing at up to 12 degrees. As a result, the height and orientation of the interface between the surface or flight vehicles and the tunnel can vary. To handle these requirements, the tunnel must be capable of changing its linear orientation, its length, and the orientation of vehicle interfaces on both ends. Mobility requirements dictate that the tunnel ramp be capable of being moved or transported from landing pad to landing pad as it is needed and be capable of being aligned with vehicles in a gross manner. Control requirements are that the tunnel ramp be capable of being operated teleroboticly or using automation techniques for fine alignments. Figure 5.2-1 shows one concept for satisfying these requirements.

The tunnel ramp is basically a trailer with a special pressurized tunnel and universal docking adapters/hatches at both ends of the tunnel. The wheels will be powered so that the ramp may be operated independently. It can either be controlled by connection to the pressurized rover itself or it may be teleoperated. The ends of the tunnel are flexible so that it can mate with the unlevel docking adapters of the lander and rover. It is anticipated that the height difference between the rover and the lander hatches will be approximately 2 meters from center to center. The height differential and maximum allowable slope for safe ingress and egress are the drivers for how long the tunnel must be. For example, if the maximum allowable slope is 20 degrees and the height difference is 2 meters, then the length of the tunnel must be about 5.5 meters.

The transfer tunnel will need four wheels for stability and structural support. The wheel base is dependent on the diameter of the tunnel which is directly related to the size of the hatch and universal adapter. According to Space Station documents the hatch width is about 1.3 meters (50 inches) with a support ring close to 2 meters (80 inches). If the tunnel outer diameter is 2 meters, then the wheel base should be no smaller for a stable operation. The front to rear wheels distance is determined by the overall length which is estimated to be approximately 5 meters. For purposes of this concept, it is assumed the maximum safe slope for the tunnel is between 20 and 30 degrees and the maximum height difference is 2 meters. The wheel base will be approximately 2.5 to 3.5 meters. This would imply then that the frame for the vehicle is about 3.5 meters long and at least 2 meters wide. Table 5.2-1 provides an estimate of the mass of this tunnel.

Table 5.2-1, Tunnel Ramp

| | |
|---|---|
| Tunnel | 1,200 kg |
| Docking Adapters | 430 kg |
| Cart | 900 kg |
| Actuators | 150 kg |
| Power & Controls | 100 kg |
| Total Mass | 2,780 kg |

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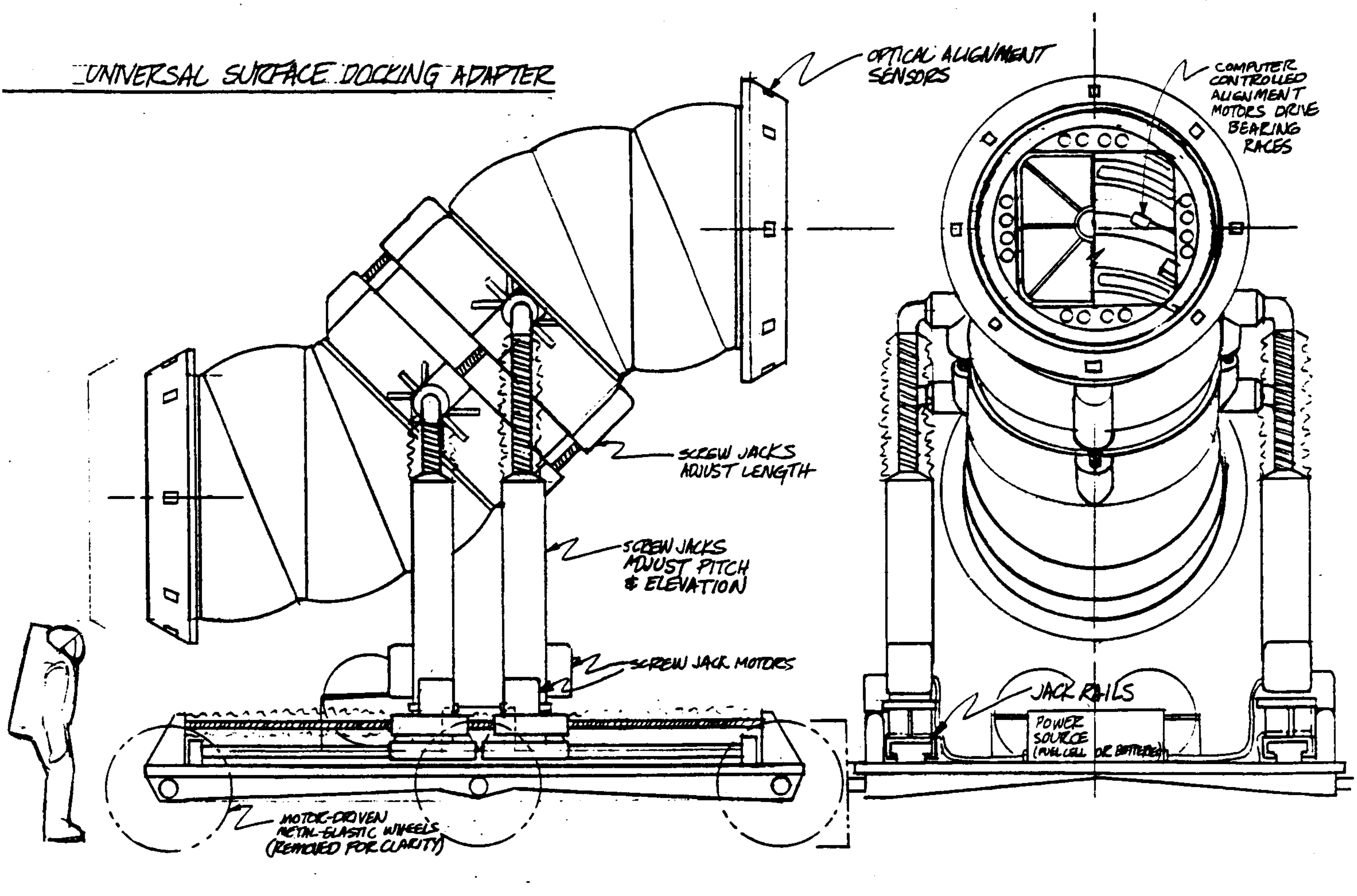


Figure 5.2-1, Transfer Tunnel

In order for the tunnel to mate with the lander and rover docking adapters it must have the capability to align its ends in the same plane(s). This requires a three degrees of freedom maneuverability at both ends of the tunnel. One possible design concept is to use a joint system similar to the new AX-5 astronaut space suit joint. These joints consist of a series of pie-shaped cylinders which are joined by wire and groove joints called Ortman couplings and sealed by O-rings. The joint is pressure tight and each ring can rotate independently on a ball bearing ring which is incorporated into the joint. Holding one cylinder still while rotating the next one causes the end face of the cylinder chain to change planes. This same principle can be utilized to alter the plane of the docking adapter. By utilizing a combination of gears and a small motor attached to each cylinder this series of joints can be rotated relative to one another. It is anticipated that the maximum slope on which the lunar lander will land is 12 degrees from vertical. The swivel joint described is presently capable of rotating through a 45 degree angle which would more than compensate for the landers off-nominal cases.

The positioning system referred to above can be controlled by a combination of a teleoperated system and an autonomous system. The teleoperation would be used to locate the entire tunnel adapter within close proximity of the lunar lander docking adapter. The final positioning of the tunnel would be controlled by the vision system which is a combination of cameras, infrared proximity sensors and intelligent software. Similar technology exists today in miniature robots used for hazardous environment operations in the nuclear industry.

Height differences are handled by a combination of adjustable supports and tunnel extenders. The tunnel supports are designed to tilt the tunnel into the proper angle to accommodate for some of the differential. The tunnel extenders will be used to maintain the horizontal distance between the supports. Some type of power screw could be used for this application. The screw will require a flexible covering to protect it from the lunar dust and temperature extremes.

### 5.2.2 Unpressurized Rover

Unpressurized rovers are needed by crews who have to use EVA to get in and out of the flight vehicle. It is assumed these vehicles will be present at the lunar base from the outset and will be similar to the Lunar Rover Vehicle used during Apollo missions. The vehicle must already be able to carry suited crewmembers and some equipment. Use in this case for crew transport should present no problems.

### 5.2.3 Pressurized Rover

The need for pressurized rovers will probably be dictated by requirements other than pad to base transfer. If the vehicle is intended to be used for this transfer, its design will have to be integrated with the design of the ingress/egress device. Other than required design integration, any possible pressurized rover requirements should be consistent with pad to base transfer.

## 5.3 CARGO FACILITIES

### 5.3.1 Cargo Handlers

Cargo handlers vary dramatically depending on the stage of base development. Early cases will involve the unloading of piece parts and smaller items from the vehicles. This can be accomplished by relatively small equipment such as block and tackle devices and winches.

Further development will necessitate unloading full cargos and large items. There are a number of ways to unload large items including cranes, fork lifts, and erectable ramps and hoists. One of these devices will probably be needed for equipment placement during base construction. Cranes, forklifts and erectable hoists can be used to move equipment around the base as well as load and unload cargo. Ramps will be more or less limited to use as cargo handlers only. The difficult activity will be unloading the first handler itself. A ramp could be included on the same flight with the handler which will need to be wheeled and can travel on its own power off the lander.

### 5.3.2 Cryogenic Transfer

Cryogenic storage equipment is needed for resource utilization activities in which liquid oxygen or hydrogen is produced in quantity on the lunar surface and is used in off-surface operations. Options for transfer could involve either permanently installed lines from storage equipment to pad locations or transfer vehicles with tankage for transfer. Since the vehicle needed for transfer can also be used for filling the storage facilities from plant supplies, vehicles can easily be designed to have the same connections. Installation of permanent lines to each pad will be major operations and beyond a Phase II lunar base.

Figure 5.3-1 illustrates a Propellant Refill Vehicle (PRV) which represents one concept for performing fuel transfer. The PRV consists of a storage tank for either liquid hydrogen (LH2) or liquid oxygen (LO2), the necessary support equipment to transfer the fluid to a flight vehicle, and the required hardware to run the vehicle (i.e. power cells, telemetry, etc.). The PRV may be used for handling both liquid oxygen or liquid hydrogen since the tank can be evacuated before unlike fluids are introduced. It is anticipated that more than one vehicle would be required.

The PRV is used for loading and unloading propellants from tanks onboard a vehicle. This could include filling and draining dedicated tanker vehicles with fixed tanks, filling propellant tanks of a reusable vehicle, and scavenging unspent fuel from landers. For a loading operation, the PRV's tank will be filled at a central depot, and it will traverse the distance to the pad. The vehicle drives up under the flight vehicle to make fluid connections with the tank. Once connection has been made, the flexible lines can be chilled and transfer can take place.

The propellant tank for the PRV is 3 meters in diameter and has a 3-meter long cylinder with spherical ends. This allows it to carry 35 cubic meters of propellants, equivalent to about 2,500 kilograms of liquid hydrogen and about 40,000 kilograms of liquid oxygen. The tank has a boil-off line that is directed through a refrigeration unit where the gas is condensed and returned to the tank in liquid form. The refrigeration unit is located at the front of the vehicle adjacent to the storage tank.

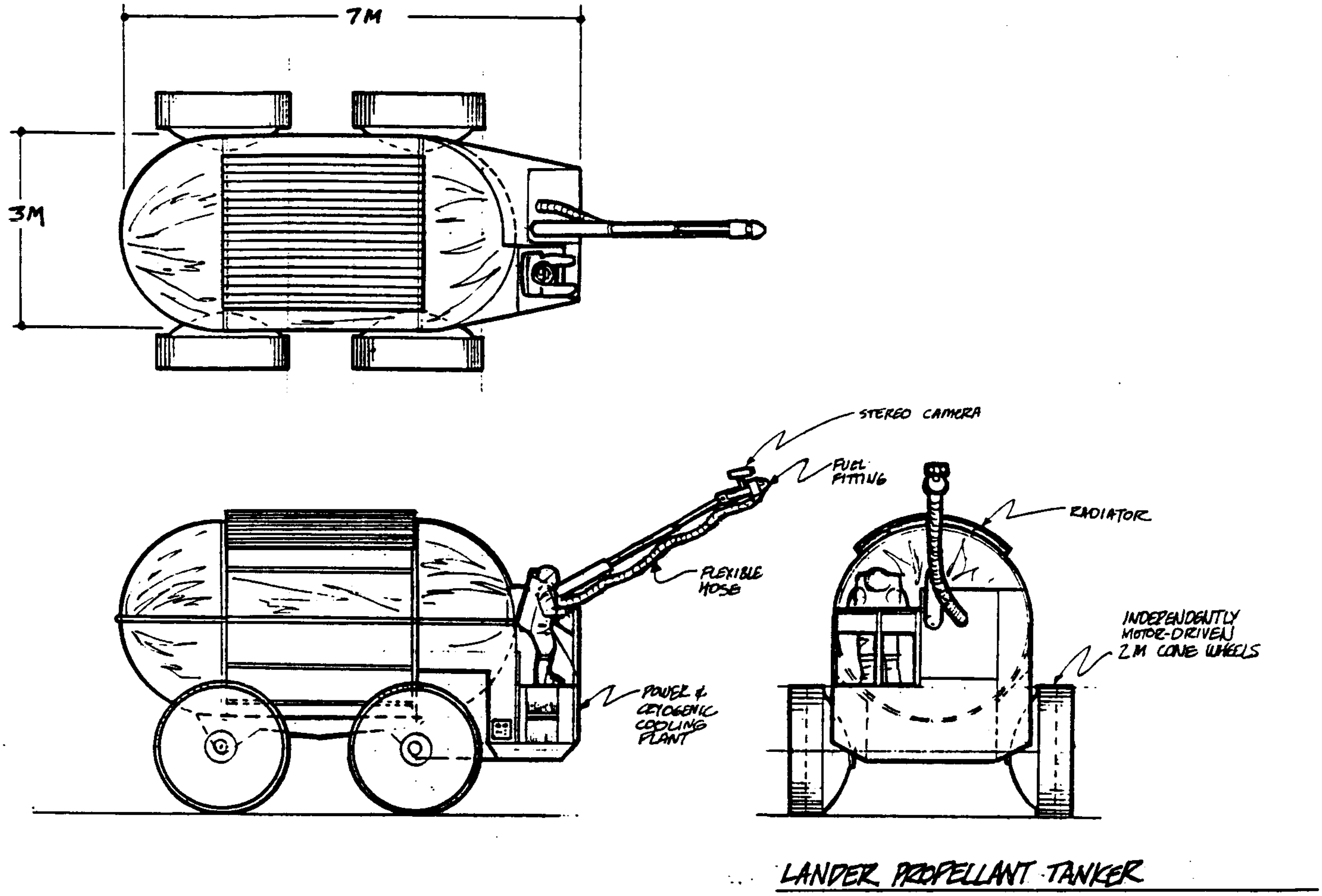


Figure 5.3-1, Propellant Refill Vehicle

Radiators are mounted on top of the vehicle for expulsion of heat from the refrigeration unit. The tank is encased in multiple layer insulation to prevent major heat gain from the lunar environment. To further prevent unwanted heat gains, the PRV should refill the flight vehicle during the lunar night or in the shadow of the flight vehicle during the day.

The PRV can be teleoperated or manually driven. Locomotion for the vehicle is provided by four electrically powered wheels. Each wheel is independently suspended and powered. Power for locomotion and other vehicle functions is provided by fuel cells located in the lower front compartment of the vehicle. The cells generate electrical power from the chemical reaction of hydrogen and oxygen. The power to operate the refrigeration system would be provided at the pad and at the propellant depot so the vehicle power system will only have to carry locomotion, control, and some other minor loads.

A boom with flexible propellant lines is included with the PRV to accomplish fluid connections. The base of the fluid transfer boom is anchored to the front deck of the vehicle. The crewmember is situated at the base of the boom from where he controls boom positioning during propellant transfer manuevers or controls the vehicle while traversing to the landing site. The fluid transfer nozzle is positioned by rotating the boom base and extending the telescoping boom elements. For accurate positioning, fine adjustments are made at flexible joints near the nozzle before mating to the lander. While the PRV is in motion, the boom is stored in the collapsed position. Boom flexibility is accomplished by using threaded telescoping elements and cabling instead of hydraulics. The operation is well illuminated from flood lights mounted at the boom base and on the leading surface of the vehicle.

The fluid transfer nozzle mates two lines to the flight vehicle, one fluid fill line and one gaseous boil-off line. The nozzle is arranged in such a way that it can be mated in only the correct orientation for fluid transfer. The machinery to pump propellant to or from the flight vehicle is located in the front portion of the PRV near the fuel cells.

No serious attempt has been made to find the mass of the PRV, but estimates are that it will mass 14,000 kilograms empty. This includes an estimated 10,000 kilograms for the tank, 2,000 kilograms for the structure, power, locomotion, and other subsystems, and about 2,000 kilograms for the refrigeration and radiator system.

## 5.4 VEHICLE FACILITIES

Vehicle facilities are those needed to accommodate landers and ascent vehicles. For the Phase II lunar base, much of the support needed by vehicles will concern their survival on the surface while they remain on standby for the crew's return. Surface stay times range from 8 to 28 days during temporary base occupation so the vehicles can expect to witness the full range of lunar surface conditions. Survival support will be provided by electrical power supplies, supplemental cooling devices, and meteoroid protection systems. More sophisticated forms of servicing such as maintenance, refueling, and transport may take place when base operations become well developed.

### 5.4.1 Vehicle Power Supply

Electrical power is a vital utility for piloted vehicles on the landing pads. The vehicle systems must be kept in working order and appropriate overall vehicle thermal conditions must be maintained. Although these vehicles will have their own onboard power systems, the lunar environment is significantly different from that of space, and mass considerations may limit electrical energy storage capabilities. Without performing detailed study, it is evident that some sort of supplemental power supply for long surface stay times will be justified. Cargo landers which will not be reused will not need this power.

There are two basic ways to provide the needed supplemental power to the landing pad. One involves the use of an electric cord extended from a central base power system and the other a self-contained portable power supply. Some baseline requirements must be established to allow comparison of these two types of systems. To that end, it is assumed that the lander will require 2 kilowatts of power for a period of 28 days. Examples of concepts for each type of system are described in the following paragraphs. For the application described, the possibility of an inaccurate landing some kilometers away from the planned site, along with other versatility needs, will weigh heavily toward the self-contained power supply. If vehicle surface stay times increase, the balance may be shifted towards the cord system. This will occur for alternate ascent stage concepts in which the crew leaves the Moon in the vehicle used by the last crew providing complete ascent stage redundancy. Both power systems have particular advantages and in the end both types may be needed. Figures 5.4-1 and 5.4-2 show drawings of both type of systems.

The cord system consists of a 1-kilometer long cord on a spool which is mounted on a four-wheeled cart. A power conditioning system consisting mainly of a transformer and rectifier is provided on the cart to provide a variety of voltages including the standard 28 V DC spacecraft electrical power. When needed, the cord is plugged into the base power system and unreeled to the site needed. Another cord can be connected between the vehicle and the power supply, and the lander will have the needed power. If additional distance is needed, another extension cord can be connected to the first, bypassing the transformer system.

The overall mass of the system is estimated at 910 kilograms. Table 5.4-1 provides a mass breakdown and dimensional data. For the 2-kilowatt requirement, a transmission voltage of 400 V AC, single phase, was chosen. This voltage is routinely handled in terrestrial applications and therefore is considered safe for base application. Higher voltages would reduce system mass at the risk of safety and lower ones would increase wire masses. The issue of transmission voltage requires further detailed analysis. The 5 amp current over 1,000 meters indicates the need for the equivalent of #3 AWG wire conductors which are less than 1 centimeter in diameter (reference 16). This results in a transmission power loss of around 2 percent. The wire is insulated to a thickness of 1/2 wire thickness. Mass estimates are made based on polyvinyl chloride densities (reference 16). Overall cord dimensions are 2.6 centimeters wide and 1.3 centimeters thick. The cord and insulation designs were made for mass estimates only; further detailed design is needed. Transformer mass is based on single-phase terrestrial equivalents. Cart weight is estimated based on a 1.0 by 1.4 meter, 0.6 centimeter aluminum plate with four wheels at about twice the weight of LRV wheels. Wheel loading is about the same as the LRV at about 200 kg per wheel. The spool is a 20 centimeter diameter tube with 65 centimeter diameter ends, 1.25 meters wide. It is made of 0.3 centimeter aluminum. No attempt was made at structural analysis for this mass estimate.

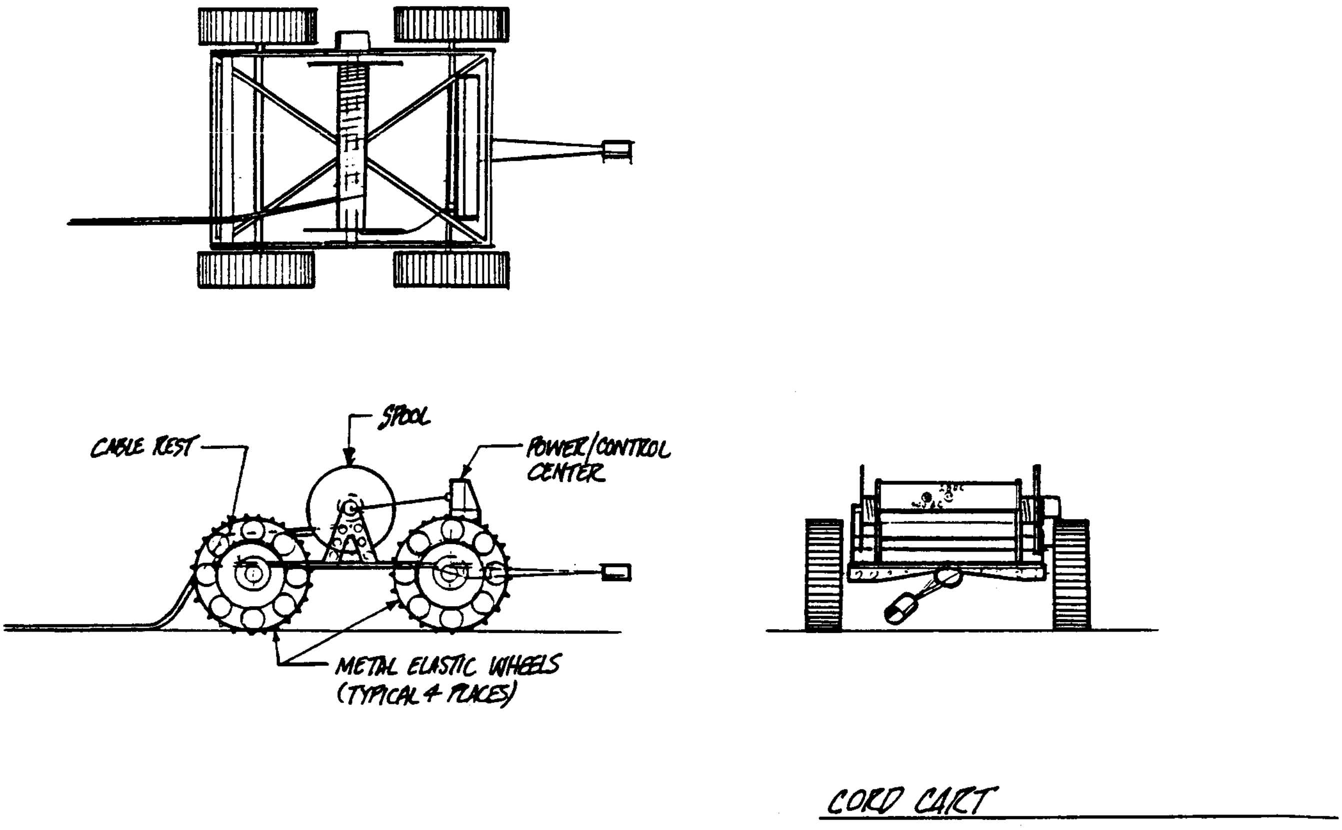


Figure 5.4-1, Electric Cord System

This system has advantages in the fact that it is simple to use and has very few maintenance requirements. The extension cord system is not energy limited but power limited. Only the power requirement enters into the design. The duration can be increased and decreased without affecting system design. As long as the base system can accommodate it, the cord power supply can be connected to a lander indefinitely. This system may require additional base power supply equipment in the form of a direct to alternating current inverter but this should not be much different from the conditioning system in mass. If power requirements can rise above 2 kilowatts for any sustained period though, the wire size and mass of the system must be increased to avoid wire overheating and system failure. There are disadvantages to this system other than inflexibility in power levels. Nominal early landings should occur no more than 450 meters from the base. If landing errors result in landings more than 1,000 meters from the base, an additional system will be needed. Later landings occur over 3 kilometers from the base and can be as far as 500 meters apart. While the first 3 kilometers can be handled with onetime installation of thicker cable, there is some inflexibility in the cord system in connecting to the various landing sites.

There are several options available for the portable self-contained system. Among them, fuel cells and nuclear isotope generators appear to provide the best possibilities. Batteries will not be examined for this system since the storage requirement of nearly 1,500 kilowatt hours will result in a massive system. Masses as low as the 5 kilograms per kilowatt-hour (kg/kwh) of zinc-silver batteries would result in a 7.5 metric ton system. In addition, solar cells will not be considered as a primary power supply. Since the system must be operated during the lunar night, solar cells cannot be used for continuous power. These solar cells can be used as a source supplemental to the primary power generation system.

A spacecraft nuclear power system on the order of 1 to 5 kilowatts is currently under development by the Department of Energy, the Air Force and the Strategic Defense Initiative Office. The system is known as the Dynamic Isotope Power System or DIPS and current mass estimates are in the range of 200 to 500 kg (reference 17). The life of these systems can be measured in years. These systems, adapted for lunar application, would clearly beat virtually any other system. However, nuclear systems use technology that is not well known, and they involve some difficult political and safety issues. An adapted DIPS type system will not be considered here. Fuel cell technology is well developed and application to the Space Shuttle and previous programs has proven it to be an operational technology. As a result, a fuel cell system is proposed for the self-contained power supply or "power cart".

The power cart consists primarily of cryogenic hydrogen and oxygen tanks, liquid water tanks, and a fuel cell system mounted on a four-wheeled cart. A solar cell can be mounted on the cart to provide extra power during sunlight periods. When a lander needs power, the cart is taken to the landing pad. The power cart is connected to the vehicle in the same way as the electric cord system. The power cart is then activated and the vehicle has the appropriate power. After use the cart can be taken back to a central regeneration station where it is charged for its next use.

The estimated mass of the fuel cell power cart is 1,290 kilograms. Table 5.4-1 provides a mass breakdown and dimensional data for this system. The fuel cell system is sized as a 7 kilowatt Space Shuttle system (reference 18). This system is currently operational and can accommodate the 2-kilowatt requirement easily as well as provide additional service for peak loads. In fact, double the system power capability to 14 kilowatts maximum would only increase system mass by 7 percent.

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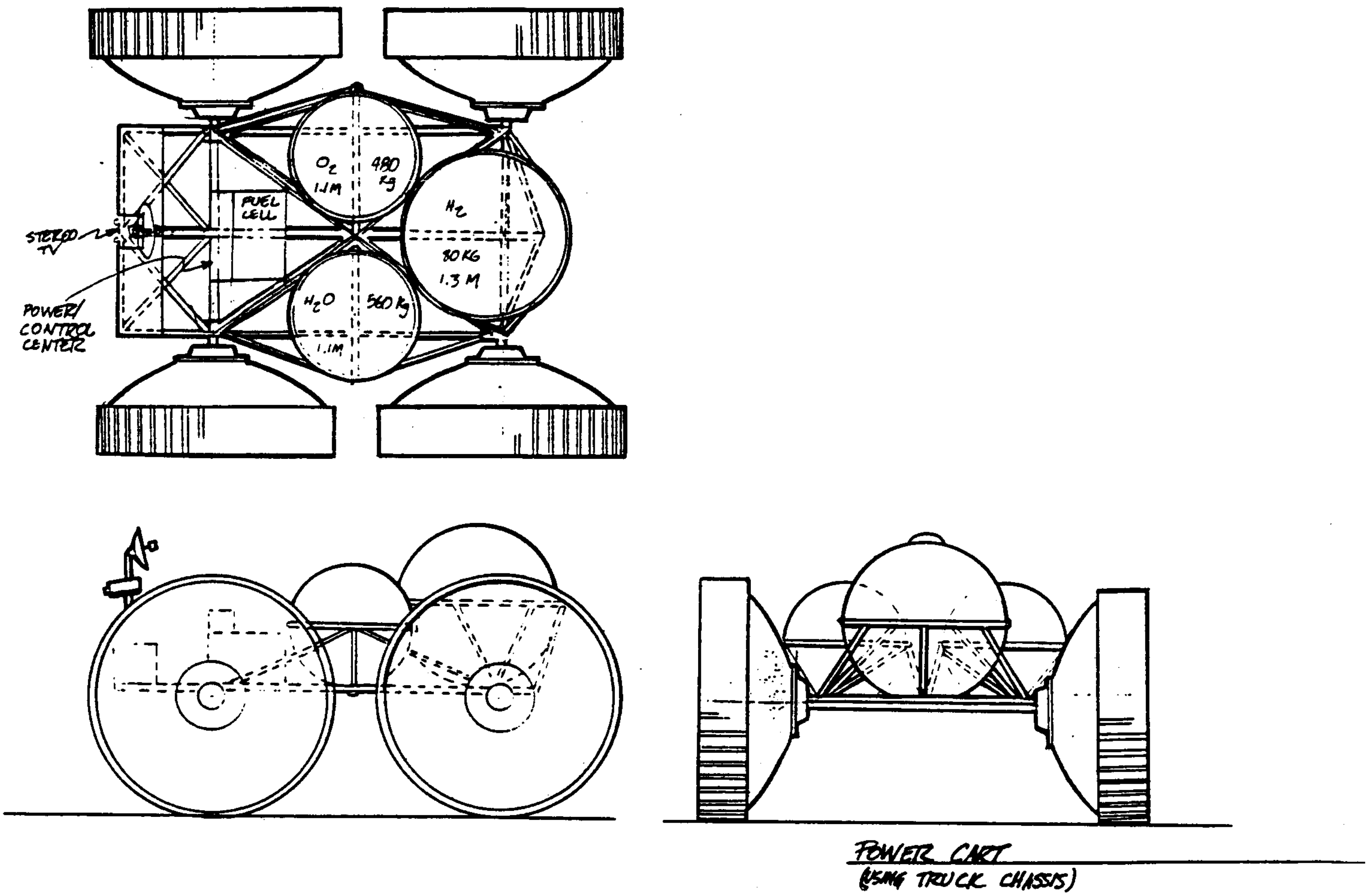


Figure 5.4-2, Fuel Cell Power Cart

Table 5.4-1, Vehicle Power Supplies

ELECTRIC CORD SYSTEM (1 kilometer)

| | |
|---|---|
| Conductor | 490 kg |
| Insulation | 250 kg |
| Power Conditioner | 20 kg |
| Cart | 90 kg |
| TOTAL | 820 kg |

| | | | |
|---|---|---|---|
| Dimensions | 2.0 m Long | 1.4 m Wide | 1.1 m High |

FUEL CELL POWER CART (2 kilowatts, 28 days)

| | |
|---|---|
| Tanks | |
| Hydrogen | 190 kg |
| Oxygen | 130 kg |
| Water | 130 kg |
| Fuel Cell | 90 kg |
| Solar Panel (1 kw) | 40 kg |
| Cart | 150 kg |
| DRY MASS | 730 kg |
| Reactants | 560 kg |
| TOTAL | 1,290 kg |

| | | | |
|---|---|---|---|
| Dimensions | 4.3 m Long | 1.3 m Wide | 1.3 m High |

Tanks

| | |
|---|---|
| Hydrogen | 1.3 m Diameter |
| Oxygen | 1.1 m Diameter |
| Water | 1.1 m Diameter |

Fuel cell reactant consumption of 0.36 kg/kwh results in storage requirements of 540 kilograms of fuel. Of this, 60 kilograms is hydrogen and the remaining mass is oxygen. The hydrogen is assumed to boil off at a rate of around 1% per day, increasing the required amount by nearly 20 kilograms. No attempt has been made to analyze the thermal requirements or to perform trades of active and passive systems for this study. The boil-off is vented and not collected. The reactants required are slightly more than those contained in one Shuttle cryogenic tank set which is 40 kilograms of hydrogen and 354 kilograms of oxygen. As a result the sizes and masses are only slightly larger. Shuttle tank masses are around 2.4 kg/kg of hydrogen, 0.25 kg/kg of oxygen, and 0.25 kg/kg of water (reference 18). Since the capacities are similar these factors were used to scale the power cart tanks. A 2.5 meter by 3 meter solar panel is mounted above the tanks to provide additional power to off-load the fuel cell when solar energy is available. This gallium arsenide panel provides a maximum of about 1 kilowatt when the Sun is at an appropriate angle and has a mass of about 40 kilograms. The cart is assumed to be similar to the cart used for the cord system except that it uses a thicker bed to support the additional load and has four cone wheels. Again, the wheel loading is similar to the LRV.

The main advantage of the power cart is its versatility. It can be taken to virtually any location, regardless of distance from the base, without power loss. The system has many applications other than to lander power service, including use as an auxiliary power supply to a long-range transportation mission. The system is not power limited as is the cord system but is energy limited. Peak power requirements over 2 kilowatts, even for extended periods, present few problems. However, if duration requirements increase over the 28 days, either power levels must be reduced or more reactants must be provided increasing mass. Other disadvantages include the need for more logistical and maintenance support than for the cord system and higher masses. If the energy supply is to be regenerated, a base regenerator must be supplied and boil-off replacement must be provided. A regenerator will not be a small system as it must contain power generation, electrolysis, liquefaction and storage equipment. If no regeneration is anticipated or if it will be delayed, an entire new tank set which is about 90 percent of the mass of the entire cart will be needed for each mission. This would be no mass savings over carrying the power system on the lander itself.

Both the cord and cart systems have compelling and complimentary advantages. Both systems can be used for many other tasks than simply supplying power to a lander. There will be need for power away from the base for a variety of transportation, construction, and other tasks, as well as for vehicle maintenance. Because of these needs, both types of systems are recommended. In fact, more than one of each may be required depending on how many simultaneous tasks are undertaken.

### 5.4.2 Supplemental Cooling System

For reasons analogous to the need for electrical power, a supplemental cooling system will be needed for piloted vehicles on the landing pads. The vehicles and their systems must be kept cool during the lunar day when reflection and reradiation from the lunar surface will add to the direct sunlight experienced in space. These vehicles will have their own onboard cooling power systems sized only for direct solar heat loads. A supplemental cooling system will add radiator surface for the lander cooling system to allow it to handle the additional cooling loads of the lunar day.

There are two concept philosophies which must be addressed in the design of the supplemental cooling system (SCS) and how it interfaces with the lander. First, if the lander will use the SCS simply as added radiator surface, it can be coupled in parallel with lander radiators and the lander will pump the appropriate fluids through the radiator. This method has advantages in a simple, passive design for the SCS but places additional pumping loads on the lander thermal control system. In addition, the vehicle and SCS cooling systems must be identical. Significant changes in vehicle cooling methods, such as a change from single- to two-phase systems, would necessitate major changes to the SCS. A second concept incorporates a heat exchanger in the vehicle and an SCS that provides pumped fluids to the exchanger at required temperatures. In this system, the SCS design can be independent of the vehicle cooling system. Improvements in vehicle cooling systems or even SCS systems may be made without concern for impacts on the entire design on the other system. However, the SCS will be more complex containing control systems and pumps which will need electrical power. Since the lander itself will need supplemental power, electricity will be available on the pad and the need for electricity will not be restrictive.

The SCS will consist primarily of a radiator sized at a minimum to reject the added cooling load from the lunar surface and at a maximum to reject the entire vehicle cooling load. Since these loads are unavailable at this time, a load of 2 kilowatts is assumed. The radiator size will naturally depend heavily on its operating temperature. The temperature of the vehicle working fluid will dictate this temperature. If the lander has a simple pumped fluid system, the SCS will need to provide working fluids in the neighborhood of 15° C (60° F). Interior vehicle temperatures will need to be around 30° C (85° F) to allow the crew to perform service and maintenance work at least and to live inside in some early cases. The air supply will need to be 25° C. Assuming chilled water is used to cool the air, air coil inlet water temperature should be no higher than 20° C. Assuming a heat exchanger interface with the SCS, inlet temperature should be 15° C to provide the 20° C chilled water. The radiator water then will have a 15° C outlet with an inlet of around 20° C.

The 5° C approach between inlet and outlet temperatures is fairly standard. Closer approaches could result in heat exchanger growth while higher values result in low radiator temperatures without coil sizes becoming large.

The radiator can be sized at 2 kilowatts for an average water temperature of 17.5° C. Assuming a 2° approach for the radiator, the average surface operating temperature of 15° C will be used. At this temperature, estimates of heat rejection are about 100 watts per square meter for simple radiators (reference 19). At this rate, the radiator will be 20 square meters or about 4 meters by 5 meters. The flow rate required will be about 5 liters per minute (1.5 GPM). Assuming 2.5 cm pipes, spaced every 5 cm on center, the power required to pump this fluid through the 400 meters of pipe will be around 100 watts.

The SCS shown in Figure 5.4-3 has a deployable radiator system in three sections. The system mass is about 1,170 kilograms. Table 5.4-2 provides a mass breakdown and some dimensional data. The system is mounted on a cart similar to the one used for the fuel cell power cart described above. This is a simplistic radiator system. Other more sophisticated radiator designs have been proposed for applications such as this. The design presented here is intended to provide a conservative, rough order of magnitude size and weight. Further detailed design must be performed once better data on the expected heat load is known. Coolant choice must also be reconsidered to insure proper operation over the entire range of surface conditions.

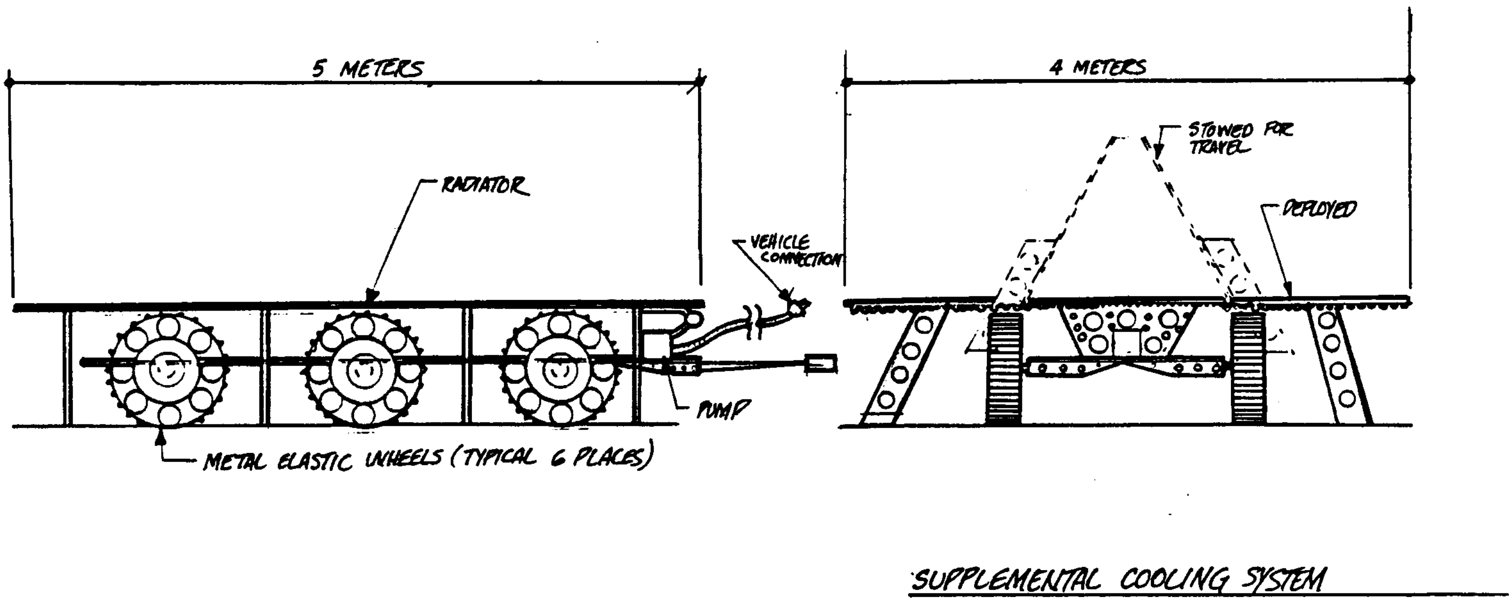


Figure 5.4-3, Supplemental Cooling Cart

Table 5.4-2, Supplemental Cooling System

| | |
|---|---|
| Radiator | 340 kg |
| Pipes | 390 kg |
| Pump | 20 kg |
| Cart | 190 kg |
| Water Working Fluid | 230 kg |
| TOTAL | 1,170 kg |

Dimensions

| | | | |
|---|---|---|---|
| Stowed | 5.0 m Long | 1.5 m Wide | 1.1 m High |
| Deployed | 5.0 m Long | 4.0 m Wide | 1.1 m High |

If operating temperatures were increased, the size and mass of this system could be reduced. However, this temperature increase would result in the need for a refrigeration system onboard since it must still provide the same coolant supply temperature.

### 5.4.3 Micrometeor Protection

It is probable that some vehicles which will remain on the surface for long periods will need to be protected from exposure to micrometeors. One concept for providing this protection is the use of a vehicle cover or blanket that can be draped over the entire vehicle or over selected systems sensitive to the expected micrometeor bombardment. These blankets would serve as bumpers supplemental to those already provided on the vehicle itself. Blankets such as this will be needed for blast protection. The same sort of material can be used. Multi-layer mylar sheets or kevlar fabrics may provide appropriate protection.

### 5.4.4 Vehicle Servicing Facilities

Reusable lunar vehicles will require some sort of maintenance. Assuming the vehicles never leave lunar space, servicing at the LEO Space Station is not available. Many concepts for vehicle servicing in near-lunar space are available. Some concepts involve an orbiting platform similar to the LEO Space Station, and some involve servicing on the lunar surface. The scale of servicing varies and can include simple checkout, refueling, modular parts replacement, or major overhaul. Each of these concepts has its own effects on facilities and operations.

Servicing facilities play one role in a broad series of trade decisions involving considerations such as landers and transportation systems, logistics and resupply plans, and base scenarios including their major base emphases. The amount of servicing and parts replacement done on the surface will depend on crew time available and the mass of parts. Crew time will depend on the stage of the base development. The mass of parts needed and the propellants required to land them will be traded against the relative ease of operations compared to those on a microgravity orbiting platform. Before appropriate decisions can be made, a vast array of servicing options must be explored and the facilities required must be defined.

During temporarily-occupied operations of the Phase II lunar base, it is anticipated that any exterior vehicle servicing will be minor and will be EVA efforts. EVA tools and aids will be needed to accommodate whatever tasks are performed. For example, heavy and cumbersome parts, such as engines which may need replacement, will require jacks and placement rigs. When and if surface fueling capabilities are in place, fueling may be handled by the same equipment as for cargo handling of fuel. If vehicles are appropriately designed, many elements can be accessible to IVA crewmembers within the vehicle itself. As the base develops and vehicle servicing increases, certain exterior tasks can be done by shirtsleeve crewmembers in a pressurizable facility attached to the vehicle. Vehicles will need specially designed interfaces to accommodate these facilities. Later, servicing activities can be moved into an unpressurized hangar facility to ease some of the EVA work. After the lunar base has developed extensively, the hangar can be pressurized and vehicle refurbishment and recycling activities can be accommodated. Detailed designs of the facilities needed to perform these operations have not been performed as a part of this study.

### 5.4.5 Vehicle Transport

When reusable pads become necessary, the landed cargo vehicles or expendable landers will need to be removed to allow the next landing to take place. Reusable single-stage piloted vehicles will not need to be removed, of course, since they will do that themselves by launching.

There are several concepts available for removal of vehicles from the landing pad. These include cranes with trailers, wheel and jack systems which can be attached to lander foot pads, or vehicles that can be attached under the center of the lander to lift it. Detailed study of these options has not been performed.

## 6.0 SITE DEVELOPMENT PLANNING

The evolution of lunar base landing facilities can be summarized in what will be known as a Site Development Plan. This plan must be meshed with other plans for lunar base development to ensure that appropriate facilities and equipment are available when they are needed. The needs and evolution of lunar surface systems depend very heavily upon objectives and goals and how they are translated into particular schemes. Generally known as scenarios, these objectives, goals and schemes are dynamic. Many scenarios for lunar development have been proposed and continue to be proposed. Scenario development and evaluation is a current and continuing process. Thus, it is obvious that no one Site Development Plan may be proposed with hopes of it being valid for long. Each lunar base scenario must have its own Site Development Plan.

The following discussion is intended to illustrate how site development planning can be accomplished. The primary interest in this planning is to affect the evolution of the lunar base in only modest ways if at all possible. This approach allows delivery schedules and crew activities to relate to the objectives of the base itself and not to a sideline effort such as development of landing facilities.

### 6.1 GENERAL SITE DEVELOPMENT PLAN

The development of lunar landing facilities for a Phase II lunar base follows one general path. There are three stages along this path: early landing facilities, temporary landing facilities, and permanent landing facilities. Depending on the nature of the individual scenario, the length of any of these stages may vary. However, the activities within each stage are the same no matter which scenario is chosen.

#### 6.1.1 Early Stage

The early stage of landing facility development takes place while the base is being prepared for occupation by humans. The stage starts at the beginning of Phase II, when the first human returns to the Moon. It ends when the base facilities can be occupied.

Landing pads will be located close to the base site, within 250 to 400 meters. The facilities will consist of unprepared landing pads, markers and navigation aids, blast protection, and vehicle power supply systems. Some method of vehicle off-loading must also be present but should be an item shared with other base functions such as construction. Figure 6.1-1 shows the general location and distribution of landing pads for early stage landing facilities.

#### 6.1.2 Temporary Stage

The temporary stage takes place during base growth periods. The starting milestone occurs when humans move into the base for their stay on the lunar surface. The temporary stage ends, obviously, when permanent landing facilities become operational. The relationship of the ending milestone to development of the base itself depends heavily on the nature of the base. This dependency will be discussed in detail in a later section.

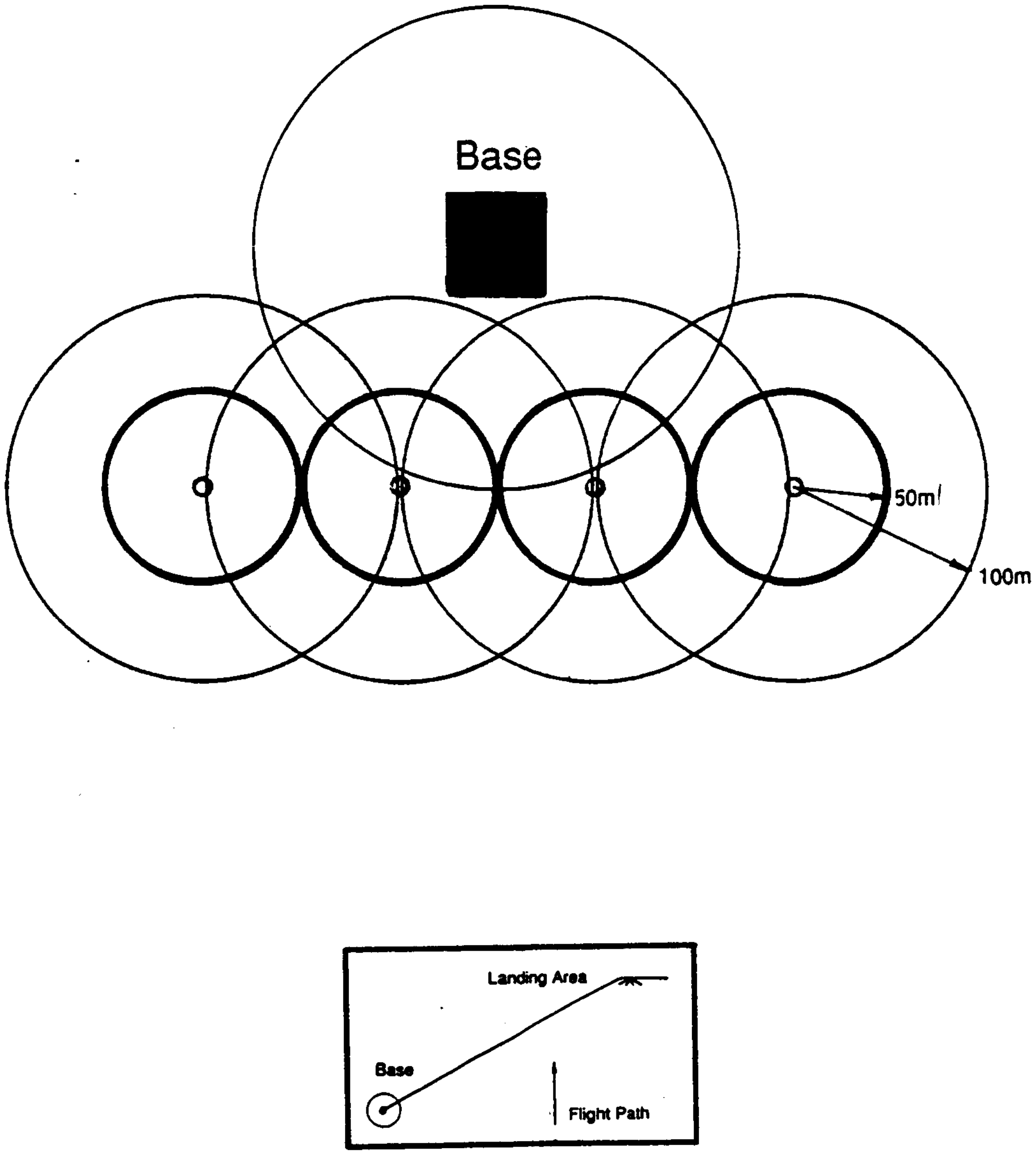


Figure 6.1-1, Early Stage Landing Area

The landing area will be remote from the base. From 3 to 5 kilometers perpendicular to the approach path will be needed. The facilities will consist of unprepared landing pads, markers and navigation aids, blast protection, and vehicle power supply systems. Shared vehicle off-loading equipment and some method of transporting cargo from the pad to the base must be present. Pads should be laid out to allow 250 to 400 meters between subsequent landings so blast effects are minimized. Figure 6.1-2 shows the general location and distribution of landing pads for temporary stage landing facilities.

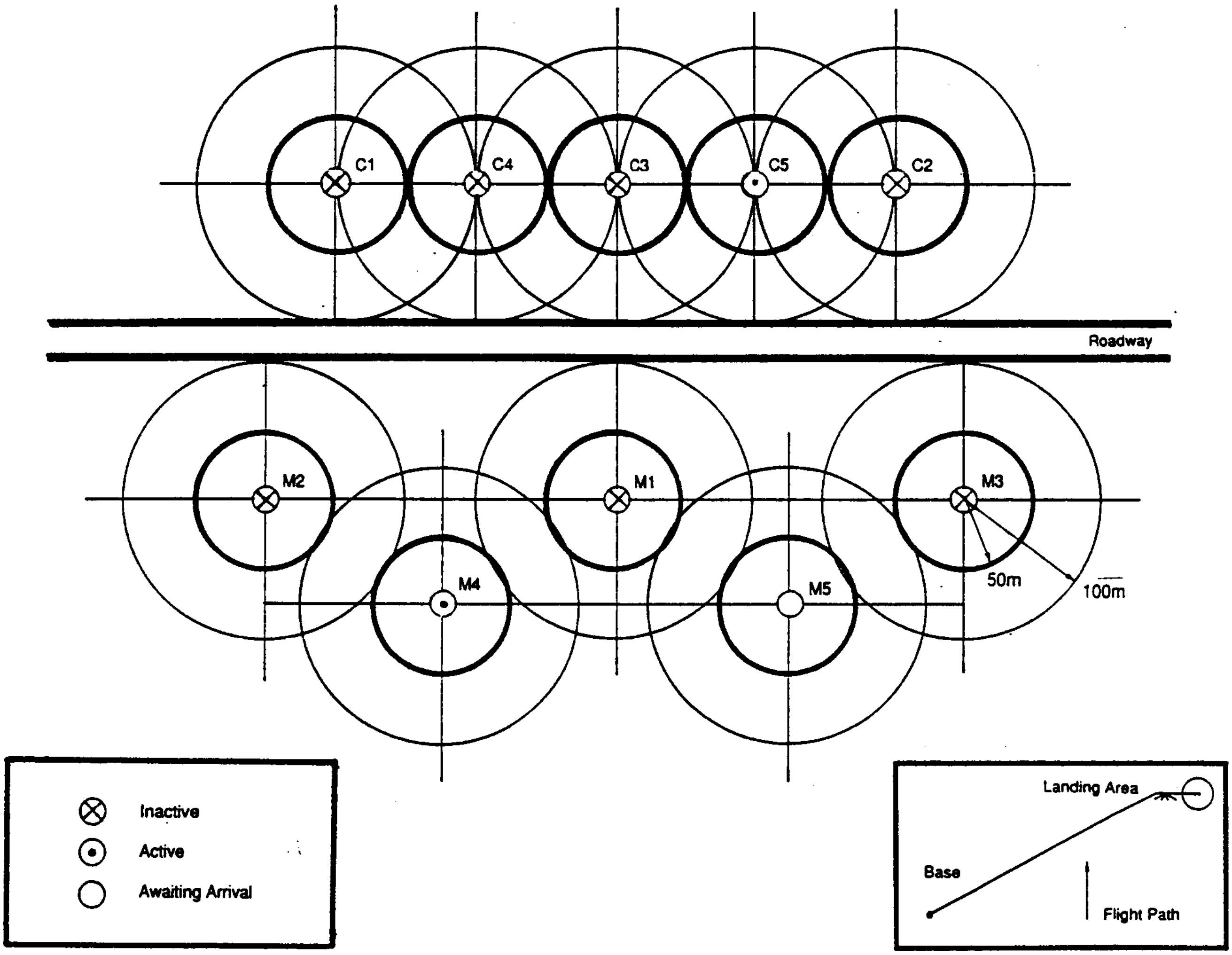


Figure 6.1-2, Temporary Stage Landing Area

### 6.1.3 Permanent Stage

The permanent stage of landing facility development occurs when the lunar base is well developed and reusable landing pads become necessary. The beginning of the stage is subject to the nature of base activity. In general, this happens when either vehicle servicing requires a high degree of alignment between surface equipment and flight hardware or when cargo must be loaded onto a launch vehicle. It must be noted that the permanent stage of landing facility development does not necessarily coincide with permanent occupation of the base itself. The development of landing facilities for a permanently-occupied base will likely be a continuation of the development started during temporarily-occupied operations.

The landing area will be remote from the base to accommodate vehicle off-nominal landing accuracies and some blast effects. The 3 to 5 kilometer distance used for the temporary pads will be appropriate and the permanent pads will probably be adjacent to the used temporary pads. The facilities will consist of reusable landing pads, markers and navigation aids, blast protection, and vehicle power supply systems. Shared vehicle off-loading and transport equipment will be present at the beginning of this stage. In addition, the cargo loading or vehicle servicing equipment which made the reusable pads necessary will be in evidence. Additional equipment to remove spent stages from landing pads must be provided to make the pads truly reusable. Pads should be about 250 to 400 meters apart to minimize the blast effects on any debris broken loose from the reusable pads. Figure 6.1-3 shows the general location and distribution of landing pads for permanent stage landing facilities. As this stage progresses, other facilities may be added or dedicated versions of existing or shared equipment as described under facilities Conceptual Design above may be shipped to the surface.

## 6.2 SCENARIO DEPENDENCE

The Site Development Plan described above is generic. In general, any planning for lunar landing and launch facilities will follow the description above. The presentation of the plan is intended to show the overall plan of development. Major variations between specific plans can be expected. The following discussions are intended to address how a specific Site Development Plan can be developed from the generic one above.

### 6.2.1 Base Objective Dependence

The objective of the base will affect primarily the transition from temporary to permanent facilities although the early stage can be affected also. The main dependence is derived from cargo operations and the need for cargo loading and alignment operations. Effects on early facilities may arise indirectly from the effect of base objectives on other factors. Base objectives represent the primary emphases of the base itself. These objectives may be scientific, including astronomical or lunar sciences. They may be resource oriented, including propellant or material production, or some other resource. Habitation may be the primary objective for study of life sciences or for political reasons. Development of technology for future missions may also be the objective of the base.

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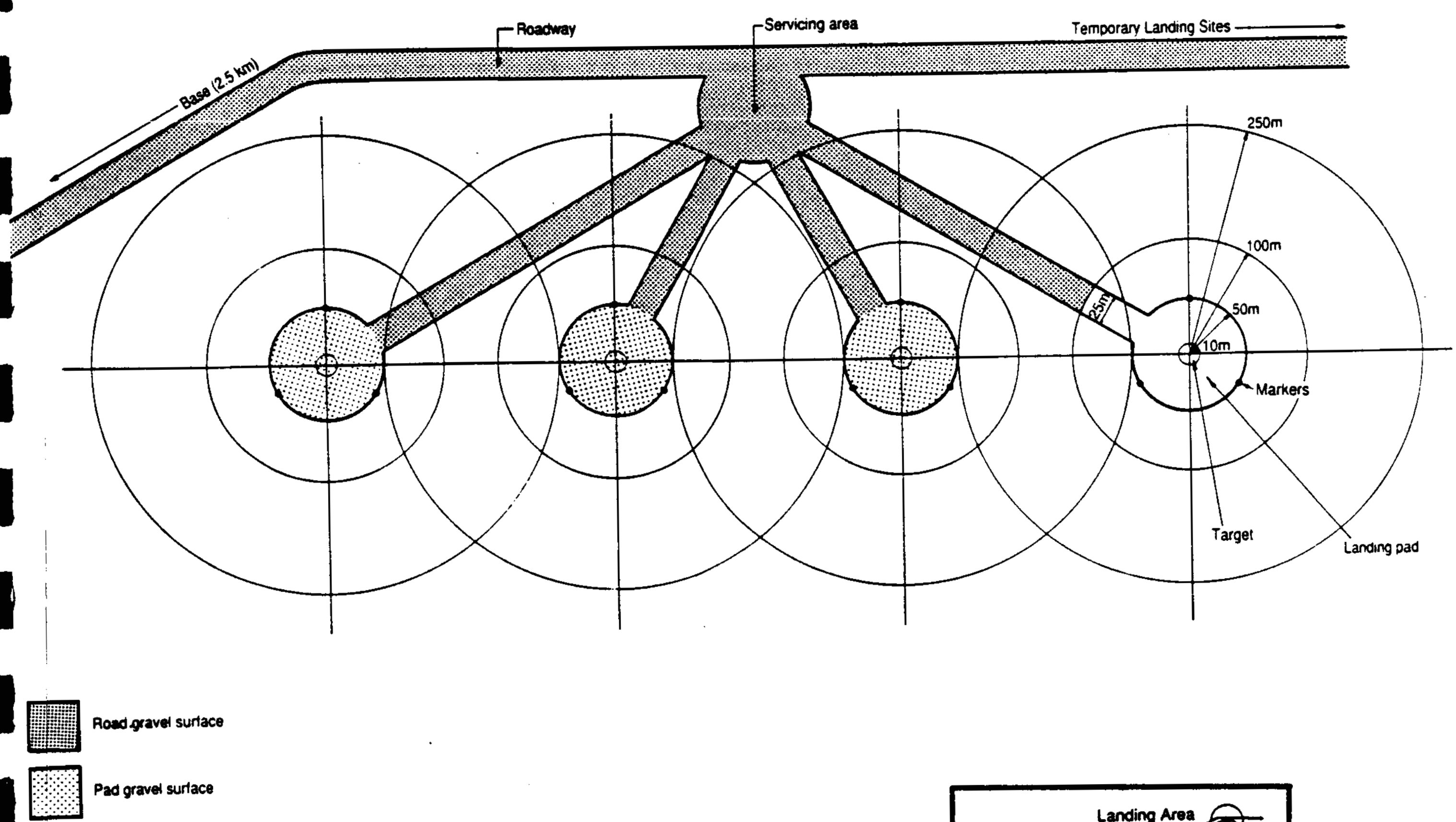


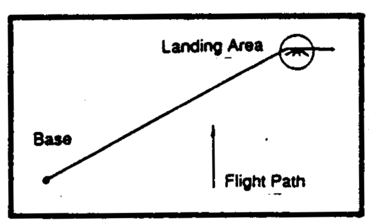


Figure 6.1-3, Permanent Stage Landing Area

Landing support for a scientific base can generally be characterized by the need for instrument and construction equipment and logistic resupply deliveries. The primary export of the base will be small amounts of materials for sample analysis and data. The materials will be the only consideration for landing and launching facilities. When and if the volume and mass of samples become sufficient to require separate sample return missions, the need for a cargo loading operation is indicated. At this point, the transition between temporary or early and permanent facilities should take place. This means that all other things aside, if the sample return requirements are low, permanent, reusable landing pads may never be needed.

A resource oriented base will have an obvious export. The specific operation is not of importance here. When the export activity begins in earnest, permanent pads will be needed. Also, permanent cargo oriented facilities are needed from before the time serious production of resources begins. Only the nature of the facilities depends on the nature of the product. Therefore, for resource objectives, the transition from temporary to permanent stages occurs when the export process starts.

A habitation base alone will in general not require a permanent landing facility. Since no product is shipped from the surface, no major cargo loading takes place. Habitation does affect the rate of base growth and thus may have impacts on the transition between early and temporary facilities.

The effect of a technology development base will vary. Definition of the actual technology development activity is needed to further identify the effects of a technology base on landing and launching facilities.

### 6.2.2 Base Growth Dependence

Two aspects of base growth affect site development of lunar launch and landing facilities. The rate of growth of habitation facilities and the growth of surface stay times affect landing facilities in different ways and at different periods. These two aspects may be related in actuality but will be treated separately here.

Habitation growth relates directly to the early to temporary stage transition. If habitation is important, the base will be rapidly developed to allow dwelling in the base. At this point, as long as some sort of vehicular surface transportation is available, the pads may be moved away to the remote sites and the temporary stage can begin. If the base is developed slowly, the early stage will be protracted and the vicinity of the base may actually become littered with spent stages and used landing pads.

Stay time growth will affect the transition from temporary or early stages to permanent stages. When surface stay times increase to the extent that reusable pad setup and maintenance becomes a fairly small percentage of available time, the permanent stage can be justified. Although not necessarily, this is usually associated with permanently occupied operations. This would be very near the end of Phase II operations.

### 6.2.3 Flight Vehicle Dependence

The specific design of the lunar lander will affect pad location, equipment protection, and servicing requirements. These effects are related to the size and thus the thrust levels and the expendable versus reusable nature of the vehicle.

If growth of flight vehicles increases or decreases the size of the engines, some change to site development may be indicated. Generally, ejecta from larger engines will be larger and travel farther and faster than for smaller engines. The results will be that the higher end of the pad to base distance ranges will be needed for larger engines. The lower figures presented here were generated for an Apollo LM sized engine at 50,000 newtons thrust. The upper ranges are generally appropriate for thrust levels higher than this by a factor of 5. In addition, the nature of surface stabilization may need some revision. The smaller engine will loft grains in the neighborhood of 5 millimeters while the larger ones can loft particles as large as 25 millimeters. Gravel stabilization may not be right for this and some more sophisticated method may be needed.

The use of a reusable lander will affect the transition to permanent stages and the nature of facilities located at the pad. When a reusable vehicle begins to need servicing on the lunar surface, facilities for this servicing will be required. If the nature of the servicing is such that simple EVA is unacceptable, whether because of crew time or servicing complexity, equipment that can align with the vehicle and provide some pressurized work area must be present. The need for alignment indicates the need for level and therefore reusable pads. Consequently, if significant vehicle servicing on the surface is planned, the transition to the permanent stage must be made. This will occur regardless of the current stage. If the early stage is the current one, the temporary stage may be skipped altogether. If the facilities needed to handle the permanent operations are not available, they must be provided. These facilities include surface transportation systems for both crew and cargo.

### 6.2.4 Other Factors

Other factors tend to change detailed aspects of site development such as when a particular equipment item is needed. Many of these other factors can be related to base growth but are treated here because of their specific nature. For most aspects of lunar launch and landing operations for the Phase II lunar base, the use of equipment shared with other lunar base functions is possible.

When a pressurized transfer vehicle is provided on the lunar surface, the need for transfer tunnels will arise. The stage of development and the design of the tunnel are related. If temporary pads are in use, one type of tunnel is indicated, while if reusable pads are present, another simpler design may be possible. More detailed discussions are provided under the Facilities Conceptual Design section of this report.

Flight vehicle design may also affect the equipment needed on the surface. Changes in flight vehicles may eliminate the ability to use shared equipment such as cranes and cargo transporters for landing and launch facilities. Specifically, the volume and mass of cargo elements may indicate the need to transition to dedicated cargo unloaders and transporters. The configuration of the lander and cargo bay may also indicate the need for a change of systems.

The nature of long-range surface transport may affect the nature of facilities. Some scenarios for surface transportation include the use of ballistic flight vehicles. Because these are reusable flight vehicles, servicing on prepared level pads may be indicated.

## 7.0 LAUNCH AND LANDING SITE CONCEPTUAL DESIGN

The following conceptual design is presented to show how the concepts discussed in this report may be applied to one particular scenario. The scenario chosen has been presented in detail in the surface operations report of the Lunar Base Systems Study.

The conceptual design is characterized by slow development of landing facilities. The need for particular equipment by the landing facility is almost always preceded by the need for the equipment by other lunar base operations.

### 7.1 BASE DESCRIPTION

For clarity, the following is a brief description of the base and its growth. The base has a broad scope of objectives including sciences, technologies, and resources. Habitation appears to be a minor objective and consequently base growth develops over a number of years. Throughout, considerable attention is devoted to science and technology objectives.

The first year, 1999, has only one piloted mission to the surface, and site certification along with some site engineering work is performed. Unpressurized rovers are provided during this year. Next, 2000, involves site engineering and placement of the first shelter facility.

2001 is the year that the shelter becomes inhabitable and the first base module is emplaced. In this year, after the fifth piloted mission, the base may be occupied. Mission surface stay duration is extended from 8 days to 24 days.

In 2002, a pilot resource plant is delivered and begins operations. In addition, pressurized rovers arrive at the surface. Base building continues throughout this year and throughout 2003.

The year 2004 is marked by further base growth and the development of full scale resource utilization facilities.

Finally, 2005 marks the end of the temporary occupation and the beginning of permanent occupation. The base itself is completed and facilities for fueling flight vehicles are added and finished. 2005 is the last year of the Phase II lunar base.

### 7.2 LAUNCH AND LANDING FACILITIES

The following describes, on a mission-by-mission basis, the lunar landing facilities as they relate to the base described above. Only piloted missions are discussed. Cargo missions occur at intervals between piloted missions.

#### 7.2.1 Year 1999

Mission 2 is an 8-day mission involved with site certification and preliminary site engineering. The landing takes place on a completely unprepared landing site next to the base. Only unmanned precursor site surveys provide surface data. The crew will live and work out of the flight vehicle. Surface transportation is available from previously landed rovers. The crew will place navigation aids and select and mark landing pads near the base for the next missions.

7.2.2 Year 2000

Mission 4 is an 8-day mission primarily involved with site engineering work. The crew lands at the site selected in the previous mission and lives and works out of the vehicle. They unload equipment to be used as construction and cargo unloading systems. Two more landing sites near the base are selected and marked. Before leaving, the crew protects the new equipment from blast products of future landings.

Mission 6 is an 8-day mission that emplaces a base shelter. The crew lands at the site selected in the previous mission and lives and works out of the vehicle. They unload a large cargo, select and mark three more landing pads near the base and, before leaving protect the equipment from blast products.

There may be sufficient base equipment to justify selection of remote pads for the next missions. However, since the crew will still live in the vehicle on the next mission, it is anticipated that the travel time to and from the pad for each EVA would be too time consuming. Emergency return to the vehicle would also be precluded. Consequently, local sites are chosen and the base equipment must be duly protected.

7.2.3 Year 2001

Mission 9 is an 8-day mission that finishes shelter setup. A previous mission provides a spare ascent vehicle. It is anticipated that the crew will use the spare vehicle to allow rotation. Consequently, after landing the crew transfers to the spare vehicle and lives and works from the vehicle for the duration. They unload large base items from previous cargo missions and select and mark two landing pads near the base. Before leaving, they set up monitoring and power connections for the vehicle in which they arrived and protect it and other base equipment from the blast of the next lander. The facilities for vehicle power and monitoring must be provided by this time.

Mission 11 is a 24-day mission in which the base begins to be occupied. The crew lands at pads selected during previous missions and moves to the base as soon as possible. Some large base element cargo is unloaded before this can occur so some work out of the lander must be done. The crew sets up monitoring and power connections for the lander in which they arrived and check out the vehicle in which they will leave. The crew selects and marks two remote landing pads for subsequent missions and protects base equipment from the blast of their launch.

This mission is a milestone in landing facility as well as base development. After this, landings will take place at remote sites. The base is left with eleven landers in its near vicinity, assuming single-stage vehicles are not yet used.

After this mission every crew will set up power and monitoring equipment for their arrival vehicle, check out their departure vehicle, and transfer to the base for the rest of the 24-day mission. These activities will no longer be included in discussions until they change.

Mission 13 is a base building mission. The crew unloads a large cargo and transfers it to the base. They select and mark two more remote landing pads. When leaving they will protect the equipment they leave at the landing site such as the unpressurized rover for transfer to the base.

Transfers of crew to base will be by EVA since no pressurized method is available. This may be restrictive since four of the available twelve EVA's will be needed. Mission planning will have to work out appropriate EVA's so as not to waste the extra time.

### 7.2.4 Year 2002

Mission 16 is typical of the previous base building mission except that a resource plant is delivered. It is possible that surface stabilization products or bi-products from the plant can begin to be stockpiled or used for roads between the base and landing area.

Missions 18 and 20 are typical base building missions during which no real change in landing operations occur.

Mission 22 is different only in that pressurized surface vehicles are delivered. Some IVA temporary crew ingress/egress will occur during this mission. As a result, pressurized transfer systems will need to be present along with the rovers. This mission will be a turning point to allow more flexible planning of EVA and easier access to monitoring and fault correction of ascent vehicles. Since no hard design of the transfer system is available, it is assumed that the unprepared landing sites are not a problem. If the design must have alignment between the rover and lander, prepared reusable pads may be needed. Unprepared pads are baselined at this time.

### 7.2.5 Year 2003

Mission 26 is a typical base building mission. Missions 30, 31, and 32 are science missions with operations typical of base building missions except without cargo operations.

### 7.2.6 Year 2004

Missions 34 and 36 are typical base building missions. Some of the efforts involve the setup of resource utilization facilities.

Mission 38 is a turning point mission. All the activities are similar to base building missions with two additions. A cryogenic storage facility is installed at the landing site. Since fuel transfer and vehicle servicing will follow soon, the crew will prepare two of the four reusable landing pads.

By the end of this mission, the remote site will have over twenty landers assuming expendable stages are still in use. Future missions will land on permanent pads.

Mission 39 is almost exactly the same as Mission 38. Two more permanent pads are developed to complete the permanent landing pad area. Operations do not yet need to include removal of vehicles from the pads. This fact is fortunate since mission duration is still only 24 days and surface time is still at a premium.

### 7.2.7 Year 2005

This year marks the commencement of permanent base occupation. There will be four missions of 180-day duration. Since there is overlap in crew stays, mission by mission planning becomes less important.

Flight vehicle removal equipment will be needed early in the year and vehicle servicing equipment will be needed by the end of the year. Throughout, low mass landing facility refinements may be appropriate such as permanent vehicle monitoring and power connections.

Mission 42, the first mission of the year and the first permanent occupation, mainly performs some base building activities. Before the next mission arrives, the crew will have to clear and refurbish the landing pads. Two of the pads, those which have expended cargo landers, can be cleared. There will be a departure vehicle and an arrival vehicle on each of the two remaining pads. Since this is the first time flight vehicles will have to be moved from the pad, equipment to accomplish this activity and an area to place the landers will be needed.

Missions 44, 46, and 47 continue to perform the same general activity described for Mission 42 except that equipment and disposal areas will already be defined. Through 2005, landing facility cryogenic storage and transfer facilities will be emplaced. Landing facilities, being mostly emplaced in 2004, will be finished and the more refined equipment will be included. In this scenario, expendable flight vehicles are still in use. At the end of the year, the Phase II lunar base stops and the Phase III operation begin. Reusable landers are the first important feature of the new operations so servicing and fueling facilities will be needed at the end of 2005.

# 8.0 CONCLUSIONS AND RECOMMENDATIONS

## 8.1 PRIMARY CONCLUSIONS

The results of this study may be summarized by the following primary conclusions. These conclusions fall into four basic categories, dependence of landing and launch facilities on the lunar base scenario, the effects of lander engine blast, design of landing pad, and equipment and facilities needs.

### 8.1.1 Scenario Dependence

Scenario dependence refers to the effects of the lunar base itself on landing facilities. The major emphasis of the base, the rate of emplacement of facilities, and the design of the flight vehicle will all play major roles in the requirements for facilities.

Base emphasis deals with the actual intended purpose of the lunar base itself. This generally falls into one of four categories: science, resource, habitation, or technology development emphases. The relationship to launch and landing facilities defines the need for permanent, leveled, reusable pads due to major export traffic. A base with a science emphasis is characterized by the need for logistic support and the deliveries of science and construction equipment whether lunar or astronomical science is studied. Because the exports will be small samples which can easily be loaded on piloted vehicles, permanent landing pads may never be required. Resource utilization bases will be characterized by eventual exports of large amounts of materials such as rocket propellants. When this export becomes significant, permanent landing pads will be needed to facilitate cargo loading. A habitation base which will have needs similar to a science base will never require permanent landing pads. The needs of a technology development base are difficult to establish since the actual activities are not well characterized.

The rate of facilities growth at the base will affect two aspects of when landing facilities will be needed. First, the sooner the base can support habitation, the sooner the landing pads will be moved away from the base itself. Next, the sooner surface stay times increase, the sooner setup and refurbishment operations for the permanent pads can be justified.

Flight vehicles will affect pad designs based on the size of their engines and the amount of reusability they incorporate. Generally, the size of the engines will define, due to blast effects, the distances between the pads and between the pads and facilities such as the base itself. In addition, the protection of equipment close to the pads from blast will be governed by the size of the engine. Reusable vehicles which require significant surface servicing will need level surfaces and permanent pads to facilitate the operations. Thus, when surface servicing becomes significant, permanent pads will be needed.

### 8.1.2 Blast Effects

The effects of engine blast are significant. While they are not critical or life threatening, they must be considered. Equipment within 50 meters of a landing may experience severe damage due to the impact of fairly large grains of lunar soil. Between 50 and 250 to 400 meters, glass surfaces can be severely damaged after just one landing and metal surfaces will be damaged significantly after several landings. Surfaces that are 1 to 2 kilometers away can experience some damage but generally after numerous landings. Optical quality glasses and reflective surfaces should be protected during landings.

### 8.1.3 Landing Pad Design

Landing pads can be designed without general regard to the specific landing site because overall lunar surface conditions are fairly uniform across the entire lunar surface. Specific examination of each site must be done to ensure the base and near-base area do not include any major landing obstacles. Landing pads, whether prepared or not, should be about 100 meters across. The area just outside this circle to 200 meters across should not include any major obstructions such as boulders or expended landers. The area from the 100-meter radius to a distance of 250 to 400 meters should be clear of unprotected equipment.

Prepared pads can be covered with lunar-derived gravel to stabilize their surfaces. This gravel may be sifted out of lunar soil or may be available from some resource processes.

### 8.1.4 Equipment and Facilities Needs

With few exceptions, lunar landing facilities and equipment are present on the lunar surface for other reasons before they are needed for landing operations. In lunar base studies, landing facilities have been assumed to use equipment delivered to the base for other purposes. This assumption has been verified by the current study. As long as rapid development of cargo producing and exporting resource plants or significant surface-based flight vehicle servicing systems are not part of the plan, landing equipment and facilities are not major drivers of delivery schedules and mission plans.

## 8.2 RECOMMENDATIONS

This report is the result of a short study. Certainly, much more work is required before the needs of launch and landing facilities can be fully appreciated.

Generally, more study is required for the subjects covered in this report. Some of the specific effects and designs must be developed and verified to a much greater extent than they have been at this time. Also, since this study was limited to the initial lunar base, the facilities needed for extensive permanently occupied or Phase III bases have only been reviewed in a cursory fashion. The launch and landing facilities of a Phase III need to be studied in detail.

The following paragraphs detail some specific recommendations for further study. These recommendations follow the subjects covered within the report itself.

### 8.2.1 Surfaces

The lunar surface is fairly well characterized at this time from a topographic and surface property point of view. To provide detail to the specific effects of surface properties, a future study should be performed which places various lunar bases at specific sites. The effects of specific terrain features can be examined for various sites so general requirements for handling these features can be developed. Site layout and planning should be done in detail at specific sites. The knowledge of what features must be avoided and what features are advantageous will provide details of the information needed from precursor orbital imaging and on-site surveying.

### 8.2.2 Vehicle Interactions

The effects of lander engine blast proved to have significant and far-reaching influence on the design of the lunar base as well as the launch and landing facilities. The calculation of these effects was done as rough order of magnitude only. They should be reviewed and performed in a rigorous manner. The effects of scaling the plume from a small RCS engine to a large descent engine could be large, so the plume must be characterized more specifically for the larger engines. The interaction of the engine exhaust and the surface will have major impacts on the characteristics of the plume and should be examined in detail. The mechanics surrounding the lofting of particles and their subsequent ejection were done very roughly and need further study. Finally, as a result of the detail on the mechanics of the plume, particle, and surface interactions, further detail should be provided on the expected distribution of particle sizes and the particle flux. Taken together, all the enhancements to blast effects can provide more reliable estimations of damage from ejecta.

Navigation system interactions should be examined in greater detail. The distances between the pads and the base and between the pads themselves depend very heavily on the possible errors in landings caused by navigation system operations and failures. Site selection must be done based on the acceptability of surface features within an area defined by the worst case of failures in updates to the vehicle navigation system. To perform more detailed examinations, navigation accuracies for the best case must be known as well as the inaccuracies resulting from the failures of various navigation systems. Failures of various other lander systems, such as engine out on multiple engine landers, must be included to provide the possible dispersions, even with perfect navigation system operation. A descent simulation may be required for this work.

### 8.2.3 Operations

The operations surrounding launch and landing facilities have only been reviewed in a general way. Future studies should provide detailed operations plans and requirements for specific facilities and equipment items. Operations plans should include work-around plans for partial failures of subsystems and safety precautions. These operations play significant roles in the selection of one concept over another.

Crew rescue operations have not been addressed here. They can be major drivers in systems designs. For example, the removal of crewmembers from landers in the event of a fire on the pad could present major design drivers for pressurized transfer tunnels. These operations and the issues surrounding them should be addressed in future studies.

### 8.2.4 Design Definitions

In general, conceptual designs and definitions should be provided in greater detail than provided here. Specifically, the structural properties of lunar-derived gravel should be analyzed to verify that it can be used for surface stabilization. Concepts for various options of equipment items should be developed in detail so trade studies covering mass, power, operations, technology requirements, logistics requirements, reliability, safety, and other issues can be performed in detail.

### 8.2.5 Site Development and Conceptual Designs

The development of lunar launch and landing facilities has been examined in this report for Phase II, the temporarily occupied base. The dependence of these facilities on the various possibilities for the Phase II base has been studied and applied to the conceptual design for one particular scenario. The conceptual design for several other scenarios should be performed to reveal hidden dependencies.

Further, the conceptual designs should not be limited to temporary occupation. Site development plans and conceptual designs should be done for various Phase III bases. Design of advanced Phase III facilities may reveal undiscovered design issues for systems that will be in place at the Phase II base. Requirements for advanced facilities may present new applications and drivers for surface construction and resource utilization concepts. Phase III launch and landing facilities will be goals for Phase II system evolution and it is vital that facilities to handle extensive and complex lunar base operations such as major propellant exports, bulk shielding material export, and flight vehicle overall and parts recycling be defined. The resulting broad picture of lunar launch and landing facilities will be a major asset to overall lunar base planning.

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