CR # 172105

# Lunar Surface Construction & Assembly Equipment Study

LBSS

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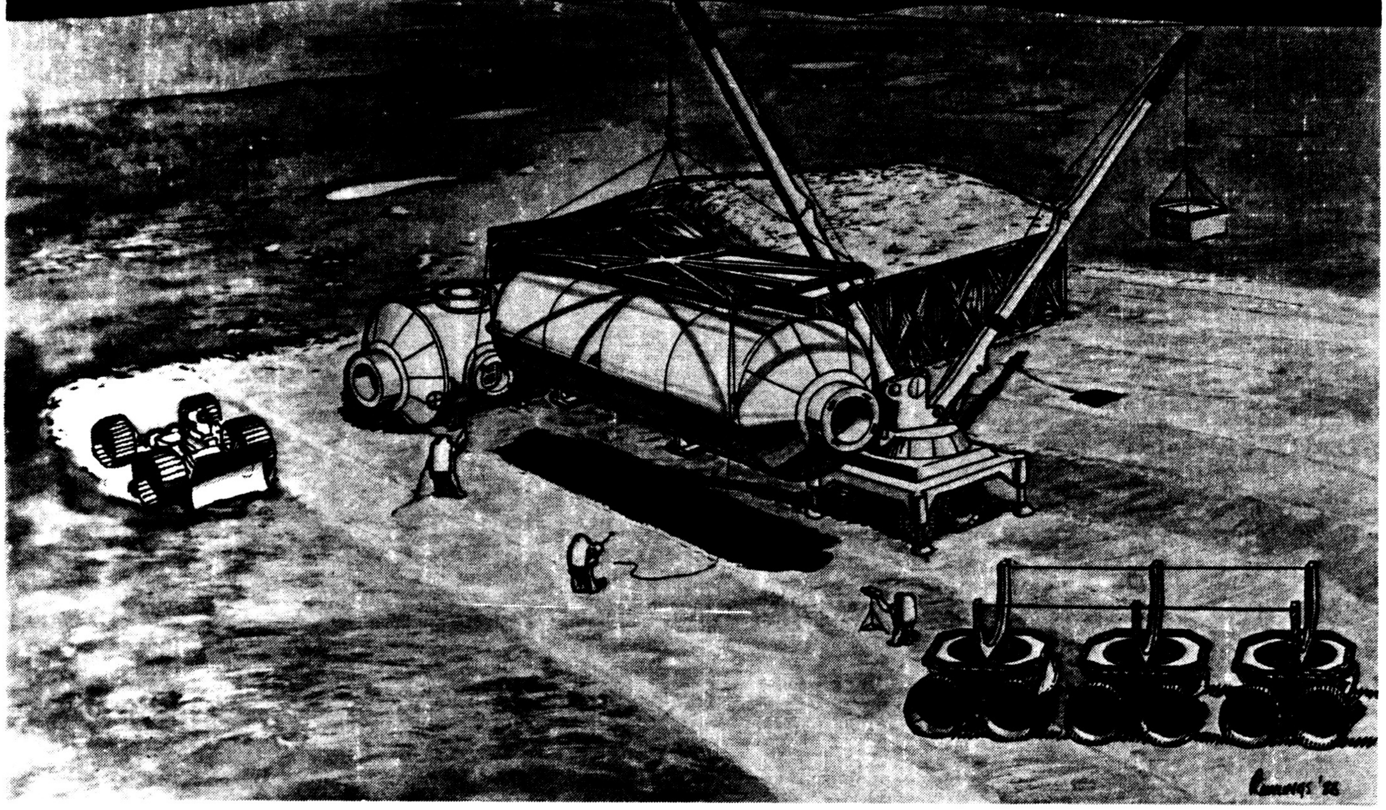

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# Lunar Surface Construction and Assembly Equipment Study
## Lunar Base Systems Study (LBSS) Task 5.3

**Prepared under NASA Contract NAS9-17878 for the**
**Advanced Programs Office**
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**By**
**Eagle Engineering, Inc.**
**Houston, Texas**
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## Foreword

The Lunar Surface Construction and Assembly Equipment Study Task was performed as part of the Lunar Base Surface Systems (LBSS) Support Contract which is a NASA Johnson Space Center (JSC) study intended to provide planning for a Lunar Base near the year 2000. The task personnel developed a set of construction and assembly tasks required on the lunar surface, determined different concepts for equipment applicable to the tasks, and identified leading candidate systems for future conceptual design. Data on surface construction and assembly equipment systems are necessary to facilitate an integrated review of a complete lunar scenario.

Dr. John W. Alred was the NASA JSC technical monitor for the contract of which this study was a part. Dr. Alred and Ms. Ann L. Bufkin were the NASA JSC task managers for this study.

Mr. William R. Stump was the Eagle Engineering, Inc. (EEI) project manager for the contract of which this study was a part.

Mr. William L. Davidson and Mr. Eric L. Christiansen were EEI co-managers for this particular study. Other Eagle participants included Mr. Stump and Mr. John A. Euker who made technical contributions, and Mr. R. Patrick Rawlings, Mr. Doug McLeod, and Mr. Michael Stovall who provided illustrative support.

In addition, Mr. Walter W. Boles of the Large Scale Programs Institute in Austin, Texas made technical contributions to Sections 6.2 and 6.3.

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## List of Abbreviations

| | |
|---|---|
| A/L | Airlock |
| ALS | Advanced Launch System |
| APC | Auxiliary Power Cart |
| bcm | bank cubic meters |
| BWE | Bucket Wheel Excavator |
| cg | Center of gravity |
| cm | centimeters |
| CNDB | NASA Headquarters' Civil Needs Data Base |
| D | Diameter |
| EMU | Extravehicular Mobility Unit |
| EST | Experiment and Sample Trailer |
| EVA | Extravehicular Activity |
| FEL | Front-End Loader excavator |
| fpm | feet per minute |
| ft | feet |
| $GH_2$ | Gaseous Hydrogen |
| $GO_2$ | Gaseous Oxygen |
| H | Height |
| HTU | Habitation Trailer Unit |
| ISRU | In Situ Resource Utilization |
| IVA | Intravehicular Activity |
| kg | kilograms |
| km | kilometers |
| kW | kilowatts |
| kWh | kilowatt-hours |
| L | Length |
| lbs | pounds |
| LBSS | Lunar Base Surface Systems |
| LEO | Low Earth Orbit |
| $LH_2$ | Liquid Hydrogen |
| LOTRAN | Local Transportation Vehicle |
| $LO_2$ | Liquid Oxygen |
| LRV | Apollo Lunar Roving Vehicle |
| m | meter(s) |
| MET | Apollo Modularized Equipment Transporter |
| MOSAP | Mobile Surface Applications Traverse Vehicle |
| MSDB | Missions and Supporting Elements Data Base |
| mt | metric tons (1 mt = 1000 kg) |
| PCRV | Primary Control Research Vehicle |
| PV | Photovoltaic solar array |
| RFC | Regenerative Fuel Cell power system |
| W | Width |
| Wh | watt-hours |

## 1.0 Executive Summary

This study was initiated to develop requirements for equipment to be used in constructing and assembling a permanently manned lunar base. A survey of lunar construction and assembly tasks was made and the requirements that these tasks place on construction equipment were identified. Major construction tasks that are most likely to occur during construction of a lunar base primarily involve cargo and soil handling operations, and assembly tasks such as:

- Unloading cargo from lunar landers.
- Transporting loads.
- Lifting and positioning loads.
- Preparing the lunar surface for a base site, landing pads, and roads.
- Providing quantities of lunar soil for habitat radiation protection.
- Assembling large structures.

Cargo handling system requirements include maximum cargo size and weight that must be moved, transportation distance to be traversed, and maximum lift and reach that these systems must have to unload and position the cargo. The maximum weight that cargo unloading and transporting equipment must be able to handle is fixed by the payload capability of the lunar lander which, for a lander concept recently studied (3), is on the order of 25,000 kg. Cargo size influences transporter size as well as road width. Sizes of a number of potential cargo elements for a lunar base are reviewed in this report. Cargo size has generally been constrained to the Shuttle payload bay envelope and the maximum cargo dimension identified was 4.5 m diameter x 14 m long. However, availability of heavy lift launch vehicles could allow delivery of payloads with greater diameter. Required lift and reach is dictated by lunar lander dimensions and cargo manifesting configuration.

Soil handling system requirements include the quantity of soil needed for radiation protection, and the required grade or slope and the amount of soil to be moved to prepare the base site, landing pads, and roads. Lunar terrain and crater density as well as the size of the base elements effects the magnitude of these jobs and the type of equipment needed. For instance, a partially buried, spherical, inflatable habitat would require such a large excavation that blasting will probably be necessary. This means a mobile drill unit will be needed. A base constructed of buried modules would probably not require deep excavations or blasting.

An important element missing from the requirements is the amount of time allowed in the schedule for completing the various construction tasks and the quantity of crew time (extra- and intravehicular activity time) available to support the activities. The schedule has a direct bearing on the required size and number of equipment, and can influence the type of construction equipment selected. More study is required to provide better task and timing definition.

The severity of the lunar environment (dust, vacuum, deep thermal and long diurnal cycles) and its remoteness indicates that lunar construction equipment should have the following design goals:

- Versatility: The systems can be made capable of performing multiple tasks by attaching different implements.

- Commonality: A modular design and common subsystem approach should be pursued where practical to reduce spares and maintenance requirements.

- Reliability: Dust-control, lubrication, and maintenance will be important design considerations.

- Low Weight: Although the equipment must be rugged for reliability, lunar materials (soil or rocks) could be used as counterweights and/or ballast to improve the stability and/or traction of the equipment and to reduce the machine's Earth launch weight.

- Telerobotics: The systems should be capable of both manual and teleoperated operation to potentially reduce EVA requirements.

Terrestrial construction equipment functions and capability are described. Several versatile machine combinations are commonly used on Earth construction sites, such as a backhoe front-end loader machine and a boom crane with multiple attachments for hoisting, grappling, and excavating.

A preliminary comparison was made of equipment options to perform the lunar construction/-assembly task set. More work is needed before an optimum set of equipment can be selected with confidence. The comparison did indicate that a possible set of equipment that could perform the lunar tasks would consist of the following major equipment elements:

- Mobile boom crane. The boom crane would be used to hoist cargo off landers and surface transporters, place soil over habitation elements for radiation protection, and provide a backup to the soil excavator. Crane attachments needed for these operations include a hoisting hook and cargo sling, dumpable soil transfer bucket, and a pile-driving ram to emplace anchors.

- Soil excavator and surface grader/leveler. Capability for excavating/grading could be provided by a front-end loader using a multi-application bucket which can be used as a shovel, bulldozer blade, or scraper. For deeper excavations, a front-end loader and a backhoe machine mounted on a single prime mover tractor is a possiblity. A compactor roll attachment can be provided for the prime mover tractor, and pulled to compact the lunar surface.

- Haulers. Several flatbed cargo transporters are required with mounting cradles for constraining large cargo elements. Soil transport trucks will be required if large soil volumes must be moved in short time periods.

- Auxiliary Equipment. Miscellaneous equipment needed for the job set includes a ramp or chute for contingency lander unloading operations, jacks for lifting a lander (in the event a lander needs to be moved), a local transportation vehicle (LOTRAN) for crew transport, and rock and soil drills for blasting large boulders or large excavations if needed. Requirements for blasting need more definition. A small drill rig could be attached to a prime mover to provide mobility. A drill device used for scientific coring could double as a construction tool.

It is recommended that conceptual designs be developed for several construction equipment elements that can accomplish a well defined set of tasks within a preliminarily specified schedule. Trade studies are required to better define the primary power source, propulsion means (wheels vs. tracks), and actuator/control systems (hydraulic, electric, mechanical linkage) for the lunar construction equipment. More detailed study of requirements for teleoperation of these vehicles from a lunar base and from Earth is also needed.

## 2.0 Introduction

The intent in this study is to identify requirements and options for surface construction and assembly equipment required in the second phase of a lunar base program. Phase II begins with the return of humans to the surface and ends when permanent habitation of the lunar base begins. This study does not assume a specific lunar base system or buildup plan. A wide range of system options and lunar base construction operations are explored, thus providing an equipment concept set which may endure through a number of planning scenario iterations. In addition, this approach is consistent with a basic criteria in construction to design equipment to be adaptable to a wide variety of applications.

### 2.1 Task Statement

The task statement specifies the study scope as follows:

> Develop a listing and description set of possible tasks (construction jobs) required for lunar surface construction and assembly of equipment, pertaining to the Lunar Base Systems Study (Phase II lunar base), but excluding those activities required for in-situ resource utilization (ISRU) or subsurface development. Jobs already identified include: pre-construction site preparation, lander payload operations (loading and unloading), regolith moving and excavation, radiation protection (bagging regolith versus frame and loose cover regolith), moving spent landers, habitat anchoring and back filling operations, winching or dragging, and contingency operations (EVA backup). Survey, compare, and summarize different concepts for surface construction and assembly equipment that have been used terrestrially or previously proposed for lunar and Mars operations, and are applicable to the above tasks. Leading candidate systems will be identified and recommendations made to be used in future conceptual designs.

### 2.2 Report Organization

The study activities have been planned to identify construction equipment types that could perform anticipated lunar surface construction and assembly tasks. Information from earlier lunar base studies (1-4, 7) has been complied in Section 3 which describes the nature of the guidelines, constraints, and requirements that surface operations and other equipment, such as landers, could place on the design of lunar construction/assembly equipment. Section 4 reviews capabilities of terrestrial equipment for construction and assembly activities. A set of generic lunar surface construction and assembly tasks is documented in Section 5. Equipment options for performing the lunar construction task set are presented in Section 6 and comparisons are developed in Section 7. A closing summary of the major findings of the study and recommendations is given in Section 8. References and an annotated bibliography of previous pertinent studies are given in Sections 9 and 10. Appendix A contains details and data used in the comparison summarized in Section 7. A list of construction equipment manufacturers is given in Appendix B.

## 3.0 Baseline Requirements

The design of equipment to be used in cargo handling, construction, and assembly operations on the Moon, will be influenced by lander dimensions (during unloading), the mass and size of the cargo elements, surface conditions, and the type of construction jobs anticipated. These factors will be described in more detail in the following sections.

### 3.1 Lunar Lander

Figure 3-1 illustrates a $LO_2/LH_2$ lunar lander conceptual design from a recent study (3). This lander is sized to deliver:

1) A 25 mt payload to the lunar surface, where the lander will be expended or will require refueling to allow ascent, or

2) 14 mt cargo down with inert mass returned to low lunar orbit (LLO) without surface refueling, or

3) A 6 mt crew module down and back to LLO (also without surface refueling).

The maximum cargo element mass that must be handled by lunar base construction equipment is therefore constrained to 25 mt. The 6 mt cylindrical crew module shown in Figure 3-1 is 4.3 m diameter x 2.7 m high (not including the docking module). Other cargo elements can be substituted for the crew module as will be described in Section 3.2. Provision for unloading cargo elements from the landers, transporting them, and emplacing them is required. The design of unloading equipment is governed not only by cargo characteristics (mass, volume, etc.), but also by the lander shape and size. Important dimensions for the illustrated lander are:

- Ground (bottom of footpads) to top of manned module (with docking adaptor) = 12.2 m.
- Ground to cargo platform (top of propellant tanks) = 8.2 m.
- Ground to center of exit tunnel = 3.9 m. (important for unloading small cargo elements
- Ground to lip of tunnel hatch = 3.3 m. from the crew module on manned missions)
- Ground to bottom of engine bell = 1.6 m.
- Distance across $LH_2$ tanks = 9.5 m.
- Distance across $LO_2$ tanks = 8.6 m.
- Distance across diagonal footpad centers = 13.0 m.
- Distance across adjacent footpad centers = 9.8 m.
- Footpad diameter = 1.4 m.

In Apollo, cargo elements were manifested and unloaded from the sides of the lunar lander (i.e. lunar roving vehicle, scientific experiment packages, etc.). For purposes of this study, major cargo elements are assumed to be manifested on top of the lander cargo platform. Lander dimensions will therefore impose requirements on the cargo unloading equipment. A recent lunar lander conceptual design (3) was used to define the following requirements:

- The equipment used for unloading must be capable of removing cargo that will be placed at least 8.2 m above the lunar surface. Actual distances from ground level to the top of the cargo will depend on cargo dimensions.

- The center of gravity (cg) of large (25 mt) cargos will be 4.3-4.8 m from the nearest edge of the lander (assuming that the cargo cg is placed in the center of the lander's cargo platform). Including lander footpad clearance, 5 meters is the minimum distance between cargo unloading equipment and the cg of large cargo elements (in the horizontal plane).

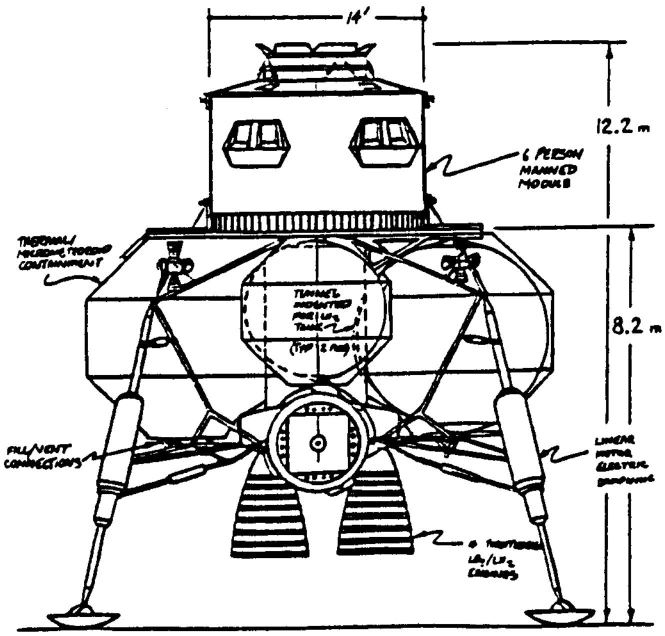
- Portions of unloading equipment that extend beneath the lander must be less than 1.6 m tall to eliminate potential contact with the lander engine bells.

It is also possible that an entire lander will have to be moved for maintenance, refurbishment, or disposal. The equipment used for such an event will be required to move the inert mass of the lander stage. This is estimated to be 9,800 kg for a lander without a crew module or 15,800 kg with a crew module (3). Both weights are empty weights (no main propellants).

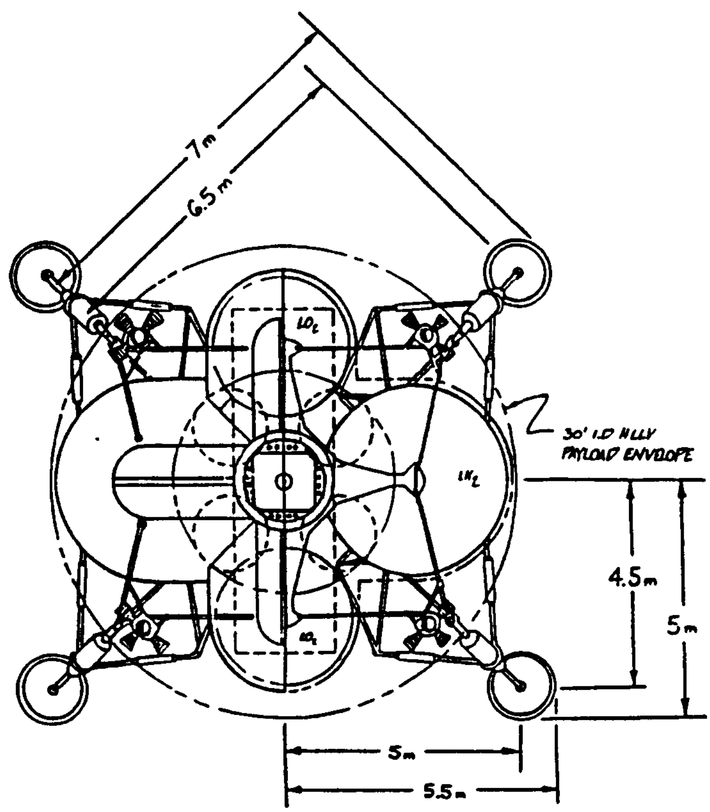
For comparison, the Apollo Lunar Module (LM) was 5.87 m tall (from ground to top of ascent vehicle, 2.97 m from ground to top of descent stage), 6.14 m across adjacent footpads, and 9.07 m across diagonal footpads (3).

**Figure 3-1.** Single Stage $LO_2/LH_2$ Reusable Lunar Lander (Ref.3)

Side View




Top View



## 3.2 Landed Cargo

Lunar unloading and transportation equipment will be required to handle various cargo elements as described in the following sections.

### 3.2.1 Bulk Cargo

Maximum mass of bulk cargo will be limited to the payload capability of the lunar lander or 25 mt (see Section 3.1). Lunar cargo elements are typically assumed to fit within the Shuttle Orbiter payload bay envelope, and bulk cargo would therefore have dimensions less than 4.6 m diameter x 18 m long. Larger payload sizes, up to 12 m in diameter, might also have to be handled since a heavy lift launch vehicle will most likely be available during a lunar base construction program. Some of the heavy lift vehicles currently under study are the Shuttle C and Air Force Advanced Launch System (ALS) which have the following characteristics (59):

| | Shuttle-C | ALS | ALS (expanded) |
|---|---|---|---|
| Payload: | | | |
| Length (m) | 23.5 | 24.4 | 38.1 |
| Diameter (m) | 4.6 | 4.6 | 12.2 |
| Capacity (kg) | 57,168 | 49,900 | 72,595 |
| to Orbit: | | | |
| Inclination | 28.5° | 28.5° | 90° |
| Apogee x Perigee (km) | 407 x 407 | 278 x 148 | 278 x 148 |

### 3.2.2 Surface Transportation Elements

A recent study (1) of surface transportation defined several pressurized and unpressurized surface vehicles, with the following characteristics (described in more detail below):

| Vehicle | Mass (kg) | Dimensions L x W x H (m) |
|---|---|---|
| • LOTRAN | 550 | 5.1 x 2.0 x 1.4 |
| • MOSAP Research Veh (PCRV) | 3,500 | 8.4 x 5.5 x 5.7 |
| • Power trailer (APC) | 1,380 | 4.1 x 3.5 x 2.4 |
| • Experiment trailer (EST) | 390 | 4.0 x 4.0 x 2.1 |
| • Habitation trailer (HTU) | 3,400 | 8.4 x 5.5 x 5.5 |

LOTRAN (local transportation vehicle) is an unpressurized vehicle suitable for local lunar base EVA tasks. LOTRAN provides short-duration (6 hr) 50 km range (100 km roundtrip) mobility for four crew with 130 kg payload or two crew with 490 kg payload (850 kg gross payload). Overall dimensions are given above with seats and antenna stowed, although because the chassis of the vehicle is articulated in two places, the vehicle can be manifested on the lander in shorter sections by detaching the rear trailer section. The LOTRAN configuration is illustrated in Figure 3-2.

MOSAP is a pressurized, mobile surface applications traverse vehicle intended for a variety of surface transportation missions ranging from short-duration local trips and transfers to long-duration traverses. The MOSAP is outfitted with the appropriate modular elements to suit the needs of a particular mission. For short duration missions (3 days or less), only a primary control research vehicle (PCRV) is required (shown in Figure 3-3). PCRV mass given above is without payload, EMU's, or crew.

For medium-duration missions (12 days, 1,000 km roundtrips), besides the PCRV, a supplemental power system and flatbed trailer would be needed. An auxiliary power cart (APC) used for the medium duration mission is shown in Figure 3-4. The cart provides 1,500 kwh of electrical energy from a $LO_2/LH_2$ fuel cell system. A drawing of the experiment/sample trailer (EST) is given in Figure 3-5. The size of the EST bed is somewhat arbitrary and can be altered with only small impact on overall vehicle mass.

Long-duration missions (42 days, 3,000 km journeys) will utilize the PCRV, APC, EST, and a second pressurized vehicle, the habitation trailer unit (HTU). The 7,000 kwh of energy required for the long-duration missions results in a heavier version of the APC, with a total mass of 5,150 kg (5.5 m long x 4.7 m wide x 3.4 m high).

### 3.2.3 Base Elements

The major base elements in terms of mass and size for some lunar base scenarios are the habitation elements (2,8). Assuming Space Station inheritance, the habitation elements consist of common modules interconnected by nodes. The dimensions and mass of Space Station modules are (9,10):

| Module | Dimensions (m) Diameter | Dimensions (m) Length | Mass (kg) |
|---|---|---|---|
| Habitation | 4.4 | 13.6 | 19,490 |
| Laboratory | 4.4 | 13.6 | 27,680 (includes 5,620 kg payload) |
| Node | 4.4 | 5.4 | 4,650 (average) |
| Airlock (A/L) | 3.7 | 3.4 | 3,740 |
| Hyperbaric A/L | 3.7 | 3.4 | 3,070 |
| Logistics (Press.) | 4.4 | 7.6 | 10,610 |

Because the laboratory mass is greater than the lander's payload capacity, certain experimental equipment for a lunar laboratory might be manifested on separate flights.

Power System

A recent conceptual design study of a lunar power plant defined a modular solar photovoltaic (PV) array and regenerative fuel cell (RFC) system providing 25 kW day and night (28). Dimensions and mass of the major power system elements are:

| | Dimensions (m) (D x L) or (H x W x L) | Mass (kg) |
|---|---|---|
| GaAs Solar Array Blankets | 4 rolls: 0.5 x 3 | 1,014 |
| Tanks: $GH_2$ | 3.81 m spherical diameter | 3,036 |
| $GO_2$ | 3.17 m spherical diameter | 1,815 |
| $H_2O$ | 2.07 m spherical diameter | 564 |
| Water in $H_2O$ Tank | | 4,927 |
| Fuel Cell | 0.9 x 0.45 x 2 | 215 |
| Electrolysis Cell | 0.76 x 3.8 | 560 |
| Radiator (6 $m^2$) | 2 x ? x 3 | 121 |
| Total 25 kW System | 3.81 m x 9.05 m | 12,252 |

### 3.2.4 Lunar Oxygen Pilot Plant Elements

A candidate process to extract oxygen from lunar materials is reduction of ilmenite ($FeTiO_3$) by hydrogen in a fluidized bed reactor operating at 900 to 1000°C to produce water and residual solids, iron (Fe), and rutile ($TiO_2$). The water product is subsequently electrolyzed to oxygen and hydrogen. The hyrogen is recycled to react with more ilmenite while the oxygen is liquefied and stored. Mass and size estimates for the major elements of a 2 mt/month $LO_2$ pilot plant were produced in a recent study (7). For a pilot plant using soil feedstock and operating during daylight only, a PV power system was sized to generate 146 kW and a RFC power system generates 9.6 kW (to make-up heat losses during the lunar night). An excavator and hauler mine and transport 327 mt of soil per metric ton of oxygen produced, and discard 326 mt of tailings per mt oxygen, in less than a quarter of the available daylight hours (7). They are oversized in order to perform multiple tasks around the base as described in another report (2). Most major process units are manifested in an Orbiter payload bay pallet as shown in Figure 3-6.

The major elements of the plant are:

| | Dimensions (m) (D x L) or (H x W x L) | Mass (kg) |
|---|---|---|
| Excavator | 2.3 x 2.1 x 3.9 | 1,968 |
| Hauler | 2.5 x 2.5 x 4 | 1,015 |
| Process Plant | 4.3 x 13.7 | 8,696 |
| PV Power System | 13.2 $m^3$ | 5,721 |
| RFC Power System | 4.3 x 7 | 3,285 |

**Figure 3-2.** Local Transportation Vehicle (LOTRAN) (Ref.1)

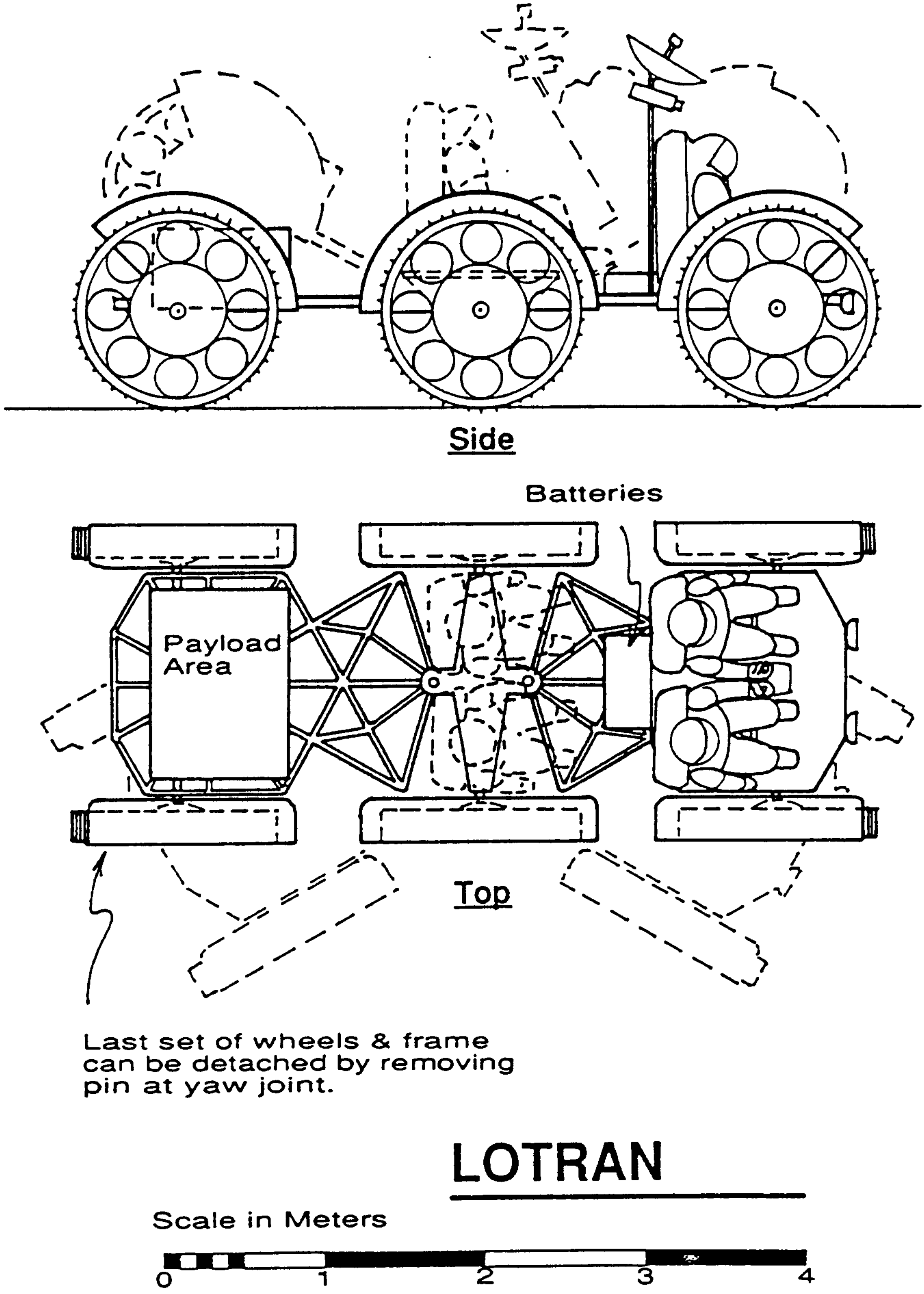


**Figure 3-3.** MOSAP Primary Control Research Vehicle (Ref.1)

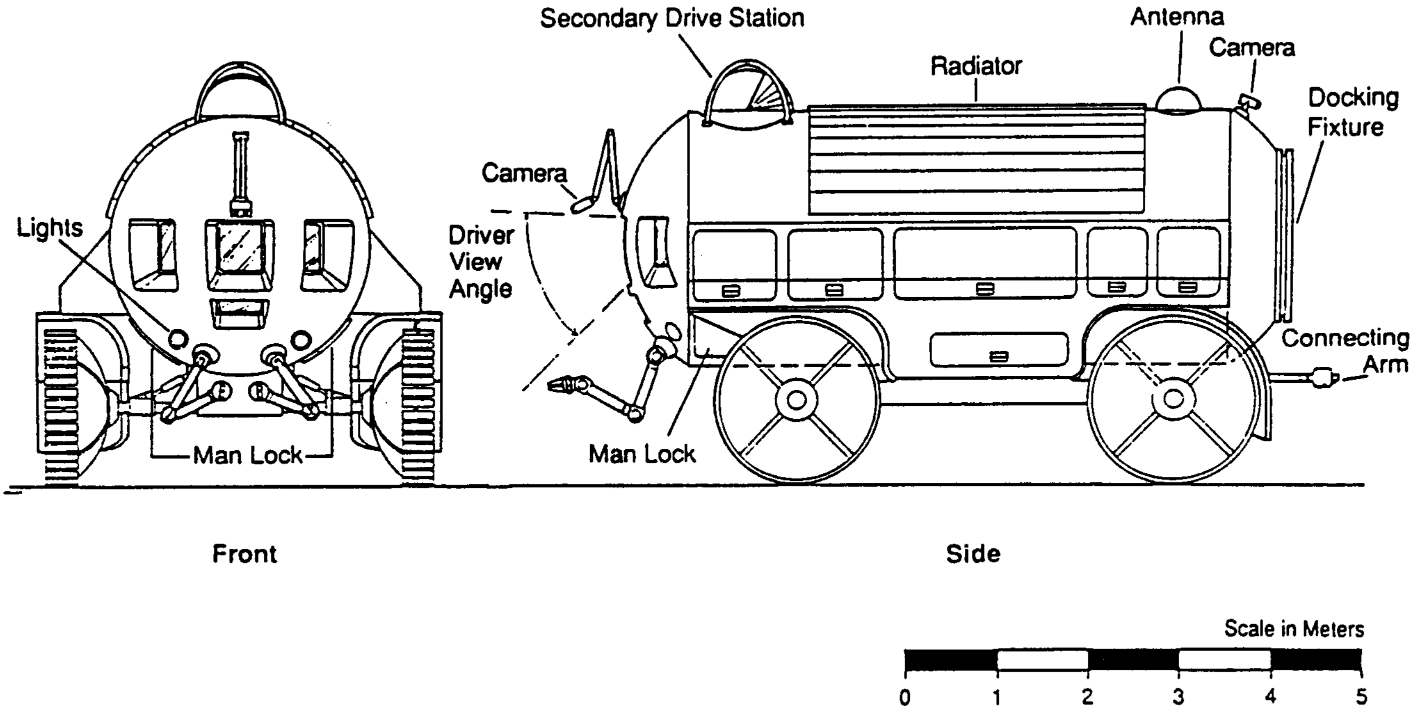


**Figure 3-4.** MOSAP Auxiliary Power Cart (Ref.1)

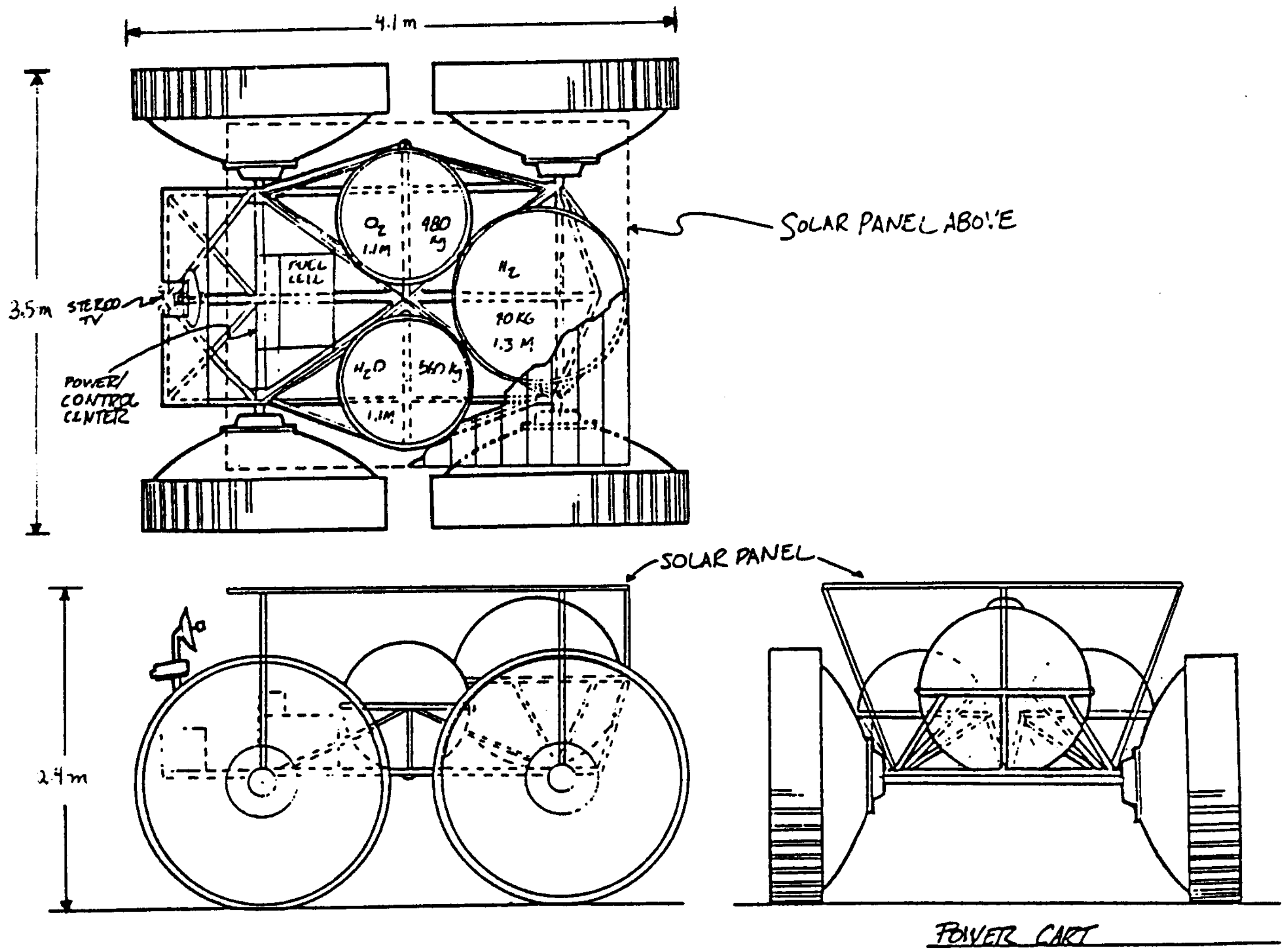


**Figure 3-5.** MOSAP Experiment and Sample Trailer (Ref.1)

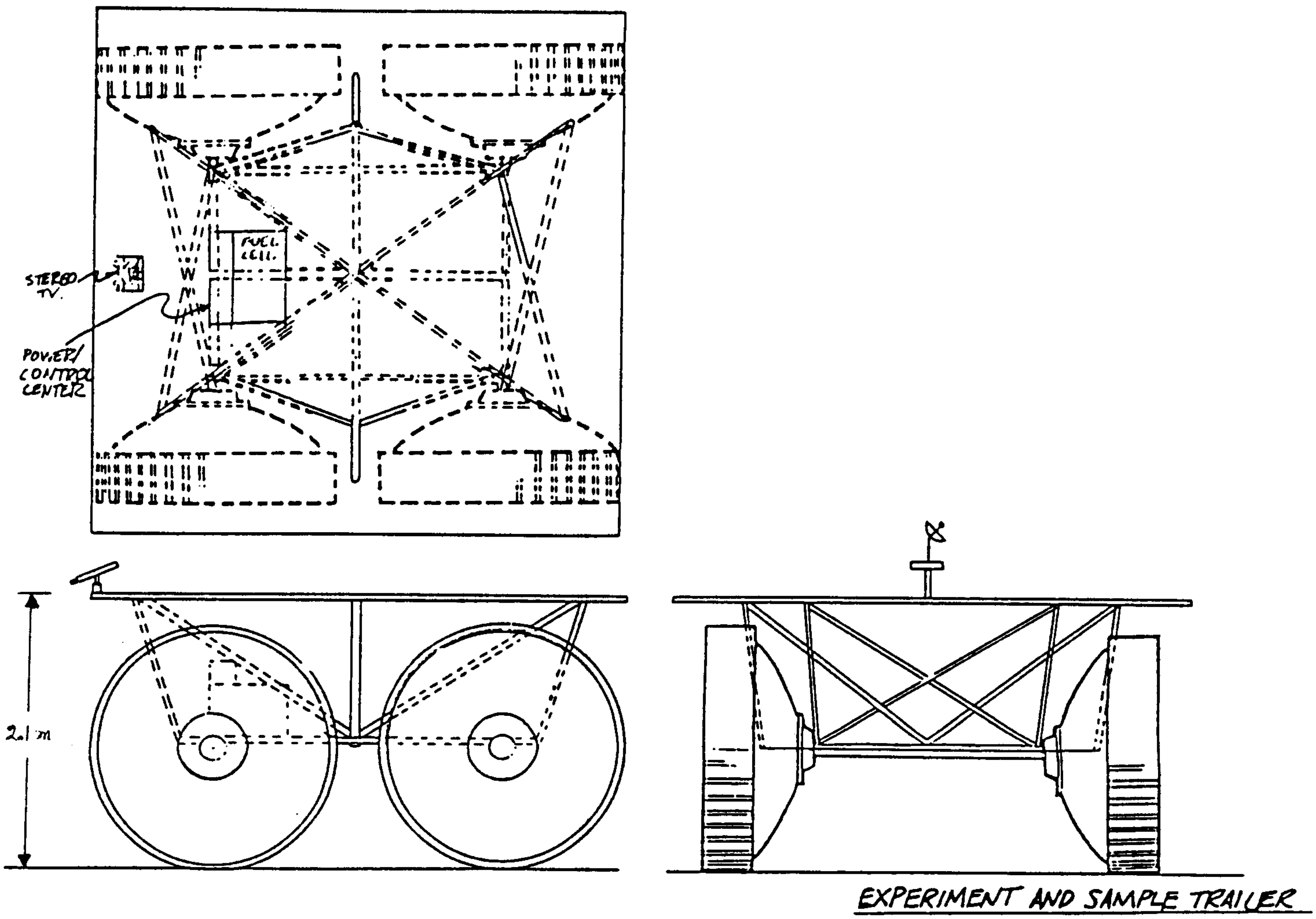


**Figure 3-6.** Lunar Oxygen Pilot Plant (Ref.7)

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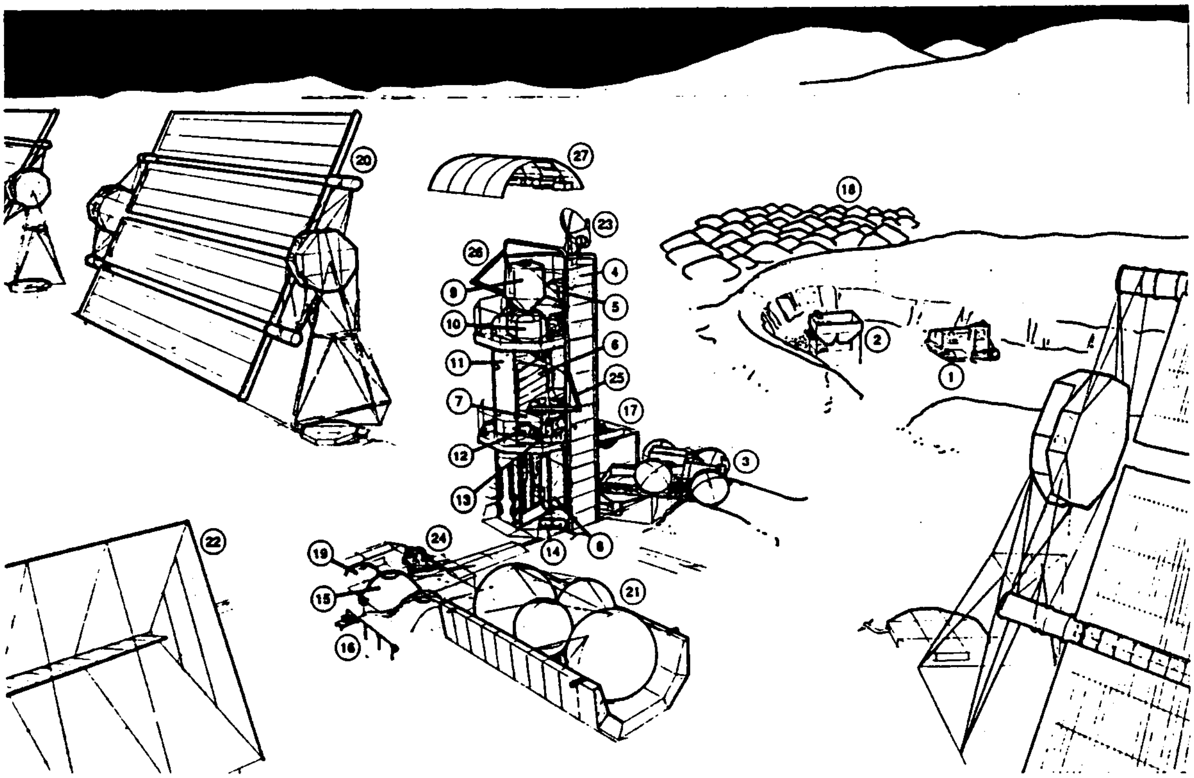


Location: Lacus Veris (87.5°W, 13°S)
View Facing North-East

1. Excavator (Front-End Loader)
2. Pit Scalper
3. Hauler
4. Support Structure (Payload Bay Pallet)
5. 3-Stage Crushing/Grinding Circuit
6. Vibratory Screen (Fines Removal)
7. Hold-up Bin
8. High-Intensity Magnetic Separator
9. Low-Pressure Reactor Feed Hopper
10. High-Pressure Reactor Feed Hopper
11. 3-Stage Fluidized Bed Reactor
12. Electric Gas Heater
13. Solid-State Electrolysis Cell
14. Oxygen Liquefier
15. Buried Oxygen Storage Tanks
16. Liquid Oxygen Loading Station
17. Tails Discharge Bin
18. Tailings Piles
19. Makeup Hydrogen Storage Tank
20. Photovoltaic Power System (Sun-Tracking)
21. Regenerative Fuel-Cell Gaseous-Reactant Storage Tanks
22. Radiator with Fixed Sun-Screen
23. Communications: High- and Low-Gain Antennas
24. Telerobotic Servicer on Lunar Surface Mobile Platform
25. Telerobotic Servicer on Remote Manipulator Arm
26. Spare Remote Manipulator Arm
27. Equipment Repair and Spares Storage Shed

### 3.3 Lunar Environmental Considerations

Considerable challenges are involved in the design of lunar construction/assembly equipment. They will need to operate reliably in a remote location with limited supplies of spares and maintenance support. These machines will need to be productive, efficient, low-mass, and rugged. The following sections describe lunar environmental conditions, including one-sixth gravity, vacuum, dust, and extreme temperatures, that will require changes in Earth design practice. Lack of certain Earth conditions, weather and wet/slippery soil conditions for instance, will improve lunar equipment performance and simplify design.

#### 3.3.1 Terrain

The terrain and bulk properties of the lunar surface and subsurface materials will impact the amount of work required to accomplish a particular task and the performance of many types of construction equipment.

Terrain Effects

The concentration of surface cratering can effect certain construction activity requirements, such as the amount of soil to be moved in a grading operation for a landing pad or road. Figure 3-7 presents a summary of crater count data used during the site selection process for Apollo 17 (31). The data shows that crater concentrations are higher in highlands regions (Apollo 14) than in old mare (Apollo 17) or young mare areas (Apollo 12 and the Apollo 17, Taurus-Littrow, landing site). Thus, more soil fill or grading will be required in highlands regions to prepare a smoothed surface. For determining crater density, the following equation relates N, the cumulative frequency of craters with diameter D and smaller (craters/$m^2$), to D, crater diameter in meters (60):

$N = 0.1\,D^{-2}$ (for $D < 40$ m in smooth mare, $D < 100$ m in rough mare, and $D < 1000$ m in some uplands)

Table 3-1 and Figure 3-8 illustrate the variability and average slope characteristics of various lunar areas. Slopes typically average 4-8 degrees over the shortest length measured (25 m). Note the higher average and standard deviations in highland regions reflect their greater roughness relative to the smoother mare and highland plains (Cayley formation). Some areas are rather rough. For example, the uplands near Glaisher would have approximately 16% of its areal surface with a slope varying by 18° or greater over 25 m long segments (one standard deviation from mean). Only 2% would vary by 27° or more over any given 25 m segment (two standard deviations). Surface slope effects the performance of construction vehicles and thereby their ability to complete certain tasks. Although low lunar gravity does not effect stability or gradeability to any great extent, the inherent stability and gradeability of each type of construction vehicle defines their slope handling capabilities. Stability varies considerably depending on vehicle configuration and other characteristics. For instance, bucket wheel excavators are usually limited to relatively flat surfaces (less than 10° or 17.6% slope) for stability while dozers can negotiate much steeper slopes. Gradeability is a measure of slope climbing ability (defined as the maximum slope that a vehicle can climb at constant speed). Crawler mounted dozers have gradeability rated to approximately 45° (100% slopes) while wheeled front-end loaders and trucks are limited to 7° (12%) slopes (11, p.31 & p.55). Some vehicles are equipped with booms (see Section 4) and can perform operations over relatively long lateral distances regardless of surface roughness and slope conditions. For instance, a typical operation might be to clear the bottom of a steep-walled crater or excavation of rocks and debris prior to emplacing a habitat. A dragline or crane equipped with a clamshell bucket that is positioned in a flat area near the lip of the excavation could perform the clearing operation, even though the body of the machine itself is not capable of traversing rugged terrain.

Surface and Subsurface Properties

The traction developed by lunar construction vehicles depends on the surface mechanical properties, as well as vehicle weight, horsepower, and gripping action of the wheel or track. Lunar surface soil properties are given in Table 3-2. Lunar soil has typical shear strength parameters of (33):

cohesion = 1 $kN/m^2$
friction angle = 35°

As shown in Table 3-2, the modulus of subgrade reaction for the lunar surface is typically 1000 $kN/m^2/m$ (3.68 psi/in). A pressure of 10 $kN/m^2$ (1.45 psi), which is approximately the pressure exerted by an astronaut's boot, would settle approximately 1 cm (0.39"). However in soft soil, such as encountered near the lip of some craters, penetration to 10 cm (4") could occur. In very firm soil, the same pressure would result in sinking to only 0.1 cm (0.04").

The degree of difficulty in excavating depends to a great extent on subsurface structure and, of course, on the excavation depth required by the task. Directly observable data of the subsurface structure of the Moon is limited to 3 m long cores obtained during Apollo 15-17. Seismic studies and radio frequency soundings probed deeper but only coarse strategraphic information was obtained, indicating the depths where sonic velocity and density changed. Table 3-3 and Figure 3-9 shows some of the lunar subsurface data. Since bedrock in mare regions lies only 3-5 m below the regolith surface, deep excavations may require drilling and explosives to break up underlying formations. However, crater events that penetrate the regolith may already have locally fractured and disrupted the underlying bedrock to a large extent. Highland sites will probably not require a drilling/blasting step for deep excavations, depending on the size of subsurface boulders. If drilling and blasting is done in highland regions to speed excavation, casing of the drill hole may be required to avoid collapse of the hole before the explosive is emplaced. Casing operations will result in a more time consuming drilling operation.

**Figure 3-7.** Size Distribution of Lunar Craters (Ref.31)

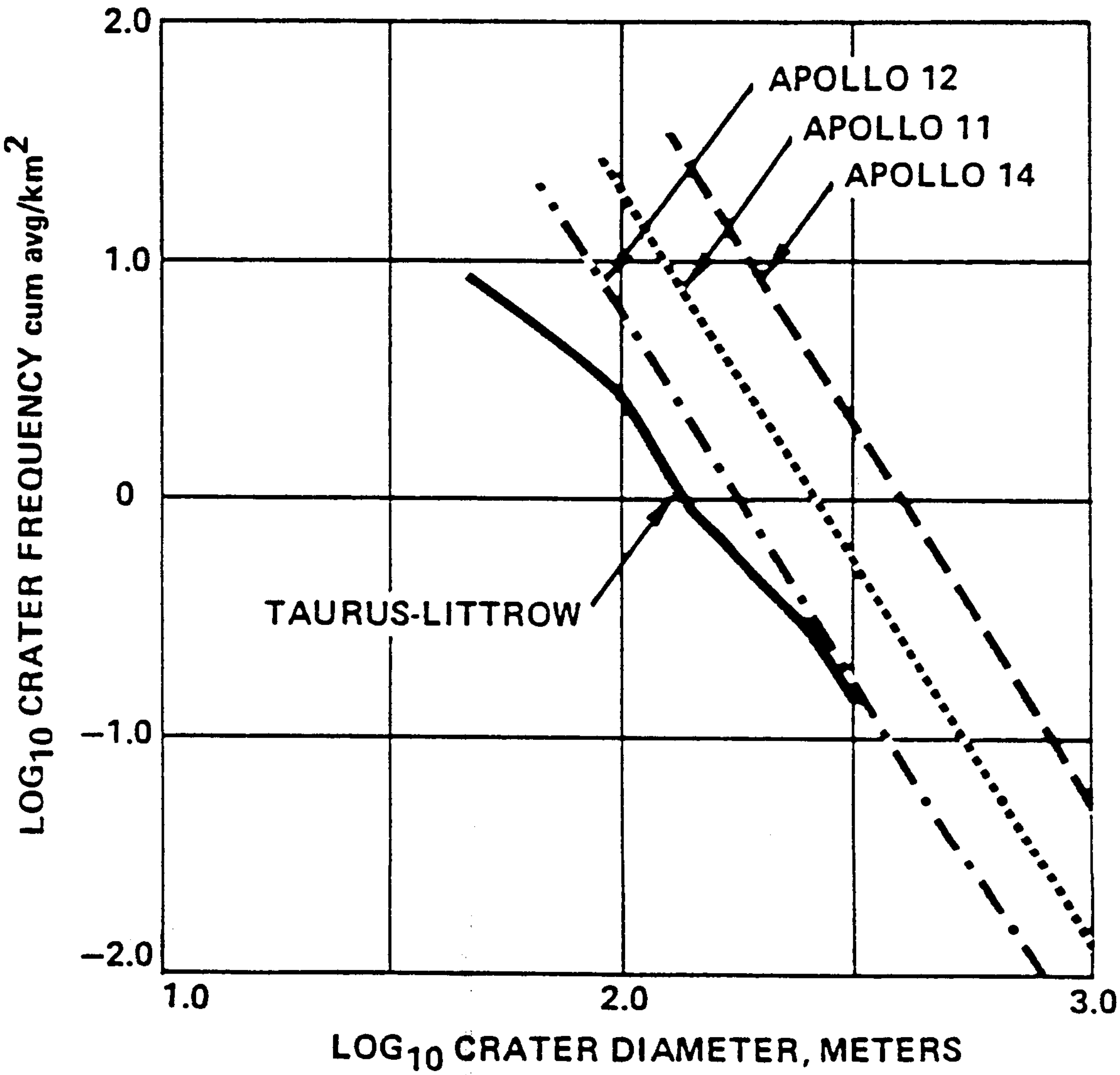


**Table 3-1.** Lunar Surface Slope as Function of Length of Segment Measured (from Ref.29)

| *Terrain type* | *Algebraic standard deviation, deg* | | | | | | *Mean absolute slope, deg* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *ΔL 25 m* | *ΔL 50 m* | *ΔL 100 m* | *ΔL 200 m* | *ΔL 500 m* | *ΔL 1000 m* | *ΔL 25 m* | *ΔL 50 m* | *ΔL 100 m* | *ΔL 200 m* | *ΔL 500 m* | *ΔL 1000 m* |
| **Mare Serenitatis** | 5.8 | 4.8 | 3.4 | 2.3 | 1.4 | 1.2 | 4.7 | 3.7 | 2.5 | 1.7 | 1.3 | 1.2 |
| **Mare Serenitatis** | 6.1 | 4.9 | 3.6 | 2.5 | 1.3 | .8 | 4.8 | 3.8 | 2.8 | 1.8 | 1.0 | .7 |
| **Cayley Plain** | 6.2 | 6.3 | 5.6 | 4.9 | 3.4 | 1.5 | 5.4 | 4.5 | 3.8 | 3.2 | 2.3 | 2.0 |
| **Uplands, near Proclus** | 6.4 | 6.0 | 5.0 | 4.3 | 3.2 | 2.2 | 5.4 | 4.6 | 3.9 | 3.3 | 2.6 | 2.1 |
| **Uplands, north of Vitruvius** | 7.8 | 6.6 | 5.9 | 5.5 | 5.2 | 4.7 | 6.2 | 5.5 | 5.1 | 4.9 | 4.7 | 4.3 |
| **Uplands, near Glaisher** | 9.9 | 8.8 | 8.2 | 7.8 | 7.3 | 6.7 | 8.4 | 7.9 | 7.5 | 7.3 | 6.9 | 6.4 |
| **Mare Fecunditatis** | - | - | - | - | 3.6 | 2.6 | - | - | - | - | 3.1 | 2.0 |
| **Uplands, near Censorinus** | - | - | - | - | 10.5 | 9.2 | - | - | - | - | 7.8 | 6.3 |
| **Littrow, landing site** | 4.5 | - | - | - | - | - | 3.8 | - | - | - | - | - |
| **Littrow, west of landing site** | 4.6 | - | - | - | - | - | 3.9 | - | - | - | - | - |
| **Hadley, landing site** | 6.8 | - | - | - | - | - | 5.7 | - | - | - | - | - |

**Figure 3-8.** Lunar Slope Frequency Distributions (from Ref.30)

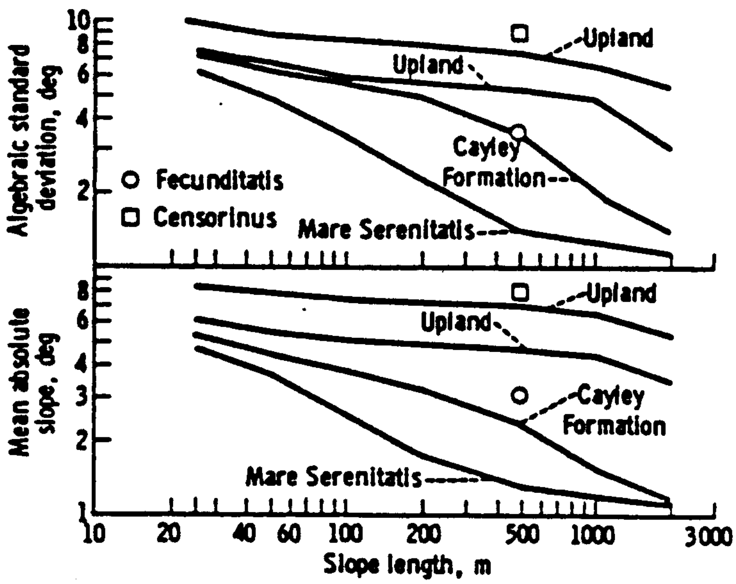


Table 3-2. Average Material Properties of Surficial Lunar Soil at Apollo 14-17 and Luna Landing Sites (from Ref.32)

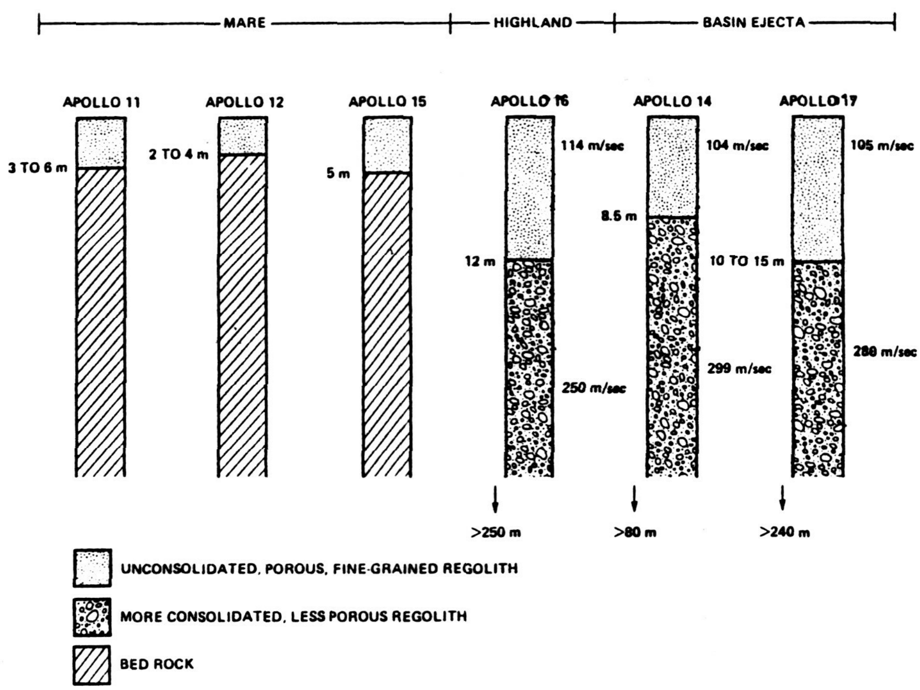
| *Soil consistency* | G,[a] *N/cm³* | *Porosity, percent* | *Void ratio, e* | $D_r$,[b] *percent* | $\phi_{TR}$,[c] *deg* | $\phi_{PL}$,[d] *deg* |
|---|---|---|---|---|---|---|
| Soft | 0.15 | 47 | 0.89 | 30 | 38 | 36 |
| Firm | 0.76 to 1.35 | 39 to 43 | 0.64 to 0.75 | 48 to 63 | 39.5 to 42 | 37 to 38.5 |

[a]$G$ = penetration resistance gradient.
[b]$D_r$ = relative density = $(e_{max} - e)/(e_{max} - e_{min})$, based on standard American Society for Testing Materials methods.
[c]$\phi_{TR}$ = angle of internal friction, based on triaxial compression tests.
[d]$\phi_{PL}$ = angle of internal friction, based on in-place plate shear tests.

Table 3-3. Best Estimates of Average Bulk Soil Density (from Ref.33)

| Depth Range (cm) | Bulk Density (g/cc) |
|---|---|
| 0-15 | $1.50 \pm 0.05$ |
| 0-30 | $1.58 \pm 0.05$ |
| 30-60 | $1.74 \pm 0.05$ |
| 0-60 | $1.66 \pm 0.05$ |

**Figure 3-9.** Depth of the Lunar Regolith at the Apollo Landing Sites (from Ref.34)
For Apollo 14, 16, 17 sites, seismic velocities of the upper units were measured and are shown at the sides of the columns.



### 3.3.2 One-Sixth Gravity

Lower gravity will have a pronounced effect on the design of many types of lunar construction equipment. For transportation machines (trucks, trailers, conveyors) low gravity can be an advantage in reducing structural mass. For other equipment types, such as excavators, low gravity can degrade performance by reducing traction.

Lunar trucks can be less massive than their terrestrial counterpart because most of the mass of the truck is usually devoted to structural support of the payload. Since an equivalent mass payload on the Moon will impose one-sixth as much structural load as on Earth, the mass of the truck can be reduced by approximately the same ratio (35). Over a wide range of capacities, the ratio of payload to empty vehicle mass for terrestrial trucks is approximately 1.3 (35 and Table 4-2). Thus, the ratio of payload to vehicle mass for lunar trucks could approach 8. For comparison, the Apollo lunar rover vehicle (LRV) had a mass of 218 kg and a loaded mass of 708 kg (1), which gives a ratio of payload to vehicle mass of 2.25. The LRV was a small vehicle. A larger lunar truck should be more efficient than the LRV and can utilize strong, light-weight composite materials. A lunar truck's payload to vehicle mass ratio could thus be expected to fall in the upper part of a range from 2.25 to 8.

The weight of a front-end loader (FEL) excavator (see Section 4.2), on the other hand, must counter-balance the weight of a fully extended, filled bucket. Because both the weight of the FEL and the weight of a full bucket decrease with gravity, the mass of a lunar FEL cannot be reduced when compared with an equivalent Earth FEL. The FEL must also be able to penetrate into the soil/rock bank it is excavating from (the "crowd" portion of the operating cycle). Penetration ability depends on the force the FEL exerts on its cutting tool (bucket) and the shape and orientation of the cutting tool, combined with the resistance offered by the formation it is excavating. Crowd force is a function of both traction (the force developed by a wheel or track as it acts upon a surface, expressed as usable drawbar pull for tracked vehicles or rimpull for wheeled machines) and machine inertia (function of speed and mass). Low gravity on the Moon tends to decrease traction. Thus, the FEL will require more ballast or reconfigured wheels/tracks to avoid performance degradation compared to a terrestrial counterpart.

The portion of the FEL mass that functions only as a counter-weight for a filled bucket or as ballast to increase traction could be replaced by locally derived materials (soil/rocks) in a lunar FEL design. This would decrease Earth launch weight. Other types of equipment might also utilize the same principal of using lunar soil as ballast or counterweight. Light-weight lunar cranes could use soil to counterbalance the payload while it is lifted (such as cargo or a clamshell load if the crane is used in an excavator role). Terrestrial bucket wheel excavators (BWE) (see Section 4.2) often use counterweights to balance the heavy weight of the digging wheel (which is usually substantial to increase its digging inertia and ruggedness). Mobile, rotary drills, used to drill blast holes for explosives placement, use the weight of the vehicle to exert sufficient down-hole pressure (or pulldown force) to allow the bit to cut properly. Since this force is lower on the Moon, drill performance will be degraded or greater mass will be required. The extra mass or ballast could be provided by lunar materials which would substantially reduce Earth launch mass.

### 3.3.3 Vacuum and Dust

The lunar vacuum and dust environments combine to present a considerable challenge for designing reliable, long-life rotating structures, seals, bearings, and lubrication. In addition, lunar dust can coat and degrade the performance of thermal control systems (radiators) and optics (such as cameras on teleoperated vehicles). Lunar soil particles are quite fine with an average particle size typically of about 0.08 mm (33). Because the particles are so fine and because they are electrostatically charged, lunar soil particles adhere and coat most exposed surfaces. Lunar dust particles would be very abrasive if they bypassed seals to contaiminate joints or bearings, resulting in short-lived components.

Metal-to-metal friction increases in hard vacuum making lubrication requirements even more important to reduce wear (36). Terrestrial liquid lubricants and greases will not work in lunar applications exposed to vacuum because volatiles will be lost (they essentially boil away). The life time of dry film lubricants are also limited (1). Certainly, substantial research and design effort will be required to develop long-lived rotating mechanisms and suitable lubricants for equipment in the lunar environment.

### 3.3.4 Diurnal Thermal and Lighting Environments

Lunar surface temperatures at the Apollo 17 landing site ranged from a maximum of 101°C (214°F) during the 14-day lunar day to a minimum of -153°C (-243°F) during the 14-day lunar night (60). Because of the insulating nature of lunar soil, subsurface temperatures (below about 10 cm) remain a relatively constant -20°C (-4°F) (37). Actual temperatures experienced by lunar equipment will also depend on the thermal properties of the equipment (surface coating absorptivity, emissivity). The effect of low temperatures is to embrittle metals, organic polymeric seal materials, and other materials. Lunar night-time operation of heavy construction equipment would not be preferred because it would result in increased wear and greater likelihood of equipment failure through brittle fracture of metal parts, unless provision for active thermal control was incorporated in the equipment design to maintain higher temperatures of key parts and surfaces. Night-time construction operations will also result in increased power requirements (over day operations) to provide high-intensity illumination of the construction or excavation site. Operations would probably proceed slower during the night, depending on the illumination level, to ensure safe operations around the construction site (which usually are congested and dynamic).

The 2-week day and 2-week night lunar diurnal cycle also effects the power system design of the construction vehicles. There are essentially two choices for equipment power supply: either a rechargeable battery/fuel cell system or getting power directly from the base power system via a cable. For equipment with small power requirements, rechargeable batteries might be the best choice. The nickel-hydrogen batteries baselined for Space Station are rated at approximately 35 Wh/kg with a 80% depth-of-discharge and 80% cycle efficiency (28). For flexible, mobile equipment (trucks, scrapers, dozers) with higher power requirements, regenerative oxygen/-hydrogen fuel cell systems (RFC) could be the best choice. RFC energy density is approximately 880 Wh/kg with reactants (for the 2-week lunar night) (28). The RFC has a 56% cycle efficiency which means that the photovoltaic (PV) array, that provides the power to regenerate the reactants used in a RFC powered vehicle, must be size to provide 1.8 x the vehicle energy requirement (the extra power is needed to make up for inefficiencies in the electrolysis step for reactant regeneration and in the vehicle fuel cell power generation step). Regenerative means, in this sense, that the fuel cell product (water) is electrolyzed to regenerate the oxygen/hydrogen reactants. The electrolysis step might not necessarily take place on the vehicle. It may be more efficient to occasionally unload the water and refuel with oxygen and hydrogen (either high-pressure gas or liquid cryogens). It should be noted that there is an energy penalty involved for transporting the fuel cell reactants and products. The size of the penalty depends on the amount of reactants/products carried which depends on the frequency of refueling. To eliminate the inefficiencies in the fuel cell type power system, it would be more efficient for the construction vehicles to draw power directly from the power network by a power cable. This may only be practical for large fixed or slow moving power users such as cranes, draglines, rotary drills, etc. (see Section 4). If the base power was being generated by a PV system with only supplemental RFC power at night, construction vehicles using power directly from the power net might be confined to day-light operation only. Both day and night operation would be allowed if nuclear-electric power was available.

### 3.4 Major Surface Operations

Types of surface operations activities have been described in previous reports (1-4, 7) and additional information has been presented in several LBSS papers (42-44, 62). The following sections describe operations requirements for construction/assembly tasks that are representative of some of the major activities expected in Phase II.

#### 3.4.1 Landing Site Preparation

Figure 3-10 illustrates the configuration of a minimally prepared landing pad for use during an early lunar base program (4). The 100 m diameter inner pad area should have slopes less than 6° over 20 m distances, no humps and depressions greater than 1 m in relief, and all rocks greater than 0.5 m in diameter removed. The 50 m wide annular region surrounding the 100 m diameter central target area should have no slopes over 12° or depressions over 2 m in relief. The amount of grading (to achieve slopes less than 6° over 20 m) and leveling (to remove rocks and 1 m depressions/humps) necessary to meet the requirements of the inner region depends on local conditions. From Section 3.1.1, most areas of the Moon have average slopes less than 6°, thus the necessity for grading appears to be unlikely. However, the distribution of craters (Figure 3-7) indicates that many areas of the Moon (particularly highlands areas) are literally saturated with craters 10 m diameter and smaller. Lunar craters with diameters from several centimeters to about 15-20 km are typically bowl shaped (33). Diameters of these craters are approximately 5.6 x crater depth (45, p.70). Therefore, the requirements indicate that a 100 m diameter landing site should have no craters with diameters greater than 5 m, or all craters more than 5 m across within the 100 m diameter area should be at least partially filled in. From the crater distribution data given in Section 3.3.1, some surface leveling/grading and crater/depression filling appears necessary to prepare the 100 m diameter landing pad areas. Scaled results from another report (43), approximately 600 $m^3$ of soil must be excavated or moved per 100 m diameter landing pad. Several pads will be needed, depending on the reusability of the lunar lander. If the lander is reused, up to six pads will be needed (43). If the early landers are expended, over 40 pads may be required (2, 4). These pads will need to be located 250-400 m from each other and base elements to avoid debris damage occuring from dust kicked up by the lander's engines.

Dozers and scrapers (see Section 4) are two possible types of excavators that could perform the shallow cut excavation that is needed for the pad leveling operation. Dozer capability to remove or shove aside rocks is excellent (for rock sizes that can be handled with available traction expressed in terms of draw-bar pull).

### 3.4.2 Prepare Roads

A roadway has been proposed to connect and ensure low-risk travel between the landing pads and base area (4, 43). Permanent landing pads were proposed located at least 3 km from the base to provide a safety margin for navigation landing errors, and to relieve some facility and surface-equipment engine-blast protection precautions otherwise required (4). The length of the roadway is therefore defined as 3 km. Width of the roadway will be determined by the cargo transporter vehicle width and an additional clearance factor. Payloads identified in Section 3.2 are limited to a maximum 4.5 m diameter for Orbiter manifesting. For stability, the transporter vehicle wheels are assumed to extend 1 m beyond the sides of the cargo, and an additional 4.5 m is included for maneuverability purposes to bring the total road width to 10 m. For moving a 10 m wide lunar lander, a minimum road width of 12 m would be needed.

As with the landing pads, road preparation is essentially a leveling operation. The crew would first survey and layout a suitable path (2). Craters and other depressions would be filled while humps would be leveled. Based on estimated landing pad fill requirements, the 30,000 $m^2$ road surface area would require excavation of 2,300 $m^3$ of surface materials to provide crater fill. Large rocks would need to be removed or buried. Final fine grading would be needed (43) and/or the road surface stablized by use of compaction and gravel applications (4). Road surfacing options are illustrated in Figure 3-11. Tiling would be the most time consuming and difficult, but would result in the longest lasting surface. Compaction is the simpliest but has potential dust problems and would require more frequent maintenance (recompaction) after exposure to traffic. Gravel derived from lunar sources appears to provide an adequate compromise. The roadbed of this concept consists of a 15-25 cm deep base of coarse (>1 cm) gravel, topped by a fine gravel (4-10 mm sized particles) finish. Approximately 4,500 $m^3$ (7,200 mt) of coarse gravel and 300 $m^3$ (540 mt) of fine gravel would be required for a 3 km roadway. Since mature soil contains only 2 percent by weight greater than 4 mm (33), either 387,000 mt of soil must be collected and seived to extract the large particles, or a more concentrated source of coarse materials is required. About 20 percent by weight of the particles in two particularily coarse soil samples, sample 12028 (Apollo 12 core sample near Halo Crater) and sample 14141 (Apollo 14 surface sample from near rim of Cone Crater), were over 4 mm in size (33, 46). Extraction from subsurface sites or near fresh craters are likely areas to find quantities of suitable rock sizes. Vibratory screens are a possible method for separating and grading the gravel materials (7).

### 3.4.3 Unload/Transport Cargo

Typical large cargo elements are defined in Section 3.2. In addition, small cargo elements might likely be manifested on pallets to simplify unloading, transport, and stowage. These elements are too large to be handled by EVA crew alone. A number of unloading options are possible including cranes, forklifts, ramps, and erectable hoists (see Sections 4 and 6). The cargo will likely be configured with loading aids such as harnesses, rings, trunnions, and alignment mechanisms, to allow quicker attachment to the cargo unloading and transport systems. Requirements for this task include:

- Unloading cargo from the lander. Crew are required to, for instance, attach crane hoist hooks to a cargo harness, lifting rings to trunnion pins, or to align and position forklifts under the cargo.

- Transporting the cargo to the base or work site. A separate trailer or truck may be employed to perform this activity. Crew would assist in positioning cargo on transport, detaching cargo unloading device, and securing cargo to transport.

- Unloading the cargo from the transport following similar procedures as with unloading lander.

- Positioning, emplacing, and securing cargo element in final position.

### 3.4.4 Emplace Habitation Module

Habitation and laboratory modules are considered to be cylindrical shapes of Space Station inheritance. In one concept (2), the modules are mounted on the surface. After site survey and layout, the 50 m x 50 m site is prepared (leveled and graded), and utilities (thermal control, power, communications data links) are routed to near connect points with feed-throughs to the pressurized elements. The modules are transported, emplaced, and systems function checked. Requirements to provide radiation protection for large volumes are time consuming. One module was covered with regolith early in the base buildup sequence as a solar flare shelter (2). Many options are possible for providing radiation protection (2, 47, and Section 6). A way to reduce the quantity of soil required below that needed to simply bury a module is to use bulkheads as illustrated in Figure 3-12. In this concept, besides a crane and trailer to handle and transport the cargo, the main equipment elements required are a prime mover (PM) with multiple possible attachments (front-loader, backhoe, bulldozer blade), a dumpable soil cart pulled by the prime mover, and a hopper/16-m long conveyor system to transport soil over the bulkhead. 1,400 $m^3$ of soil is required to cover a 4.5 m diameter x 7.2 m long shelter with 4 m (700 $g/cm^2$) of soil. If bulkheads were not used and soil was allowed to conform to a 35° angle of repose, 2,600 $m^3$ of soil would be needed. A later study (47) suggested that 785 $g/cm^2$ of soil is needed and that this corresponds to 2.62-7.85 m of soil depending on packing density (from 3 to 1 g/cc).

Another initial habitat option is to land a module on an integral lander stage and live out of it without unloading it from the lander (43). A frame is installed around the module/lander and soil placed on the frame in sufficient thickness to provide the required radiation protection. For 1 m thick protection, 310 $m^3$ of soil is needed (43).

### 3.4.5 Emplace Inflatable Habitat

An inflatable has been described as a candidate for providing a high-volume habitat (42-44). The inflatable is a 14.3 m diameter sphere (1,530 $m^3$). It is emplaced by first creating a 5 m deep hole (430 $m^3$) with explosives packed into 7 m deep cores drilled into the regolith and underlying material (43). Radiation protection is provided by 710 $m^3$ of sandbags (43).

### 3.4.6 Set-up Photovoltaic Power Plant

A main element of the photovoltaic (PV) power plant described in another report (28) is the fixed, flat array of gallium arsenide solar cells. The array blankets are spread directly on a graded and leveled surface. For maximum power output, the surface should be graded to expose the greatest array area to the sun. For the Lacus Veris site (87.5°W, 13°S), the grade would elevate the south end of the arrays 13° so they would slant northward. The PV arrays would cover an area of 2,272 $m^2$ to provide 100 kW during the lunar day and enough addional power to recharge fuel cells that provide 100 kW during the lunar night (534 kW peak power output). To level and grade an area of 2,272 $m^2$ would require movement of approximately 175 $m^3$ of soil.

**Figure 3-10.** Minimally Prepared Landing Pad for Early Operations (from Ref.4)

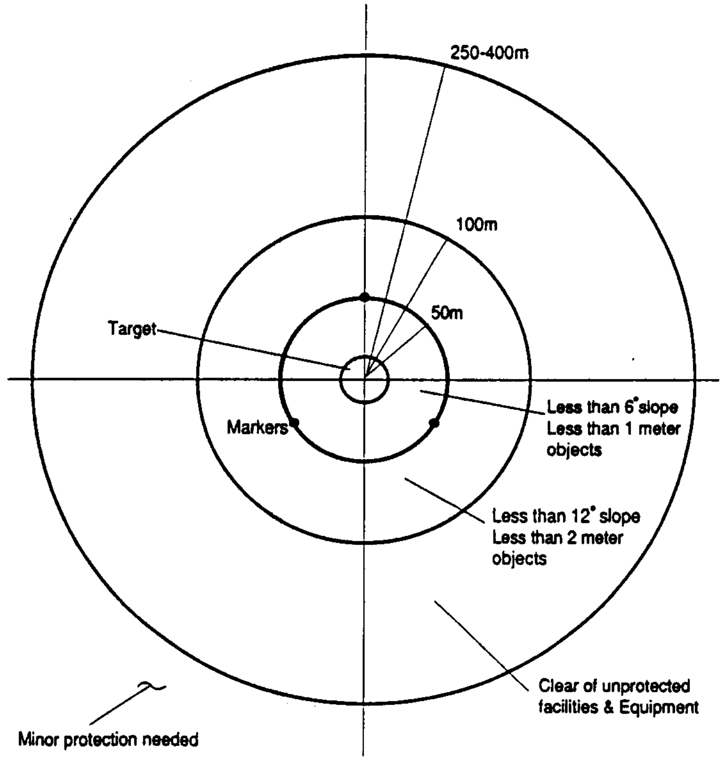



**Figure 3-11.** Surface Stabilization Concepts (from Ref.4)

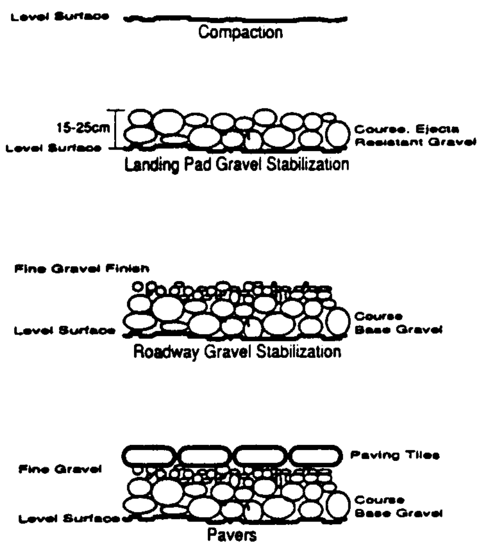
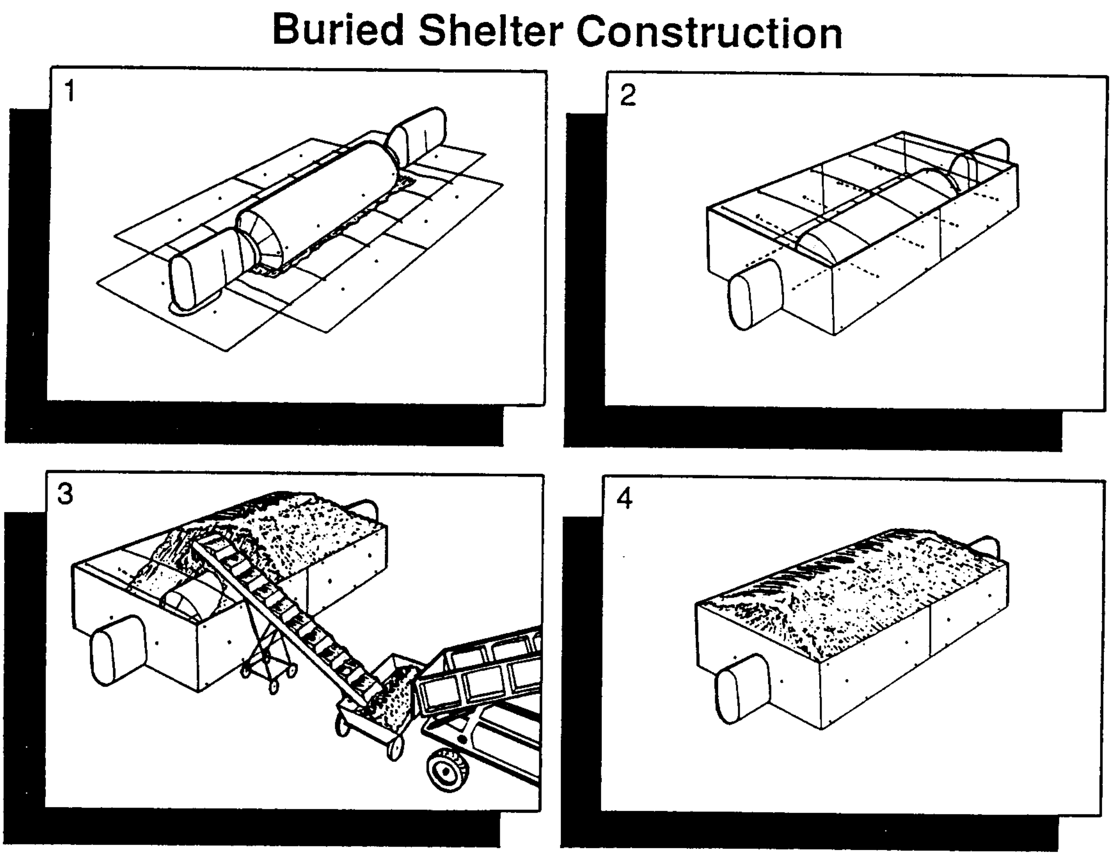


**Figure 3-12.** Assembly Sequence for Covering Radiation Shelter Using Bulkheads (from Ref.2)



## 3.5 Remote Telerobotic Operation of Construction Equipment

Although some of the early construction and assembly tasks will be one-time operations (such as unloading the first lander), others involve operations that will likely to be repeated frequently, even after a permanent base is established (such as hauling soil, excavating, clearing/grading surfaces, etc.). If a lunar surface activity is to be repeated frequently and is not too complex, then teleoperation, with the eventual goal of nearly-autonomous operation, is recommended as a design goal for this equipment (with direct manual-controls provided as backup) as a way to reduce extravehicular activity (EVA) requirements. Some construction activities appear too delicate or complex to be completely teleoperated, such as final positioning and connection of modules, and final site surveying/inspection. These would at least require on-site EVA personnel to monitor and/or control. Types of operations that appear to be capable of teleoperation include: hauling soil from an excavation area to a discharge point, and soil collection or excavation by a bucket wheel excavator or possibly other types of excavators.

Teleoperations controlled from the lunar base take place with negligible time delay and would be the easiest to implement. Earth teleoperations of lunar equipment offers the highest potential payback by leveraging costly lunar surface time with relatively inexpensive Earth operations time. However, the three-second round-trip communications delay time will require progress in automation and robotics research. Human supervisory control of a nearly autonomously operating vehicle is indicated. Significant on-board computational capability, combined with strategically located navigational markers/beacons around the base and construction site, will be required for Earth teleoperations control (2, 38). Although requiring much specific development work, current technology trends support the concept of teleoperated simplier lunar construction equipment (soil-moving, hauling, grading, etc.). For instance, remote teleoperated control of servicing robots has been advanced by the oil production industry. A large oil production platform (60 m x 45 m x 12 m), resting on the seabed at 500 m, has been successfully operated and maintained almost exclusively by telerobots (39). In addition, telerobotic technologies are currently being pursued for Space Station applications such as "telescience" or teleoperation of Space Station laboratory experiments (40), and remote operation of the Orbital Maneuvering Unit (OMV) for satellite servicing missions (41).

## 4.0 Terrestrial Construction Equipment Types

Construction equipment has developed and improved over the years, but the equipment can still be grouped into five types; (1) erection equipment, (2) excavators or earth movers, (3) hand tools, (4) mechanical advantage devices, and (5) transporters. These types are itemized in this section with a summary description of the functions and applications. The functions provided by the equipment include:

| Equipment Type | Equipment Options | Functions | | |
|---|---|---|---|---|
| Erection Equipment | Boom Crane | Lift | Transport Bulk | |
| | Bridge Crane | Position | Transport Items | |
| | Tower Crane | Pour | Winch | |
| | Forklift | Pull | | |
| | Gin Pole | Push | | |
| | Scaffolding | Stack | | |
| Excavators/Earth-Moving Equipment | Bucket Wheel Excavator | Backfill | Melt Regolith | |
| | Dozer | Bag Regolith | Mix | |
| | Front-End Loader | Blast | Pour | |
| | Dragline | Bury | Pull | |
| | 3-Drum Slusher | Clear | Push | |
| | Hydraulic Excavator | Compact | Rip Surface | |
| | Electric Shovel | Drill Regolith | Sift | |
| | Scrapers | Drive Piling | Trench | |
| | Drills | Dump | | |
| | Boom-crane w/ clamshell | Excavate | | |
| | Crane w/ piledriver ram | Grade | | |
| Hand Tools | (see Section 4.3 for list) | Backfill | Erect Scaffold | Pull |
| | Surveying Equipment | Bolt | Excavate | Push |
| | Sampling/geoscience tools | Bury | Latch | Rivet |
| | Excavation tools | Clear | Level | Seal |
| | Unpowered tools | Compact | Lift | Survey |
| | Power tools | Cut | Mix | Trans. Items |
| | Construction/assembly aids | Drill Regolith | Nail | Trench |
| | | Drill Structure | Position | Winch |
| | | Dump | Pour | Weld |
| Mechanical Advantage Devices | Come-along | Lift | | |
| | Pulleys | Position | | |
| | Electric Hoists | Pull | | |
| | Jacks | Push | | |
| | Ramps | Stack | | |
| | Rollers | Transport Bulk | | |
| | Skids | Transport Items | | |
| | Wheels | Winch | | |
| Transporters | Conveyors | Lift | | |
| | Overhead Trolleys | Dump | | |
| | Trucks | Pour | | |
| | Trailers | Pull/Push | | |
| | Tractor (Prime Mover) | Transport Bulk | | |
| | Railroad | Transport Items | | |
| | Forklift | | | |

## 4.1 Erection Equipment

### 4.1.1 Boom Cranes

The boom type crane has a major advantage over other types of lifting equipment. The load being moved can be easily maneuvered. Load maneuverability is available in other types of lifting equipment, but it is not as easily accomplished. Other methods may require repositioning or restructuring part of the lifting or supporting apparatus. The boom crane, however, can promptly relocate a load anywhere within its radius of operation and maximum load constraints. The major disadvantage of the mobile crane is the mass required to act as a counterweight to prevent overturning during lifting operations. The boom crane can be mounted on a mobile unit (Figure 4-1a) or may be fixed in place. The fixed crane is often referred to as a derrick (Figure 4-1b). Mobile hydraulic cranes with telescoping booms are also available (13). Various crane attachments are used for hoisting and holding tasks including a conventional hook, lifting tongs, and electromagnets. Additional attachments are available to convert a boom-crane to an excavator or pile driver (61, p.13-7; 14). A clamshell bucket attachment is used for handling loose materials (sand, gravel, crushed stone). Clamshells are often applied for lifting materials vertically from one location to another, and removing materials from cofferdams or sheet-lined trenches. One type of clamshell, a Hayward electrohydraulic single-rope clamshell (see Figure 4-1a), can be hung from the crane or derrick hook by an eye on the clamshell and simply requires that an electric line be plugged in (14), therefore eliminating the time-consuming task of feeding line into the bucket or shifting lines on the crane. This type clamshell is opened and closed by energizing electric and hydraulic actuators contained within the clamshell.

### 4.1.2 Bridge Cranes and Gantries

The bridge crane has a traveling hoist moving on a rail system in the loft of the crane structure which bridges over the load to be handled (Figure 4-1c). The bridge crane, essentially has no counterweight requirement. However, the bridging requirement results in expansive dimensions for the crane. The traveling hoist has a cross track, as well as an along the track movement which facilitates flexibility in maneuvering the load within the crane bridging envelope. In some cases, the bridge crane is designed with wheels to be mobile. In this report, a mobile bridge crane is referred to as a gantry. A gantry has lower maneuverability than a mobile boom crane. Because the gantry is so large, it must be assembled and may weigh more than a mobile boom crane.

### 4.1.3 Tower Cranes

A tower crane is a crane installed on a high, fixed tower which services the 360 degree area underneath the elevated crane (Figure 4-1d). It is often used in high rise building construction where the building is constructed and rises around the crane tower. At building erection completion, the crane is removed and the tower disassembled. The tower crane can promptly relocate a load anywhere within its radius of operation and maximum load constraints. A counterweight is required to balance the load.

### 4.1.4 Forklift

A forklift is a mobile truck with a lifting implement mounted on the front (Figure 4-1e). The implement is a lifting fork which can move a load up and down on a vertical rail. The forklift is primarily used to retrieve items, move items from place to place, and place items at desired locations in warehousing or cargo loading and unloading. A counterweight is required to balance the load. Forklifts are available in capacities from 1 to 50 tons, with the 1-2 ton vehicles the most common (63).

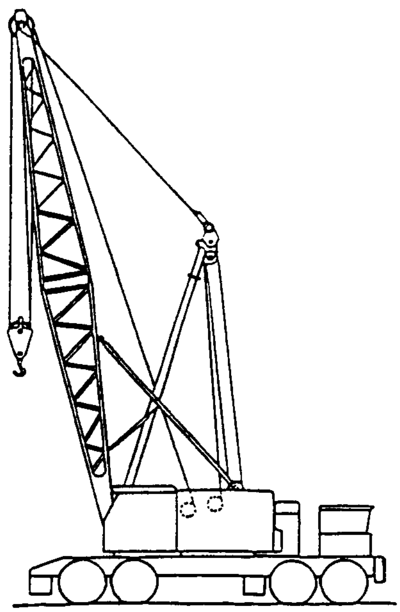
### 4.1.5 Gin Pole

A gin pole is a portable erection device which consists of a pole with hoisting gear on top and which is held up over the load with guy wires (Figure 6-7a). The gin pole is used in the erection of light members when it is not practical to move in a crane. The advantage of the gin pole is the ability to assemble a lifting device in place from small, lightweight components for a special requirement. The disadvantage is that the gin pole has almost no load maneuverability. In addition, large tension forces may occur in the guys. Underwood (6) states that, "When the top of the pole is given a drift of one-third the height, the stress upon a guy may become equal to one-half of the load". Use of the gin pole is labor intensive since the pole and guys must be set up for each lift and disassembled to prepare for next job.

### 4.1.6 Scaffolding

Scaffolding is a temporary platform assembled to enable manual work at the desired elevation above ground level. The scaffolding is assembled from standardized set of frames and members for each special application. Although prefabricated scaffolding could reduce setup time, the use of scaffolding is by nature labor intensive because its purpose is to allow access for manual construction activities.

**Figure 4-1a.** Mobile Boom Crane (Ref.14)



Clamshell Bucket Attachment for Boom-Crane (electrohydraulic, single-rope type) (Ref.14)

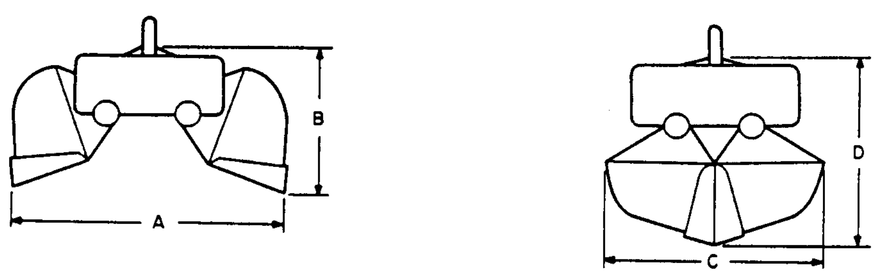
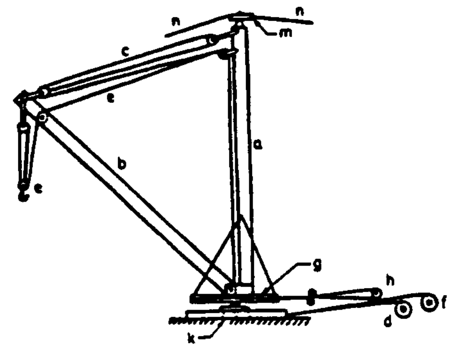


**Figure 4-1b.** Fixed Boom Crane (Derrick) (Ref.14)




The mast a is carried at the foot by k and at the top by pivot m, held by rope guys n. The boom b is pivoted at the lower end of the mast. The rope c, passing over sheaves at the top of the mast and at the end of the boom and through the pivot k, is made fast to drum d and varies the angle of the boom. Hoisting rope e, from which the load is suspended, is made fast to drum f. The bull wheel g is attached to the mast and swings the derrick by a rope made fast to the bull wheel and passing around the reversible drum h.

**Figure 4-1c.** Gantry (Ref.14)

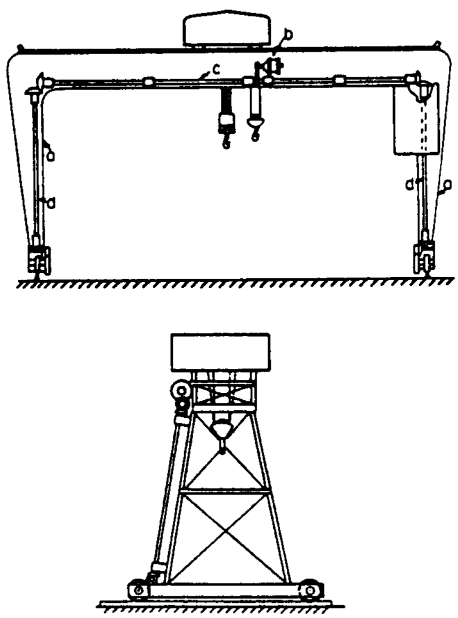



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**Figure 4-1d.** Tower Crane (Ref.14)

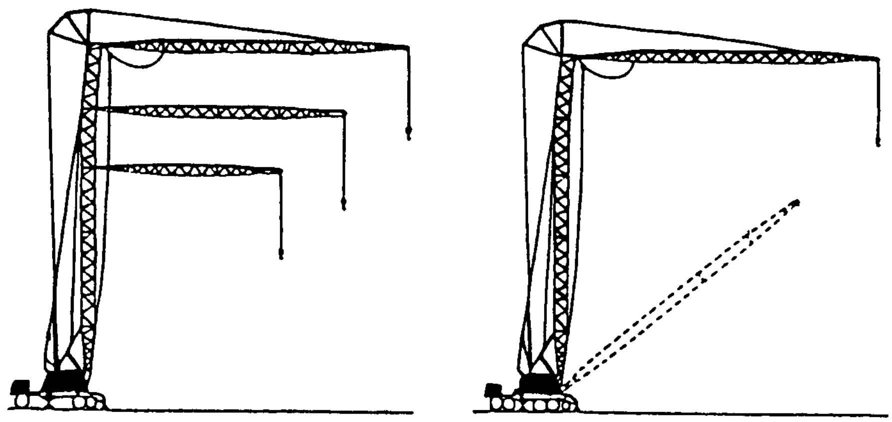
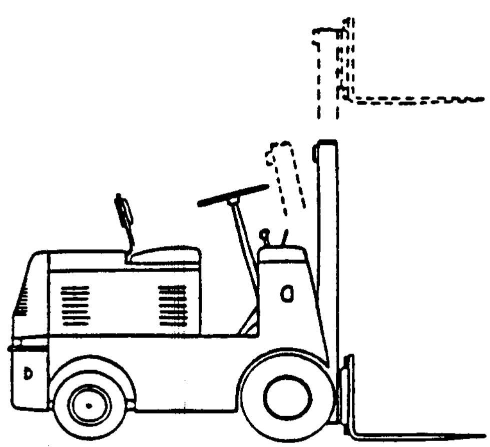


**Figure 4-1e.** Forklift (Ref.14)



## 4.2 Excavators

Various types of excavators are available to collect soil and rock. They differ in key characteristics including:

- Continuous vs. cyclical excavation.
- Depth of excavation and digging (excavation) profile.
- Cycle time and production rate.
- Operating weight, power requirements, and other performance factors.

The following sections provide a brief description of terrestrial excavators. Cycle time and performance factors for these machines are compared in Section 4.6. Often, several different equipment elements are used as a system to excavate, load, and transport the mined material. Some of the many combinations are:

- A dozer/ripper working in combination with a front-end loader (FEL), with FEL loading trucks.
- Front-end loader loading trucks without dozer.
- Dozer/ripper working with a scraper.
- Bucket wheel excavator, transfer conveyor/hopper system, and trucks or belt conveyor transportation system.
- Draglines loading trucks.

Drilling and blasting may precede these operations to break up rock or consolidated formations.

### 4.2.1 Bucket Wheel Excavators

Loaders, shovels, and draglines are cyclic excavators because the actual excavating phase is interrupted by a swing to dump operation. Bucket wheel excavators are unique due to the ability for continuous excavation of unconsolidated materials. They dig with a rotating bucket wheel which discharges the material onto a belt conveyor or a series of conveyors until it is discharged from the machine (Figure 4-2a). Although the bucket wheel excavators have some capability to excavate below their own level, they are rarely applied in this manner. The advantage (continuous excavating ability) of a bucket wheel excavator that is employed loading trucks can be lost unless trucks are always available.

### 4.2.2 Dozers

The dozer is a track or wheel driven tractor with a front mounted blade for excavating and transporting (pushing) material over short distances (Figure 4-2b). It makes long skimming cuts off the top surface. A ripper can be attached to the back of the dozer to fragment and loosen consolidated material. The ripper is a large single tooth or multiple teeth that scarify the surface material to depths of 2 to 11 feet. Dozers are also used to push or pull other equipment. A tamping roller can be towed by a dozer to compact soil (15). The roller drum can be ballasted with sand or concrete to produce very high soil pressures that makes it effective in shattering exposed rocks and forcing the fragments into the soil to produce a relatively smooth surface (13, p.115). The dozer is one of the simplest pieces of equipment in terms of its basic operations and operator training. Wheel and crawler types are available. The primary difference between the tracked and wheeled configurations is the force applied to digging, ability to maneuver under sloppy ground conditions, and overall mobility to move between job sites. Useful tractive effort on firm earth surfaces is limited to about 60 percent of weight for wheeled dozers while crawler dozers develop drawbar pulls up to 90 percent or more of their weight (11-14).

### 4.2.3 Front-End Loaders

The front-end loader (FEL) is a wheel or track driven tractor with a front mounted bucket used in excavating, loading, and transporting material (Figure 4-2c). Wheel mounted front-end loaders often have articulated frames. It digs by filling its bucket through a combination of crowding action produced by propelling, bucket orientation by a wristing action, and a hoisting action. Ballast is often added on wheeled FEL's and dozers to increase machine weight, thereby increasing traction and allowing the machine to more fully utilize its power during pushing or pulling operations (adding weight to a hauler will effectively reduce payload capability). Although lead weights can be mounted on the frame, the most common practice of ballasting is to add a solution of calcium chloride ($CaCl_2$) and water to the tires of the machine (11, 12). A crawler type loader is available with a multipurpose bucket that can be used as a shovel, bulldozer, clamshell, or scraper (14, p.10-27). The multipurpose bucket consists of two hinged parts, both with cutting edges, that closed form a shovel bucket or opened form a bulldozer blade or clamshell.

### 4.2.4 Draglines

The dragline is unique because of the long reach and ability to excavate to substantial depths below itself. The dragline has a long truss boom (Figure 4-2d). A bucket hangs from the boom. It is connected by one hoist cable vertically over the boom tip to the hoist powered drum on the main machinery deck. A second cable used to drag the bucket horizontally over the surface is connected directly to the powered drag drum on the main machinery deck. The weight of the bucket and its load provide the digging force while the drag motion pulls the bucket along the surface towards the machine. The hoist motion raises the bucket with sufficient tension kept in the drag line to keep the bucket oriented so as to retain the load. The upper works of the machine is rotated on the base so that the load can be dumped right or left. Dumping is performed by releasing the tension in the drag cables, permitting the bucket to rotate and discharge the material. The larger draglines (up to 13,000,000 kg) accomplish local mobility with a walking device and are referred to as walking draglines. To move the machine, cams are rotated to lower shoes to the ground, lifting and sliding the dragline base rearward two to four meters. Crawler mounted draglines are available for smaller sized draglines up to 340,000 kilograms.

### 4.2.5 3-Drum Slusher

Slushers are used in terrestrial underground mining operations to move ore 15 to 120 m (16, p.12-18). These machines usually have simple forward/backward motion of the slusher bucket because of the confined nature of the shafts they are clearing (16). They are somewhat akin to the cable operated dragscraper but without a boom. The 3-drum slusher has been proposed as a lunar soil excavator (15). This slusher concept consists of a scraper bucket attached with cables to two anchored pulleys and a unit containing three independent take-up cable drums and motors (see Figure 4-2e). In this concept, the loading cycle is begun by pulling in on the two outhaul cables to position the bucket for the start of the loading cut. Bucket motion in the lateral direction (more complicated than just forward/backward) can be accomplished by adjusting the pull-in rate of either of the outhaul cables. The bucket is filled by releasing the outhaul cables and pulling in on the inhaul cable. An elevated loading station (ramp, screen, and hopper) provides a method to load a truck or conveyor at the discharge point of the slusher. The pulleys should be elevated on booms to keep the cables out of the dirt because excessive dust contaimination would reduce the lifetime of the cables and pulleys (15, p.339; 11, p.301).

### 4.2.6 Hydraulic Excavator (Backhoes and Shovels)

The hydraulic excavator is used primarily as an excavating and loading device (Figure 4-2f). The operating cycle consists of a cutting pass through the bank, loaded swing to the discharge area, dump empty, and swing back to the digging face. As a backhoe, the machine digs downward and back towards itself. As a shovel, it digs upward and away from itself. While the shovel can dig below itself, this feature is only used during ramping down to establish a lower operating level. Primary use of the shovel is digging above its floor. The backhoe can excavate above its floor, but is seldom used in this manner. The below grade excavating capability of the backhoe is particularly suited to tasks such as trenching and excavating where floor conditions warrant keeping machines off the bottom of the pit.

### 4.2.7 Electric Shovels

The shovel is one of the oldest type of excavating machines (Figure 4-2g). The equipment has grown with time and the operating power has progressed from steam, to gas, to diesel, and to electricity in the large units of today. They are used primarily for loading large trucks or mobile hoppers. An operating cycle consists of a digging cut, a loaded swing to the discharge area, the dump, and empty return swing to the digging face. They have a swing angle of 70 to 120 degrees with the cycle time ranging from 25 to 35 seconds.

### 4.2.8 Scrapers

The scraper is used to excavate material in thin horizontal layers, transport the material considerable distances, and then deposit it in a spreading action. A blade for scraping is mounted between the front and back wheels (Figure 4-2h). It is loaded by propelling forward with the cutting blade lowered below the level of the front wheels so as to take a shallow cut of material. The material is forced into the body cavity (bowl) which is raised and closed when full. The scraper then transports the material to the disposal area where it can be dumped or spread uniformly.

### 4.2.9 Graders

Motor graders are wheeled machines mounting a blade between the front and rear wheels. The advantage offered by a grader is that the grader operator can precisely position the blade by adjusting its height and angle. However, graders are not very versatile; they are efficient at grading but not generally applied elsewhere. Excellent maneuverability of the grader is provided by sharp turning front wheels.

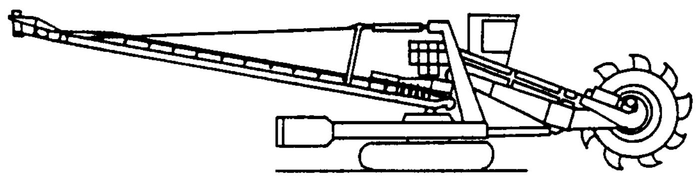
### 4.2.10 Drills

Explosives are used to break up hard, consolidated formations prior to excavation to avoid excessive machine wear and increase productivity. The explosives are packed in holes that are drilled to depths approximately equal to the depth of the planned excavation. The number, spacing, and diameter of the holes depend on the type of explosive used and the power required to produce the desired fragmentation in the specific formation. Another method for breaking rock that is safer than explosives involves injecting an expanding compound into the drilled rock which subsequently fractures. Pneumatic and hydraulic percussion drills are usually applied for small diameter holes (15 cm maximum). Rotary drill rigs are the most common for larger diameter and deeper holes. The mass and power required are dependent on formation conditions (soft, hard), bit type and diameter, and rotary speed. Both wheel and track mounted units are available (Figure 4-2i). Some of the larger mobile units are provided with power from a trailing electric cable. After the mobile drill rig is positioned, the mast supporting the drilling mechanism is raised, and the wheels (or crawlers) are raised off the ground with leveling legs. Drilling is accomplished by applying a rotary torque and with the weight of the vehicle providing a high down pressure. A vertical, rotatable carousel provides drill pipe which is added on in increments with increasing drill depth. Drill pipe handling is a semi-automated operation that allows drill pipe changes to be made in 3-10 minutes, during which drilling is interrupted. Compressed air is injected down the center of the drill pipe (and then exits back up the periphery of the drill hole) to remove chips/drill cuttings and to cool the drill bit. Dust and debris in the exit air are removed in cyclones and/or filter bags.

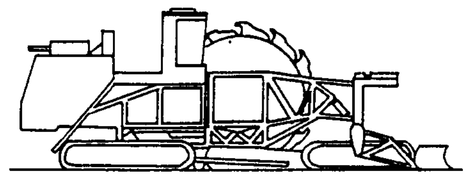
### 4.2.11 Bag Filling Equipment

Equipment to package dry-bulk solids into bags, cartons, or drums are commonly used in the food and chemical industries. The packaging process usually consists of bulk solid storage bins, feeders that transfer the solids to weighing and package filling equipment, conveyors to move the packages to a palletizing area, then forklifts or conveyors that transfer the loaded pallets to storage or shipping areas (Figure 4-2j). There are two principal types of automatic weighing and filling machines: 1) simultaneous fill-and-weigh, where the material is weighed as it is poured into the container, and 2) preweigh, where the material is weighed prior to being poured into the package.

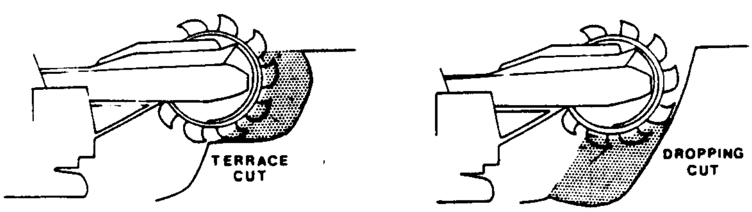
**Figure 4-2a.** Bucket Wheel Excavators (Ref.11)



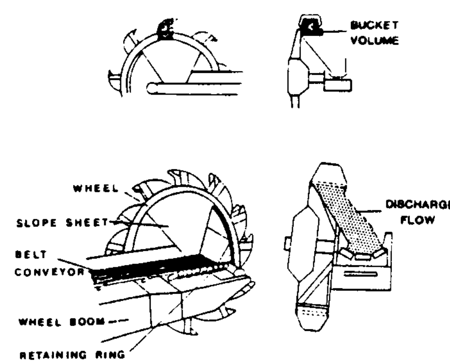
MEDIUM SIZE WHEEL

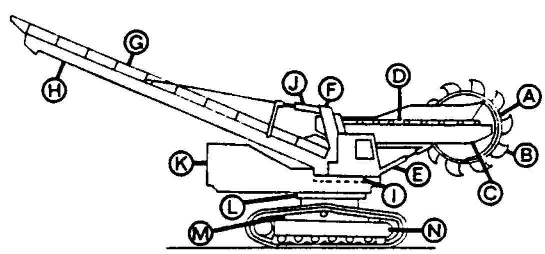


SMALL FIXED WHEEL



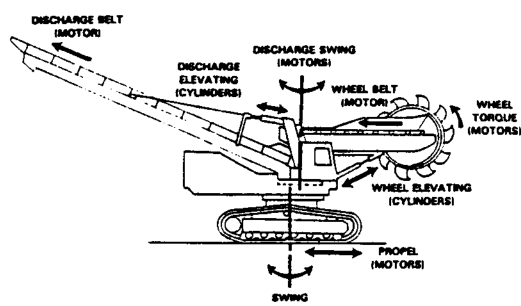

DIGGING PROFILE




A Wheel
B Bucket
C Wheel Boom
D Wheel Conveyor
E Wheel Elevating Cylinder
F Gantry
G Discharge Conveyor
H Discharge Boom
I Discharge Swing Bearing
J Discharge Elevating Cylinder
K Revolving Frame
L Swing Circle
M Undercarriage
N Crawler Side Frames

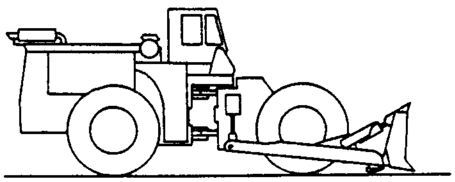
*Wheel Nomenclature*



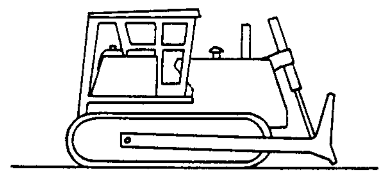

*Wheel Powered Functions*

**Figure 4-2b.** Dozer (from Ref.11)

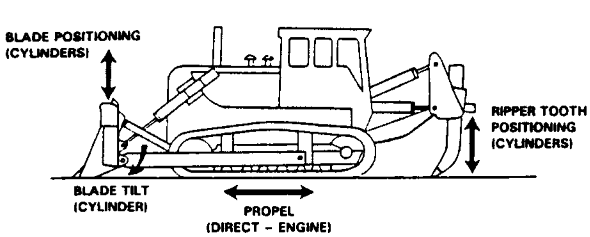


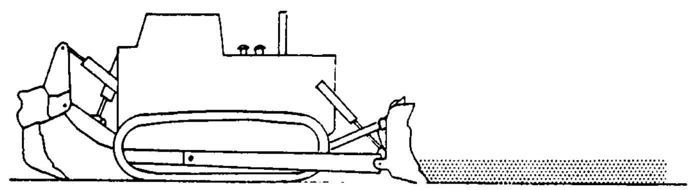


WHEEL DOZER



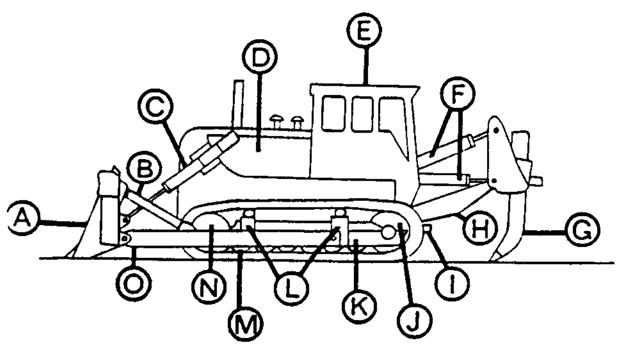
CRAWLER DOZER



DIGGING PROFILE

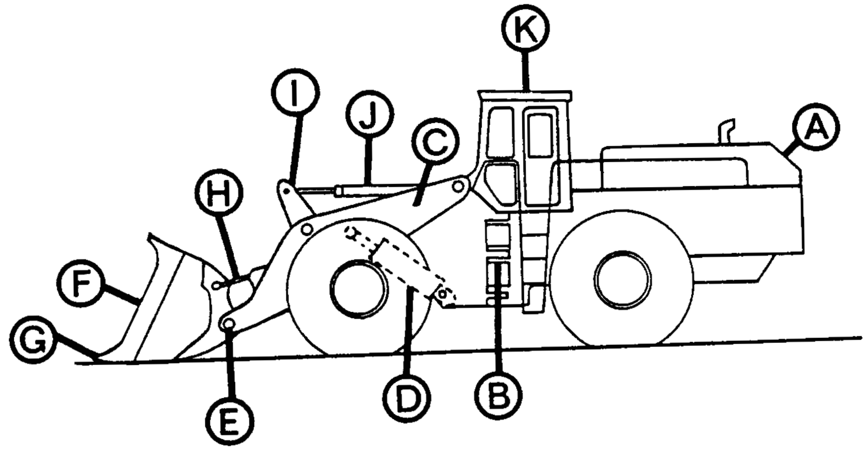
*Dozer Powered Functions*




| | | | |
|---|---|---|---|
| A | Blade | I | Ripper Beam |
| B | Pitch Strut | J | Sprocket |
| C | Hoist Cylinder | K | Crawler Frame |
| D | Engine | L | Track Carrier Roller |
| E | ROPS-Cab | M | Track Roller |
| F | Ripper Cylinders | N | Track Idler |
| G | Drawbar | O | Push Arm |
| H | Ripper Shank | | |

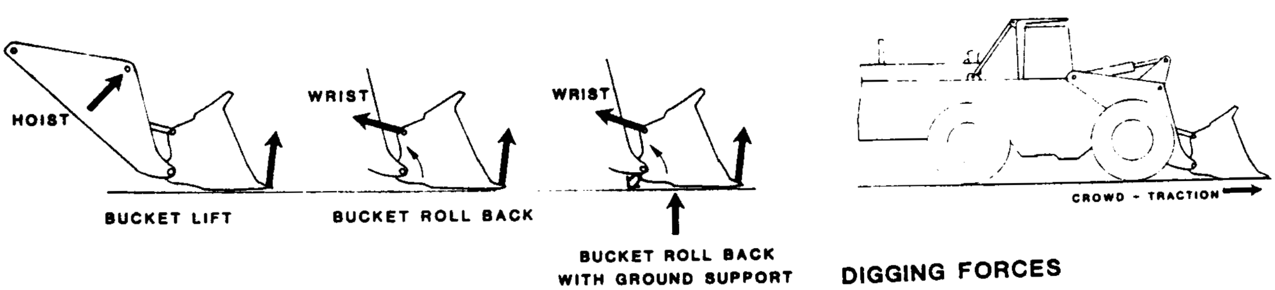
*Dozer Nomenclature*

**Figure 4-2c.** Front-End Loader (from Ref.11)

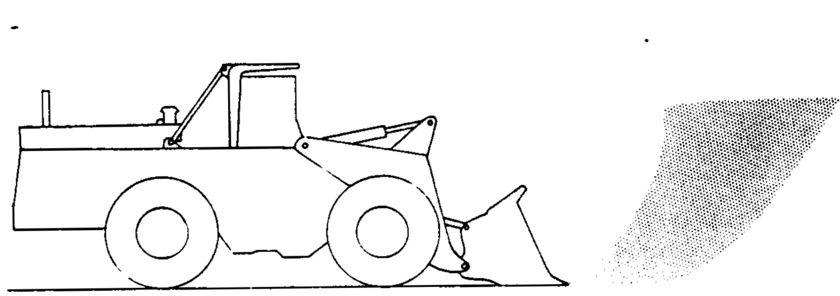



| | | | |
|---|---|---|---|
| A | Engine | G | Bucket Teeth (cutting edge) |
| B | Articulating Hinge Point | H | Bucket Link |
| C | Lift Arm | I | Bellcrank |
| D | Lift Cylinders | J | Bucket Cylinder |
| E | Bucket Hinge Pin | K | ROPS |
| F | Bucket | | |

*FEL Nomenclature*



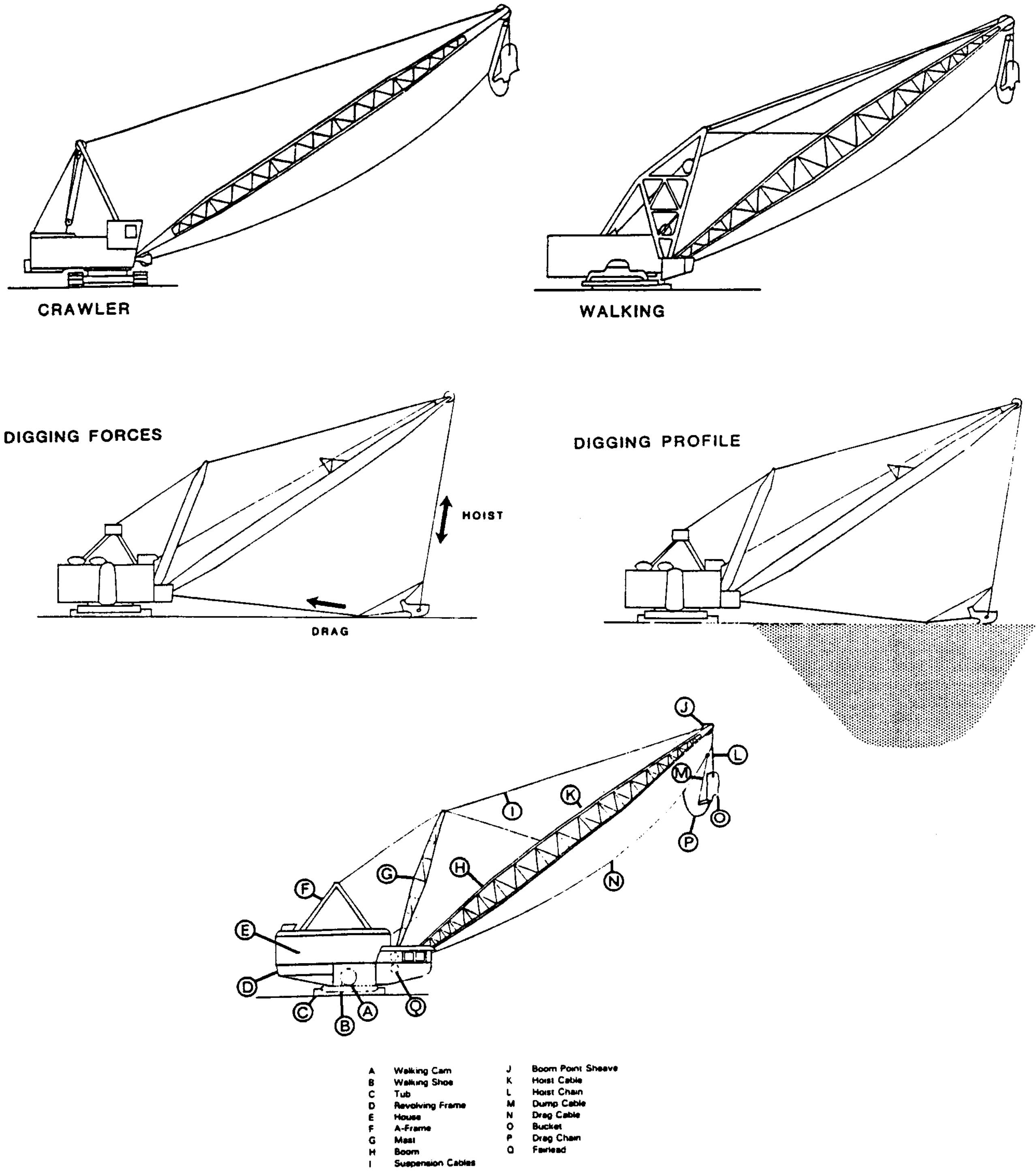

DIGGING FORCES



DIGGING PROFILE

**Figure 4-2d.** Dragline (from Ref.11)






*Walking Dragline Nomenclature*

**Figure 4-2e.** 3-Drum Slusher (from Ref.15)

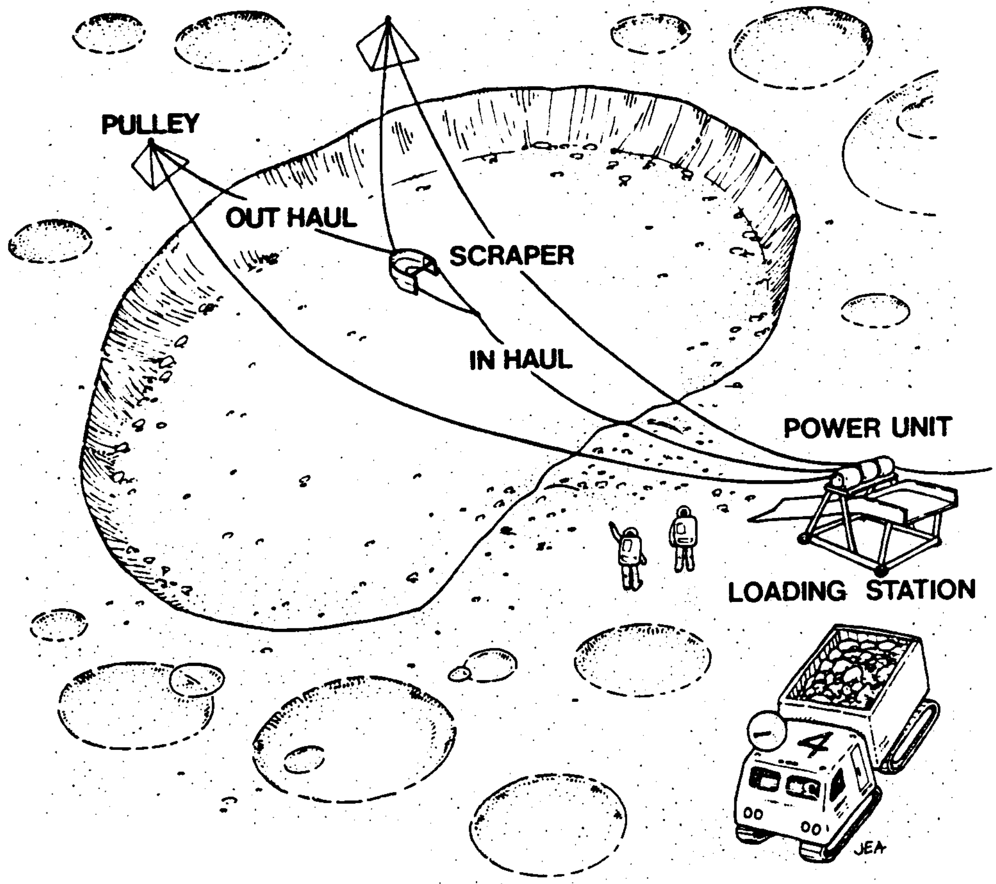


**Figure 4-2f.** Hydraulic Excavators (from Ref.11)

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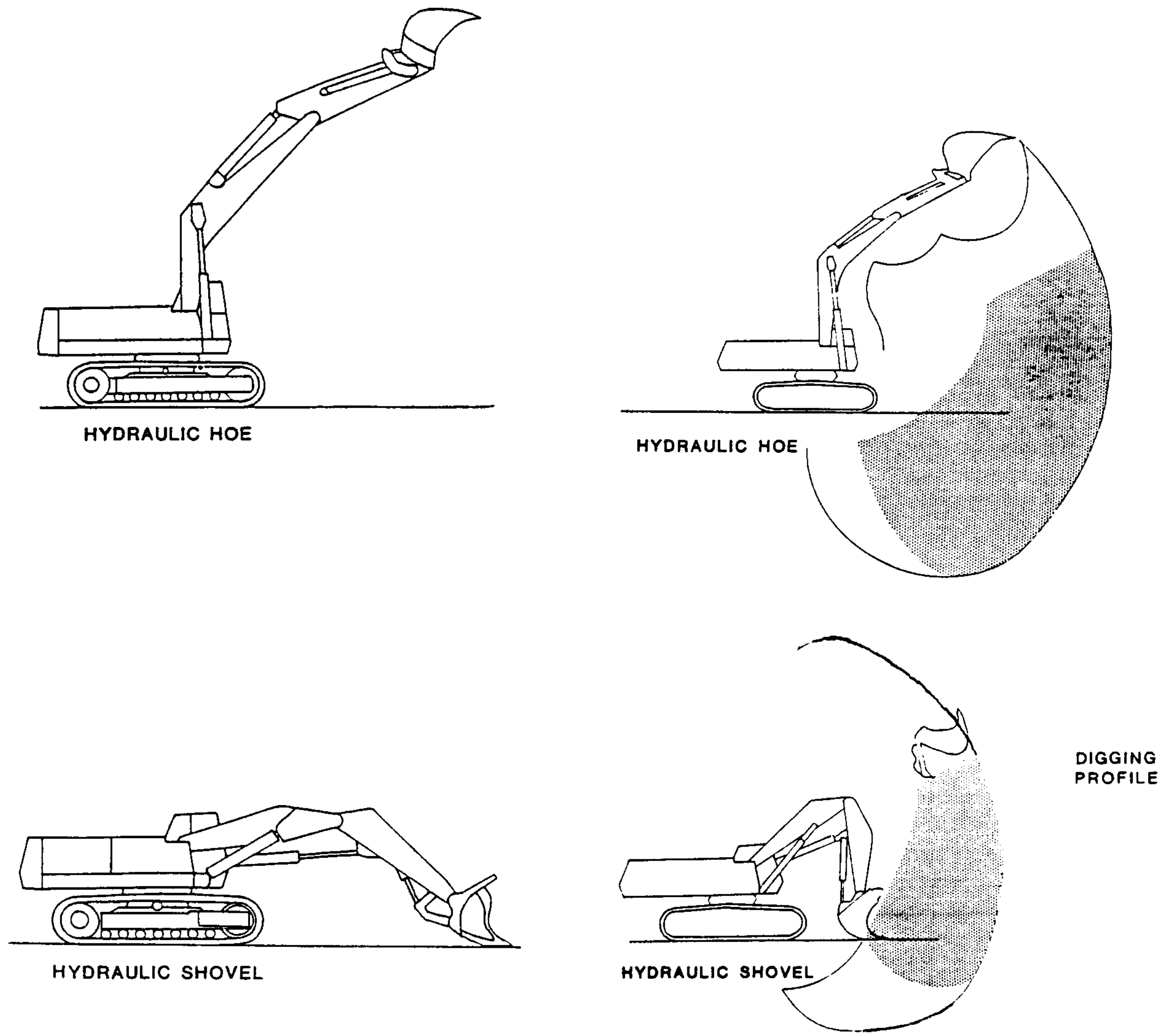
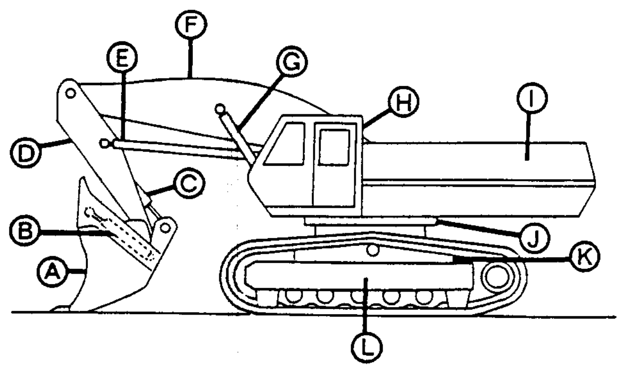



*Hydraulic Shovel Nomenclature*

| | | | |
|---|---|---|---|
| A | Bottom Dump Bucket | G | Boom Cylinder |
| B | Dump Cylinders | H | Cab |
| C | Bucket Cylinders | I | Upper Structure |
| D | Arm (stick) | J | Swing Bearing |
| E | Arm Cylinder | K | Undercarriage |
| F | Boom | L | Crawler Frame |

**Figure 4-2g.** Electric Shovel (from Ref.11)

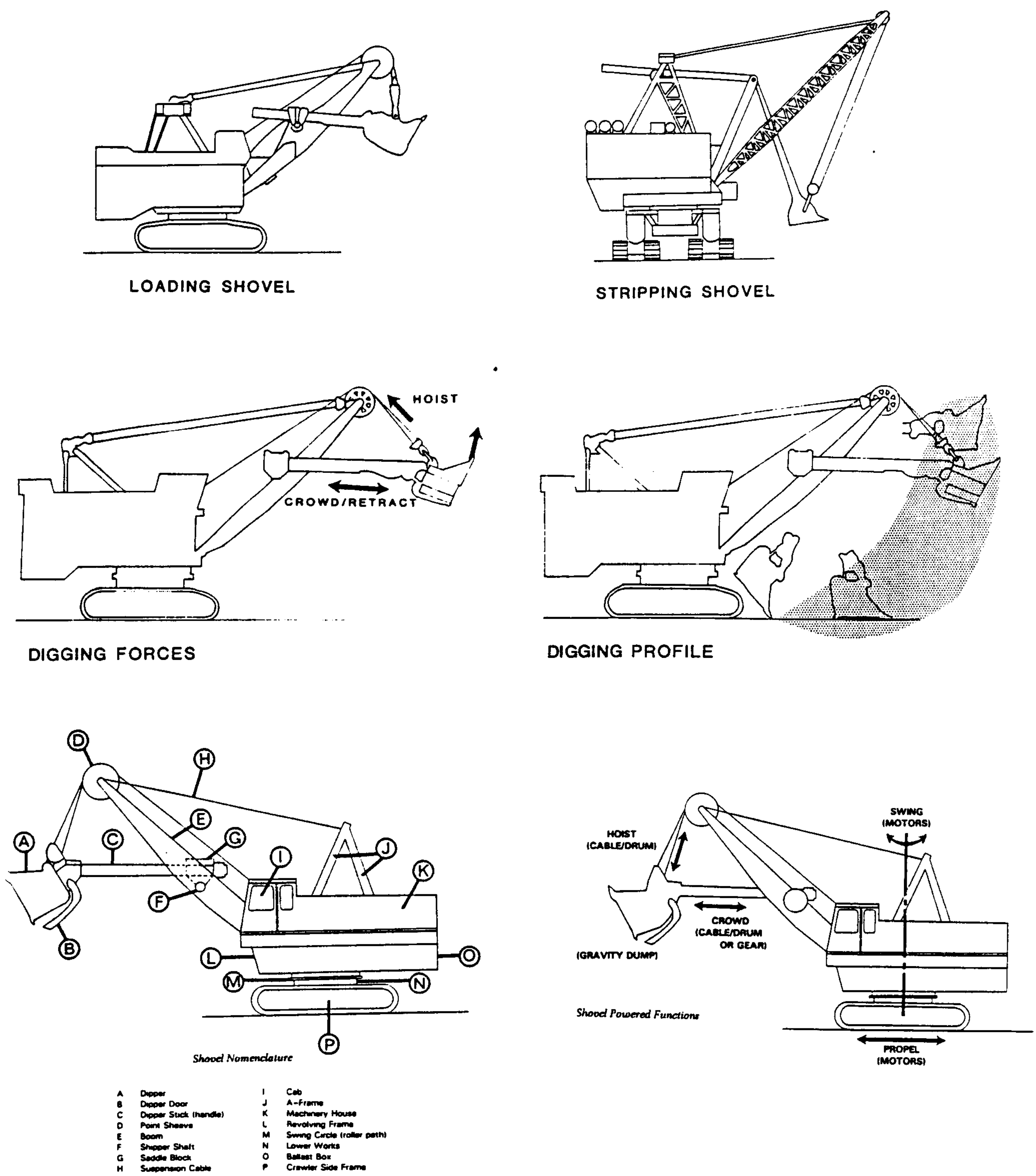
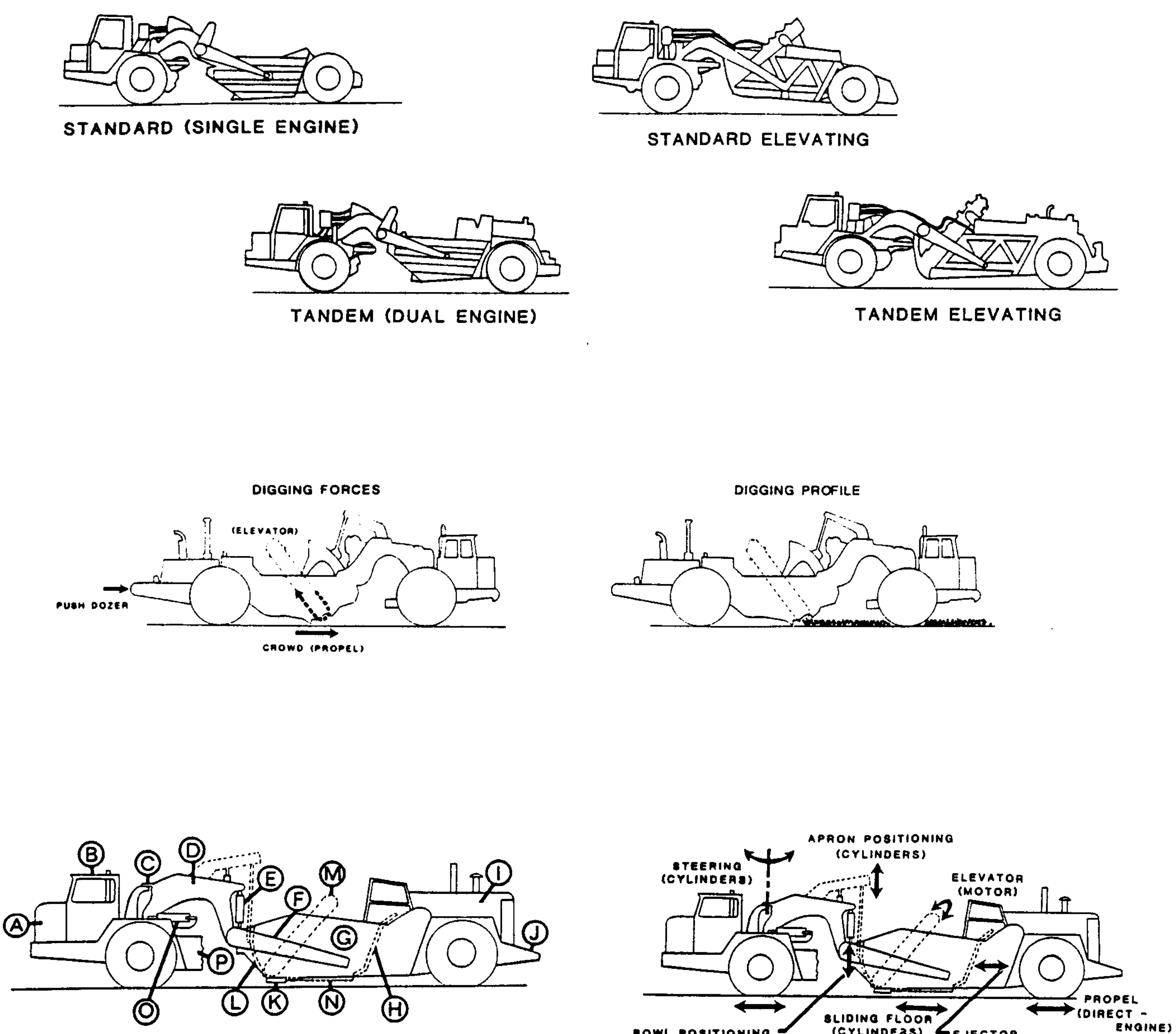


**Figure 4-2h.** Scraper (from Ref.11)




*Scraper Nomenclature*

| | | | |
|---|---|---|---|
| A | Tractor Engine | I | Scraper Engine |
| B | Cab | J | Push Block |
| C | Hitch | K | Cutting Edge |
| D | Gooseneck | L | Apron |
| E | Bowl Cylinder | M | Elevator |
| F | Draft Arm | N | Sliding Floor |
| G | Bowl | O | Steering Cylinders |
| H | Ejector | P | Transmission |

*Scraper Powered Functions*

**Figure 4-2i.** Mobile Drill Rig (from Ref.11)

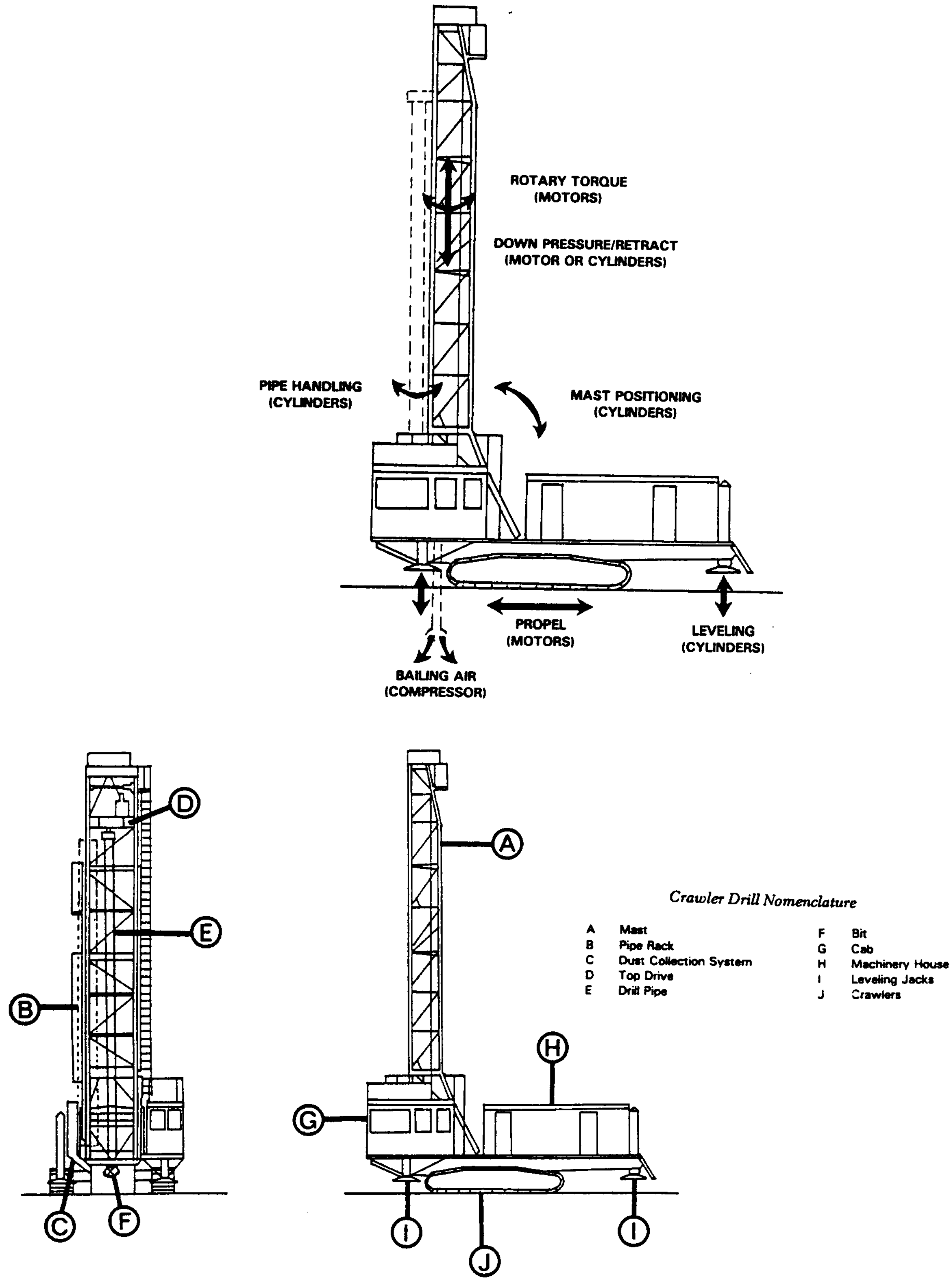


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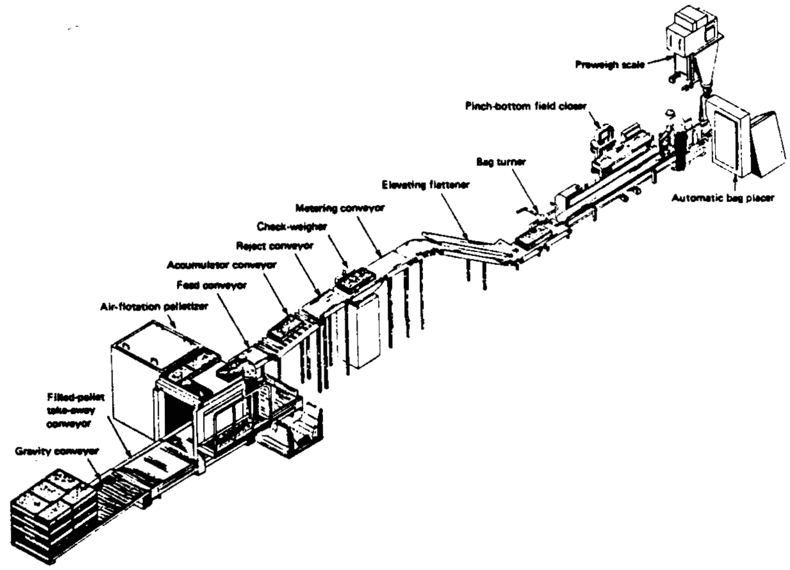
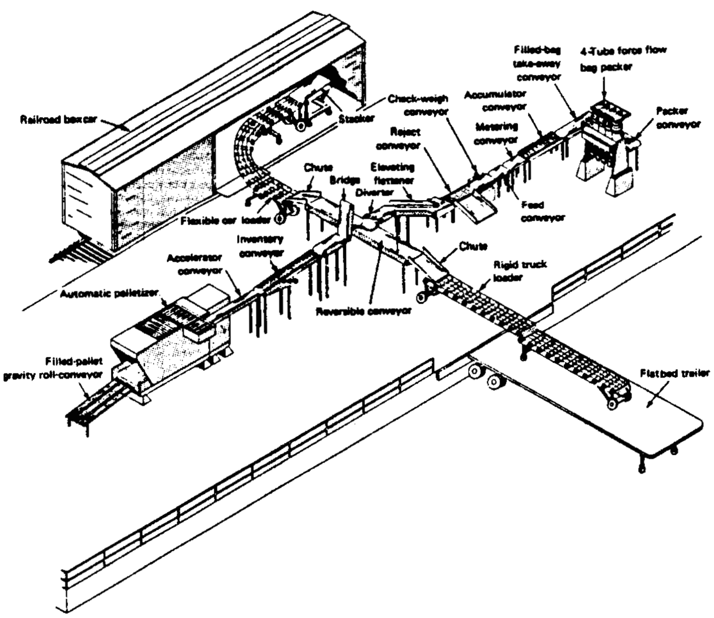
**Figure 4-2j.** Bag Filling Equipment (from Ref.63)

**Typical pinch-bag closure system with automatic bag filling and semiautomatic palletizing. (Pinch-bag closure is a method that heat seals a filled bag closed by applying adhesive or hot pressing with the adhesive preapplied to the open end).**




**Typical forced-flow bag packer with automatic palletizing and truck and railcar loading facilities.**



## 4.3 Hand Tools

Hand tools are used in light construction tasks (low volume excavation, trenching, low mass transporting) and assembly tasks (bolting, riveting, drilling, cutting, hammering, etc.). A review of pertinent Apollo tools and a listing of terrestrial construction/assembly hand tools is provided in the following sections.

### 4.3.1 Apollo Tools

Sampling tools used during the Apollo lunar missions (see Figure 4-3) provide a basis for future development of lunar construction/assembly hand tools. Data on some of the Apollo tools is summarized from literature sources (17-24) below.

| Tool | Mass (kg) | Battery Power (W) | Dimensions (cm) |
|---|---|---|---|
| Rock Hammer | 1.3 | | 44 cm long x 20 cm across head |
| Soil Penetrometer | 2.7 | | |
| Scoop | 0.4 | | 7.5 x 7.5 x 2.5 |
| Trench Tool (Spade) | 1.3 | | 75 x 2; Spade: 15 wide x 20 long |
| Tongs | 0.9 | | 81 cm long x 5 cm diameter |
| Drill (3 m deep cores) | 22.7 | 450 (300 Wh, 40 min) | 57.6 x 24.4 x 17.8 |
| Core tubes for drill | 10.8 (for 9 tubes) | 260 x 3 (each) | |
| Equipment Transporter | 13.6 | | |

### 4.3.2 Space Shuttle EVA Tools

A number of powered and unpowered tools have been developed and space qualified for use on Shuttle missions (64-66). Extravehicular activity tools normally manifested on each mission include (65): diagonal cutters, needle-nose pliers, hammer, probe, vise-grip pliers, bolt puller, forceps, lever wrench, tube cutter, hand winch, centerline latch bypass tool, three-point latch tool, centerline pry bar, 3/8-inch drive ratchet, 3/8-inch drive extension, 3/8-inch drive ratchet with 7/16-inch socket, 1/2-inch box socket ratchet wrench, 1/2-inch open-end wrench, loop pin extractor, and EVA scissors. Auxiliary tools that have been developed for use with the Orbiter but must be requested for use on any particular mission include: power ratchet tool, battery screwdriver, battery power tool, powered screwdriver, and a module service tool for replacing subsystem modules.

Many of the tools used for Shuttle and Apollo missions could be used with little or no modification in lunar construction tasks.

### 4.3.3 Terrestrial Construction Hand Tools

Hand tools used prior to assembly include equipment to survey and sample the site. Additional hand equipment provides limited soil/rock excavation capability.

Surveying Equipment. Typical surveying equipment to layout and mark a construction site includes:

- Electronic distance measurement equipment.
- Field data processing equipment.
- Leveling rod.

- Markers, tape, indicators.
- Measuring Tape.
- Sun compass, azimuth.
- Theodolite with internal level or inclinometer.

Sampling Equipment. Equipment to characterize the subsurface structure prior to excavation includes:

- Active seismic equipment.
- Coring drill.
- Density measurement by nuclear activated Compton scattering of gamma-rays.
- Penetrometers.
- Sample bags, sample containers.
- Trenching tools/equipment.

Construction (Excavation) Tools. The following hand tools would provide capability for small excavations and rock removal.

- Crow-bar.
- Pick.
- Rock drill (percussion, rotary).
- Shovel.
- Sledge hammer and rock chisels.
- Wheelbarrow.

### 4.3.4 Terrestrial Assembly Tools

Typical assembly tools include:

Unpowered tools.

- Bolt puller.
- Bolt cutter.
- Clamps.
- Fasteners: adhesive, bolts/nuts/washers, pins, tape, nails, rivets, screws, etc.
- Files.
- Hammers.
- Levels.
- Pipe wrenches.
- Pliers.
- Plumb bob and line.
- Pry bar.
- Punch.
- Ratchet (socket wrench and end-fittings set)
- Rules.
- Saws.
- Screw drivers.

- Sledge hammer.
- Shears.
- Squares.
- Wrenches.

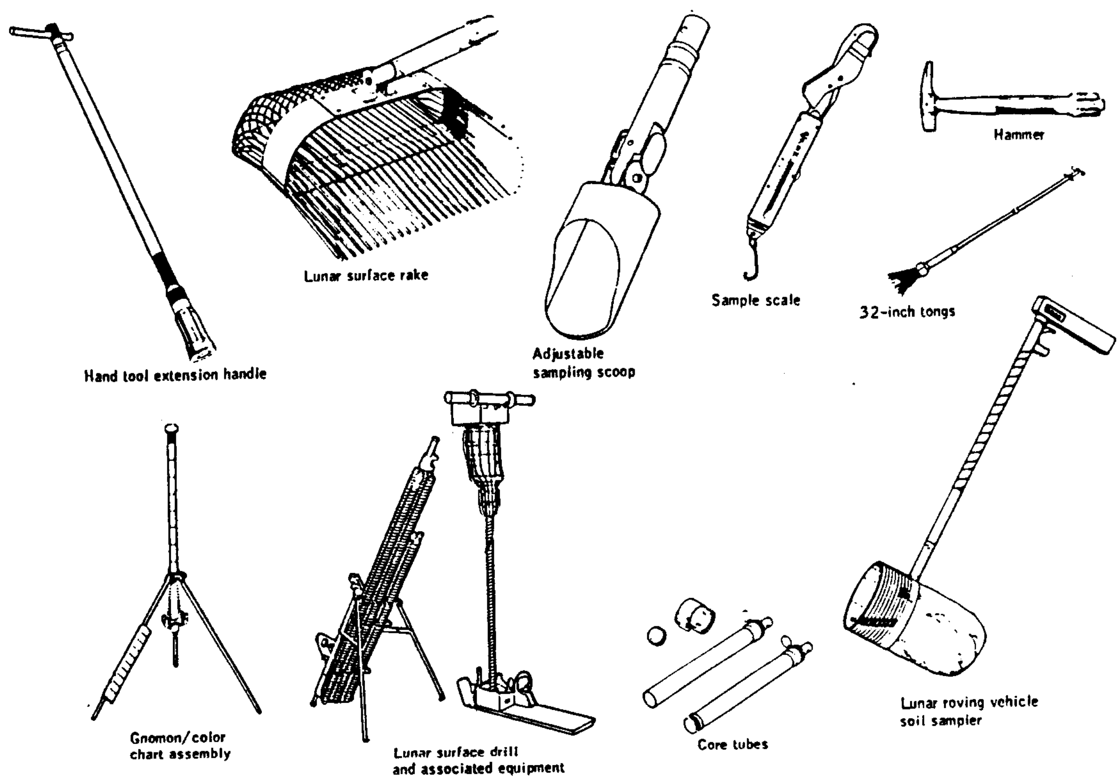
Power tools.

- Drills.
- Ratchet (power).
- Riveter.
- Sander.
- Saws.
- Stapler.
- Variable-speed power tool w/ screwdriver and wrench attachments.
- Welder.

Construction/Assembly aids.

- Balance carrying pole.
- Drop cloth, netting.
- Ladder.
- Lights: flashlight, fixed, mobile, battery and cable powered.
- Ropes, chains.
- Tool storage belt.
- Sample/equipment tow cart.
- Wheeled tool cart.

**Figure 4-3.** Apollo Hand Tools (from Ref.25)



## 4.4 Mechanical Advantage Devices

Mechanical advantage devices are small to medium size devices that increase the productivity of construction/assembly efforts by enhancing the power that a single person can exert.

### 4.4.1 Come-along

Come-alongs are hand-operated devices used to pull or lift loads at any angle over short distances (see Figure 4-4a). A reversible ratchet mechanism in the lever permits the operator to apply tension to the load or to relax tension by releasing the ratchet or friction brake. Come-alongs are used for such tasks as tensioning wires or skidding machinery. The following lists capacity, mass, and retracted distance for typical come-alongs having a minimum hook travel of 1.32 m (14):

| Pull/Lift Capacity (metric tons) | Net Mass (kg) | Retracted Distance Between Hooks (cm) |
|---|---|---|
| 0.68 | 7 | 35.5 |
| 1.4 | 12 | 40.5 |
| 2.7 | 16 | 48.5 |
| 5.4 | 30 | 61.0 |

### 4.4.2 Pulleys

Several pulleys in combination are commonly used with a cable, chain, or rope to increase the applied force for hoisting or hauling loads. A single pulley can be used to change the direction and point of application of a pulling force, or to transmit power from a rotating machine. A pulley block combination is shown in Figure 4-4b. The force necessary to lift a load is equal to the weight of the load divided by the number of ropes run between the pulleys (4 as shown in Figure 4-4b). The following lists data for hand-operated chain blocks (spur-geared) that are available (67):

| Capacity (mt) | Lift (m) | Weight (kg) |
|---|---|---|
| 1 | 2.4 | 45 |
| 2 | 2.7 | 93 |
| 3 | 3 | 100 |
| 5 | 4 | 190 |
| 9 | 4 | 280 |
| 18 | 4 | 560 |

### 4.4.3 Electric Hoists

Electric hoists are used for repetitive and high-speed lifting. There are two types of electric hoists (see Figure 4-4c): chain, available in capacities up to 4.5 metric tons (weight), and wire rope, rated up to 18 metric tons. The hoists may be suspended by an integral hook or attached to a trolley rolling on an I-beam or monorail. Trolleys can be plain push-type, geared (operated by a hand chain), or motor-driven (used for heavier loads). Control is usually by push button and of the "deadman" type, the hoist stopping instantly upon release. The following data for chain and wire-rope electric hoists is from the literature (14).

**Electric Chain Hoists w/ Hook Suspension**

| Capacity (metric tons weight) | Lifting Speed (m/min) | Net Mass (kg) | Motor Power (kw) | Retracted Distance Between Hooks (cm) |
|---|---|---|---|---|
| 0.11 | 10 | 28 | 0.19 | 38 |
| 0.23 | 10 | 31 | 0.37 | 38 |
| 0.45 | 10 | 48 | 0.75 | 40.5 |
| 0.91 | 5 | 48 | 0.75 | 40.5 |
| 0.91 | 10 | 51 | 1.49 | 43 |
| 1.81 | 5 | 58 | 1.49 | 63.5 |

**Electric Wire-Rope Hoists w/ Plain Trolley**

| Capacity (metric tons weight) | Lifting Speed (m/min) | Net Mass (kg) | Motor Power (kw) | Distance From Beam to High Hook (cm) |
|---|---|---|---|---|
| 0.45 | 18 | 195 | 1.5 | 66 |
| 0.68 | 11 | 195 | 1.5 | 66 |
| 0.91 | 9 | 210 | 1.5 | 63.5 |
| 1.36 | 9 | 210 | 2.2 | 63.5 |
| 1.81 | 9 | 220 | 3.0 | 63.5 |
| 2.72 | 5 | 255 | 3.0 | 63.5 |
| 4.54 | 4 | 320 | 3.4 | 71 |

A winch is similar to a hoist except that it is located in a fixed position and acts on a drum which stores cable (wound on drum).

### 4.4.4 Jacks

Jacks are portable, manually operated devices for moving heavy loads through short distances. Three types are in common use: screw jacks, rack-and-lever jacks, and hydraulic jacks.

Screw jacks are operated by rotating a bar inserted in holes in the screw head or by using a ratcheted lever fitted to the head. Screw jacks are available that can lift loads up to 22 metric tons (weight) to distances ranging to 36 cm (14). A screw jack derivative, the geared bridge jack, will lift 45 metric tons (14).

The familiar automobile jack is an example of a rack-and-lever jack. These jacks consist of a lever that pivots within a hollow housing and engages a rack (toothed bar) that passes through the housing. The load can be either raised or lowered by manually biasing the lever pawl. The load is lifted either on the top of the bar or on a toe extending from the bottom of the bar. Direct-acting rack-and-lever jacks are available to lift 18 metric tons to heights of 46 cm. More complex geared jacks lift up to 32 metric tons.

The main components of a hydraulic jack is a cylinder, piston, and lever-operated pump. Hydraulic jacks are available that lift 91 metric tons up to 56 cm (14).

### 4.4.5 Ramps

Ramps can be either solid sheets or rails that are utilized as an aid in raising or lowering objects (such as loading or unloading cargo elements from the lander). A ramp acts to reduce the required force involved in moving objects over a vertical distance. This also tends to improve the ability to maintain control of the raising/lowering operation when limited force is available. Advantages of a ramp are maximized when the objects to be moved have rollers, wheels, or skids that reduce friction on the ramp. The force necessary to move an object through a given vertical distance is reduced from the weight of the object with no ramp to (when using a ramp) the sum of the object's weight mutiplied by the sine of the angle the ramp makes with the ground and the force to overcome friction on the ramp. When frictional forces are low (as when using rollers, or other friction reduction mechanisms) and the ramp angle is not steep, the force required to push a load up a ramp can be substantially less than that required to haul it vertically upward. Depending on the speed desired to pull an object up a ramp, the required power (force times speed) for the loading operation can also be reduced. However, more energy will be expended to move an object using a ramp than by moving the object directly up through a given vertical distance (because friction must be overcome on the ramp).

### 4.4.6 Rollers

Roller conveyors consist of tubes that are free to rotate on an axle, but which are confined within a frame (see Figure 4-4d). Unpowered roller conveyors are set at a definite grade to facilitate movement of goods on the track. These conveyors are used in the movement of all sorts of packaged materials that have smooth surfaces and which are sufficiently rigid to prevent sagging between rolls. The size and spacing of the rollers depends on the size and weight of the object to be moved, but as a general rule, three rollers should be in contact with the package to prevent hobbling. The grade of fall required to move the object depends on the weight and character of the material in contact with the rollers, but typically varies from 1.5 to 7 percent. Power-operated roller conveyors move materials up an incline.

A low-technology alternative is to use round bars or tubes (i.e. rollers) that can simply be placed under objects to assist in moving them. As an object is pulled over them, they must constantly be recycled to the front of the object to continue the process.

### 4.4.7 Skids

Pallets or skids are flat, horizontal platforms on which material is stacked so that it can be picked up and moved by a forklift (see Figure 4-4e). Equipment is also often rigidly mounted to a skid so that it can be more easily moved.

### 4.4.8 Wheels

Properly sized wheels attached to a cargo element, or to a pallet that is holding the element, can simplify the movement of the cargo element. The wheel design depends on the load to be carried, the surface conditions which must be traversed, available power, and other factors (1).

**Figure 4-4a.** Come-Along Hoist (from Ref.14)

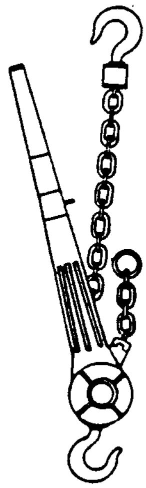


**Figure 4-4b.** Pulley System (from Ref.14)

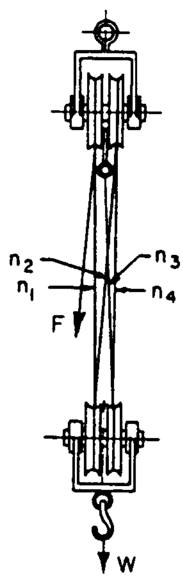
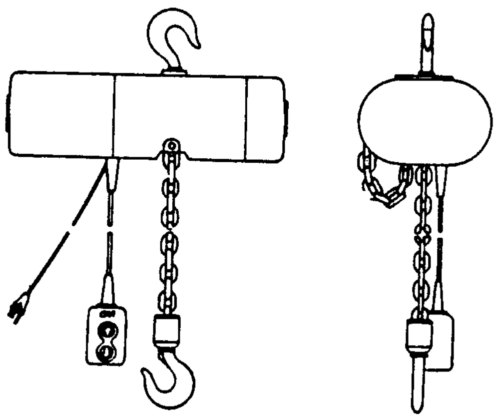


**Figure 4-4c.** Electric Hoists (from Ref.14)

Chain



Wire-Rope

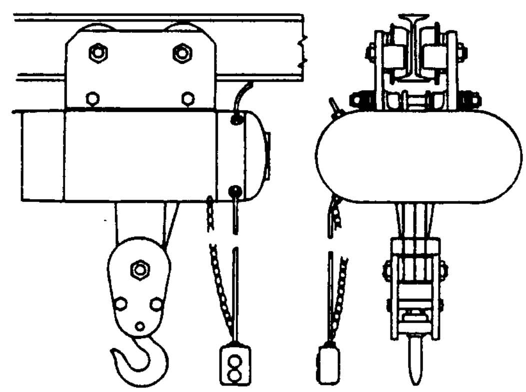
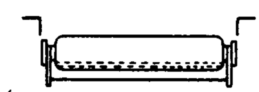


**Figure 4-4d.** Cross-Section of Roller Conveyor (from Ref.14)

Single Roller



Multiple-Roller

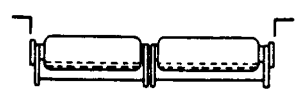
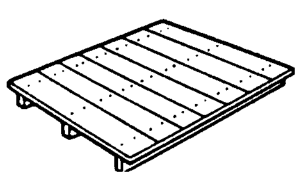
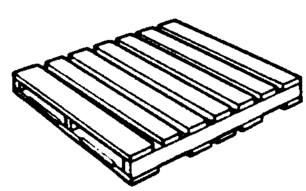


**Figure 4-4e.** Pallets (from Ref.14)

Single-Faced



Double-Faced



## 4.5 Transporters

The capability to transport cargo elements and quantities of soil/rock will be required during lunar construction and assembly operations. The following describe frequently employed terrestrial options for transportation.

### 4.5.1 Conveyors

Belt conveyors consist of a continuous belt, a head (drive) pulley, a take-up pulley, and carrying and return idlers (see Figure 4-5a). Belt conveyors are capable of transporting large quantities of material (4500 metric tons/hr) at 5 m/s over many kilometer distances in a fully-automatic mode. A major advantage with belt conveyors is that they provide continuous haulage. Belt conveyors can be routed over rolling terrain, but are limited to elevation angles of 30° or less (the limit is reached when the material tends to slip on the belt). Typically, belt conveyors are fixed, with limited mobility. However, shiftable belt conveyors are available that are skid mounted units made up of 5-6 m long modules that can be shifted laterally in steps of a meter or so. 15-35 m long mobile belt conveyor modules are also available that can be arranged to deliver material from one section to another as shown in Figure 4-5a. Individual belt modules (or flights) are required to be relatively straight. Changes in direction can be accomplished with by overlapping two belt conveyor sections at different angles. The top of the belt is usually arranged in a U-shape to carry more material with the outside pulleys of each set of three idler pulleys at a 20° angle.

The following is a partial list of other conveyor types often used in specialized applications. Although well suited for certain situations, they have some fundamental weakness that limits their general applicability (such as short maximum lengths).

Screw Conveyors. Consisting of a rotating screw turning in a trough or enclosed pipe, these conveyors transfer up to 4.7 $m^3$/min (26). Length is limited to under 60 m and inclination for a standard-pitch helix to 35°. Capacity is reduced 78% with a 35° incline from the capacity achieved when horizontal.

Continuous-Flow Conveyors. These are low-speed conveyors that contain solid surfaces or skeleton-type conveying elements that are mounted on a continually circulating loop within a fully enclosed duct. They work on the principle that a surface pulled transversely through a mass of granular, powdered, or small-lump material will pull along a cross-section of material greater than the area of the surface itself. A major advantage with these conveyors is that they can follow complicated paths (regular or irregular) in a plane. This feature makes the continous-flow conveyor extremely versatile since it can be both a horizontal conveyor and elevator with a single drive. Capacity is determined by the speed and cross-sectional area of the conveying elements. Volumetric flow rate capacity is approximatly 100 percent of the volume swept out by the elements for conveyors inclined at less than the angle of repose of the material conveyed, and 50-90 percent for steeper inclines or elevators (14, p.10-46). Continuous-flow conveyors do not require a feeder. They self-load to capacity without overloading. They occupy little space, need little support because the casing enclosure forms a rigid girder, and can be fed and discharged at multiple points.

Bucket Elevators. Consisting of a series of closely spaced buckets mounted on cables, chains, or a belt, bucket elevators are the simplest and most dependable units for making vertical lifts. Capacity is usually calculated by assuming the buckets are three-fourths full. When loaded by a feeder, speeds of 0.3 m/s are attainable (14).

Tube Conveyors. Tube conveyors are a combination of belt conveyor and aerial or suspended cable conveyor. Material is loaded on the belt in the normal manner. The belt of the tube conveyor is then molded into a tube that completely envelops the load during transport. At the destination, the belt is unrolled and material discharged in the normal way. The tube conveyor shown in Figure 4-5a consists of a continuous loop belt supported at its edges by two cables. The cables are brought together to suspend the load in a teardrop shape below the cables. Trolleys or carry rollers are positioned at intervals up to 100 m from towers or suspended from a fixed support cable. The rollers keep the belt closed by fitting under V-sections at the underside of the outer edges of the belt. The conveyor drive propells the twin cables/belt in the usual manner when the belt loop passes around horizontal drums at either end of the route. Curves in both horizontal and vertical planes are possible. The mininum curve radii for turns are 300 x tube diameter for fabric belts and 1000 x tube diameter for steel cord belts. Capacities of 400 mt/h on a 0.5 m wide belt are reported (27). Three outstanding features with this type conveyor are: 1) exceptionally clean operation because dusty loads are enclosed for essentially the entire transport distance (particularily important in windy terrestrial conditions), 2) suspended cable makes concept ideal in traversing rough terrain, and 3) only 10 percent of the components of a conventional belt conveyor are required for the suspended tube conveyor concept saving on maintenance (27) and possibly transport mass.

### 4.5.2 Overhead Trolley

An overhead trolley (see Figure 4-5b) consists of an overhead track (enclosed tube, open tee, or I-beam type) which supports a series of trolleys or wheels. The trolleys are connected together and propelled by a chain, cable, or other linkages in an endless loop. Loads are suspended from the trolleys. Lightweight to heavy-duty trolleys and tracks are available to handle a wide range of payloads. This conveyor is usually applied in manufacturing situations where a single fixed path is required that moves at a selected speed. "Power-and-free" conveyors are also common which differ from powered trolleys in that the loads are suspended from free trolleys that are not permanently attached to the propelling conveyor but are simply pushed by the conveyor. Multiple paths are therefore possible with power-and-free overhead conveyors. Conveyed work pieces can be switched automatically from one portion of the conveyor to another; either or both of these conveyor tracks can be powered or unpowered. Gravity flow and manual means are used in unpowered sections to move the work pieces.

### 4.5.3 Trucks

A truck is a basically an engine on wheels which can provide utilitarian services as a tractor for pulling or pushing trailers and implements. In some cases, the implement is built into the body as in a dump truck or a flatbed for cargo transportation. Several types of trucks for mining operations are available including rear and bottom dump versions (see Figure 4-

5c).

### 4.5.4 Trailers

Trailers for transporting materials and cargos include:

- Flat bed trailers for cargo (see Figure 3-5).

- Bottom-dump wagons. These units are used terrestrially to reduce the time required to unload dry materials (sand, grain, coal, etc.) which flow easily (13, p.253).

- Rear-dump wagons for transporting all types of materials.

- Scraper wagons drawn by tractor (see Figure 4-5d). These four-wheel trailers are used to pick up, transport, and dump surface materials. General rules of thumb used to match a drawn, self-loading scraper to the right size tractor are that the tractor should have at least 12 net kw/m$^3$ of wagon capacity (measured on a "struck" or non-heaped basis) and have an operating weight 10 to 20 percent more than scraper payload weight.

### 4.5.5 Tractor (Prime Mover)

Tractors are either wheeled or tracked vehicles that can pull or push trailers and scrapers, and can be equipped with accessories to perform various tasks. Accessories include:

- Front-mounted bulldozer blade operated by cable or hydraulic control. Several different blades are available including straight, universal (U-blade), angling, push (cushion) blade, root rake, rock rake, stump dozer, and tree dozer. Angledozers are fitted with an long, narrow blade set at a 25° angle to the direction of travel for side casting at higher speeds than push dozing. Angledozers are often employed in backfilling trenches, clearing roads, and sidehill benching (creating an earthen face or wall for excavation by loaders or other units). Straight blades are effective for ditching when pitched backward 10° or to push heavy materials (pitched forward). U-blades are applied in pushing loose material and can handle 15-20 percent more material than straight blades. Push blades are designed to push other equipment (i.e. scrapers) without damaging them. Additional details are given in Section 4.2.

- Cable (double-drum winch) control unit. This unit is used for pulling equipment, controlling other implements, or freeing itself if it gets stuck.

- Rear-mounted ripper to loosen consolidated or hard materials.

- Tractor crane. A boom with limited swinging radius.

- Side boom. A boom mounted on one side with a counterweight on the opposite side used to lay coss-country pipelines.

- Drills. A tractor often provides mobility and power for some drill functions (air compressors and hydraulic pumps).

- Welder. Power and mobility for welding machines provided by tractor.

- Front-end shovel and Backhoe. Four-wheel drive tractors with loader on front and backhoe excavator at rear are available.

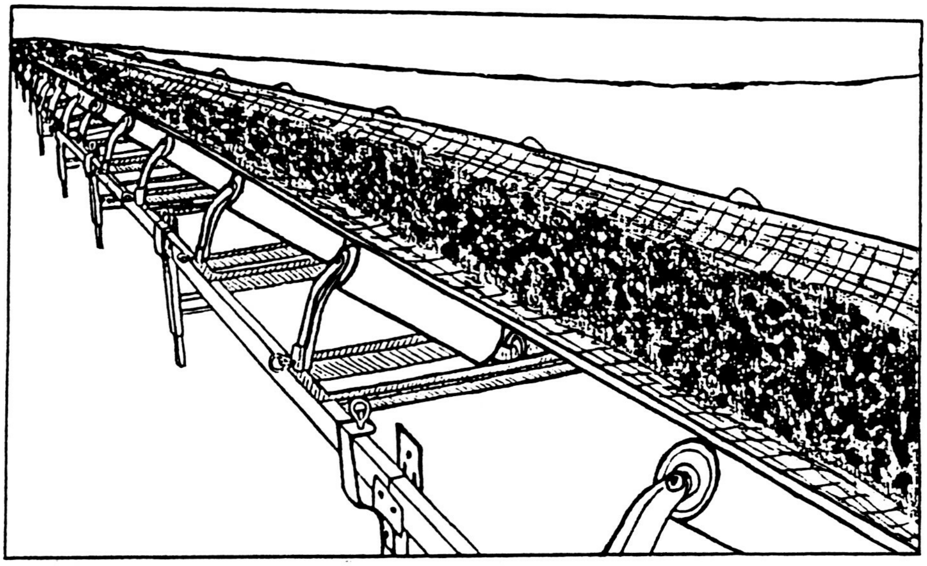
- Towed or pushed compactor rollers.

### 4.5.6 Railroad

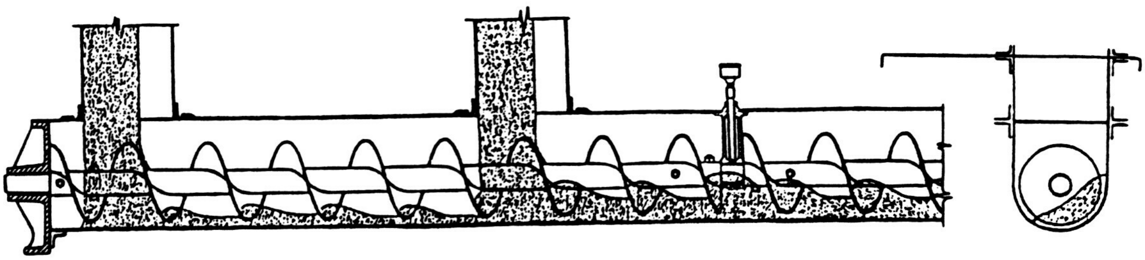
Locomotives and rail cars are used to haul large quantities of raw materials and cargo long distances over a fixed path. Rail cars have been designed for handling bulk material with rapid discharge capability by various dumping mechanisms. A 10 metric ton locomotive is capable of hauling 250 metric tons on a horizontal track or 80 metric tons up a 2% grade (14).

**Figure 4-5a.** Conveyors

Belt Conveyor (Ref.14)



Screw Conveyor (Ref.26)



Tube Conveyor (Ref.27)

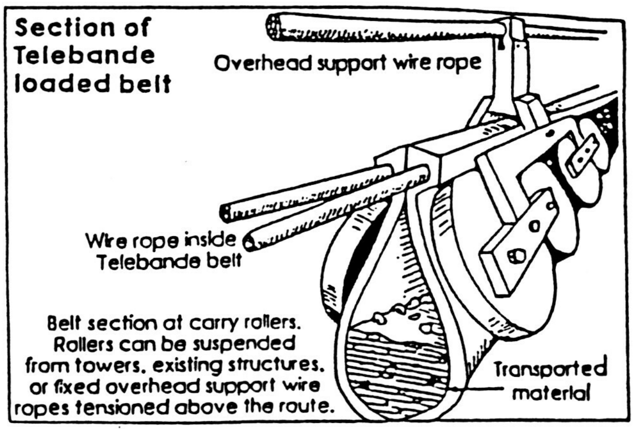
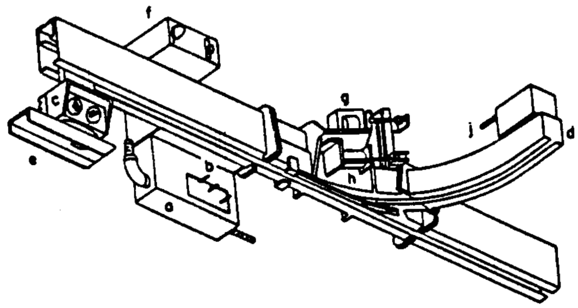


**Figure 4-5b.** Overhead Trolleys (Ref.14)



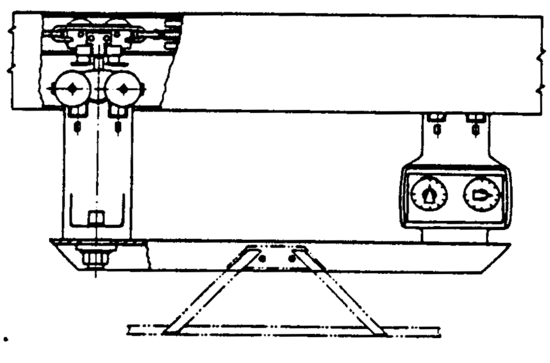
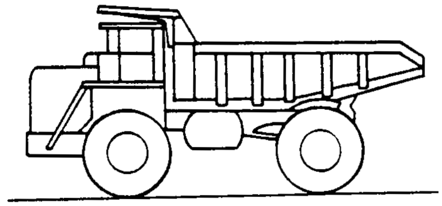
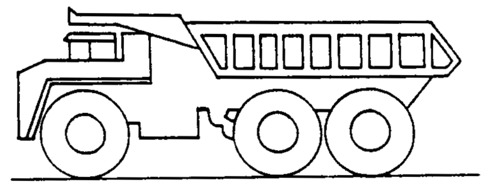



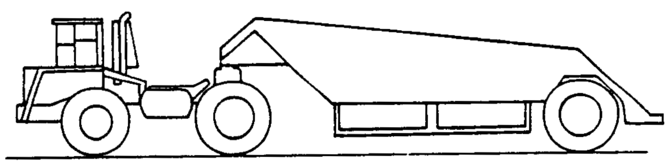
**Figure 4-5c.** Trucks (Ref.11)



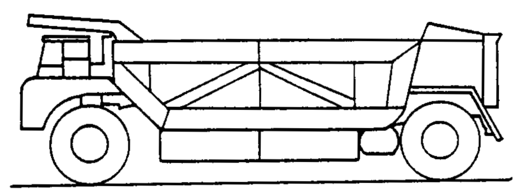
2 - AXLE REAR DUMP



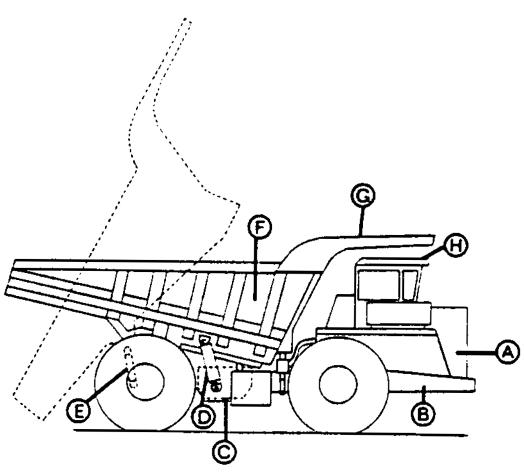
3 - AXLE REAR DUMP



3 - AXLE BOTTOM DUMP

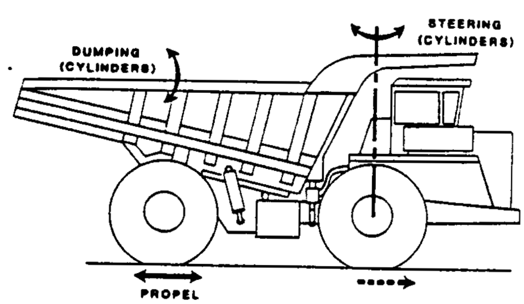


2 - AXLE BOTTOM DUMP



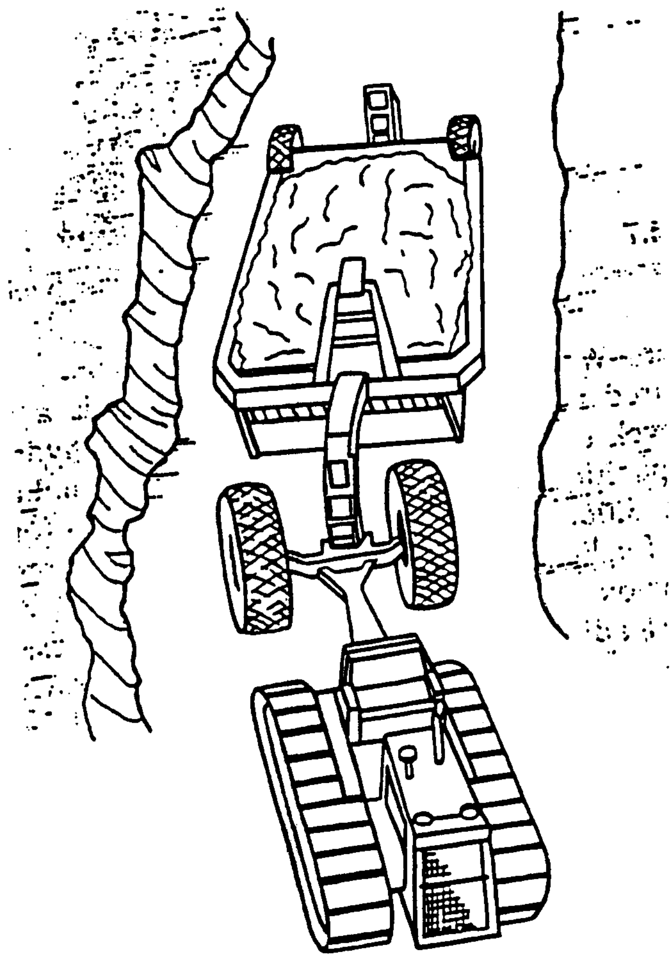

*Truck Nomenclature*

A Engine
B Main Frame
C Transmission
D Body Lift Cylinder
E Suspension Cylinders
F Body
G Canopy
H Cab




*Truck Powered Functions*

**Figure 4-5d.** Tractor pulled Scraper (Ref.14)



## 4.6 Terrestrial Construction Equipment Application Considerations

Considerations when selecting construction equipment include:

- Task Requirements. Volume and rate of soil moved, constraints on type of lunar material needed, mass/size of cargos to be moved, distance and speed of cargo transport.
- Site Conditions. Type of material excavated, nature and degree of consolidation, stability of banks (face or side of excavation), amount and size of rocks.
- Equipment parameters. Mass, size, and power requirements for given productivity. Production constraints (excavation profile, maximum rock size). Operations (crew time, automation) and maintenance requirements. System reliability, mobility, and versatility (ability to perform multiple tasks).

Features of the power and drive systems of terrestrial construction equipment is given in Table 4-1. The crawler (tracked-type) locomotive mechanism is associated with higher complexity ratings and potentially lower reliability than wheeled propulsion, but it offers the advantage of greater traction and drawbar pull.

A comparison of equipment parameters for various types of equipment is given in Table 4-2. These numbers are only averages because performance ratios vary with machine size. Typical variability of machine mass and power requirements with size are illustrated in Figures 4-6 and 4-7.

A list of additional comparison factors important in proper selection of excavators, transport units, and drills is given in Table 4-3.

General ratings of the strengths/weaknesses of different excavating equipment, grading/leveling equipment, and transport equipment are shown in Tables 4-4, 4-5, and 4-6.

**Table 4-1.** Construction Equipment Power and Drive Systems (from Ref.11)

| | Power-Plant Type | Drive System | Locomotion Type | Implement Actuation System |
|---|---|---|---|---|
| Dozers | diesel | torque converter/ transmission | tracks or wheels | hydraulic cylinders/ linkages |
| Scrapers | diesel | torque converter/ transmission | wheels | hydraulic cylinders/ linkages |
| Front-End Loaders | diesel | converter or electric motor | wheels | hydraulic cylinders/ linkages |
| Hydraulic Excavators | diesel | hydraulic | tracks | hydraulic cylinders & gears |
| Electric Shovels | electric | electric | tracks | cable & drums/ gears |
| Draglines | diesel or electric | electric | tracks or walking shoes | cable & drums/ gears |
| Wheel Excavators | diesel or electric | hydraulic and/or electric | tracks | hydraulic cylinders & gears |
| Trucks | diesel | converter or electric motor | wheels | converter or motors & gears |
| Rotary Drill | diesel or electric | hydraulic/ electric | tracks or wheels | chain & gears |

**Table 4-2.** Mass and Power Ratios for Construction Equipment (from Ref.11,13,16) (approximate averages)

| | Machine Mass per Capacity (metric tons/m³) | Cycle Time (min) | Machine Mass per production rate* (mt-hr/m³) | Total Power per machine mass (kw/mt) | Energy per machine mass and distance traveled [kw-hr/mt-km] | Service Life (hrs) | Swell Factor | Fill Factor | Work Cycle Factor |
|---|---|---|---|---|---|---|---|---|---|
| **EXCAVATORS** | | | | | | | | | |
| Dozers (tracked) (30 m passes) | 5.3 | 1.4 | 0.15 | 7.0 | | 12,000 | 1.25 | 1.0 | 0.83 |
| Scrapers (standard) (610 m one-way haul distance) | 1.72 | 5.2 | 0.18 | 8.2 | [0.21] | 12,000 | 1.0 | 1.0 | 0.83 |
| Front-End Loader (10 m haul, 0.4 min load/dump per cycle) | 7.1 | 0.7 | 0.12 | 7.0 | | 12,000 | 1.25 | 0.95 | 0.83 |
| Hydraulic Excavators (shovels) | 17.8 | 0.8 | 0.40 | 3.9 | | 30,000 | 1.25 | 0.90 | 0.83 |
| Electric Shovels | 32.0 | 0.5 | 0.42 | 1.3 | | 75,000 | 1.25 | 0.95 | 0.83 |
| Draglines (walking) | 67.6 | 0.5 | 0.89 | 1.5 | | 100,000 | 1.25 | 0.95 | 0.83 |
| Bucket Wheel Excavators (medium size) | 68.9 | 0.3 | 0.62 | 1.2 | | 30,000 | 1.25 | 0.75 | 0.83 |
| **TRANSPORTERS** | | | | | | | | | |
| Trucks (Rear dump) (1.1 km, travel time 4.5 min, remainder load) | 1.07 | 10 | 0.21 | 11.5 | [0.23] | 20,000 | 1.0 | 1.0 | 0.83 |
| Scrapers (standard) (610 m one-way haul distance) | 1.72 | 5.2 | 0.18 | 8.2 | [0.21] | 12,000 | 1.0 | 1.0 | 0.83 |
| Belt Conveyor (based on 36" wide belt, 20° idlers, 1 km long, 100 fpm) | 1.0 | 33 | 0.55 | 0.46<br>1.56 | [0.25] (horiz.)<br>[0.85] (5° slope) | 88,000 (belt) | 1.0 | 1.0 | 1.0 |

PRE-EXCAVATION PREPARATION (BLASTING)

| | (mt/cm) | (m penetration/min) | (kw/mt) | Life (hrs) |
|---|---|---|---|---|
| Rotary Drills (crawler) | 3.5 | 0.32 (max.) | 3.8 | 30,000 |

(ratios per maximum bit diameter, cm, with bit diameter range 13-38 cm, penetration based on hard rock formation)

* Production rate has been compensated for typical fill, swell, and productivity factors (inefficiencies).

Material swell factor: Ratio of material volume in bucket to volume in natural un-mined or "bank" condition.
Bucket fill factor: Amount of material as a percent of rated bucket capacity which is actually delivered per bucket per cycle.
Work cycle factor: Percent of time actually working in a given period of time (typically use 50 minutes work per hour). This factor compensates for time spent waiting for another unit (if two units are functioning together as in excavator/hauler team), delay time (other time when a machine is not performing during the work cycle), and operator break time.

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**Figure 4-6.** Operating Weight of Excavation/Loading Equipment (from Ref.11)

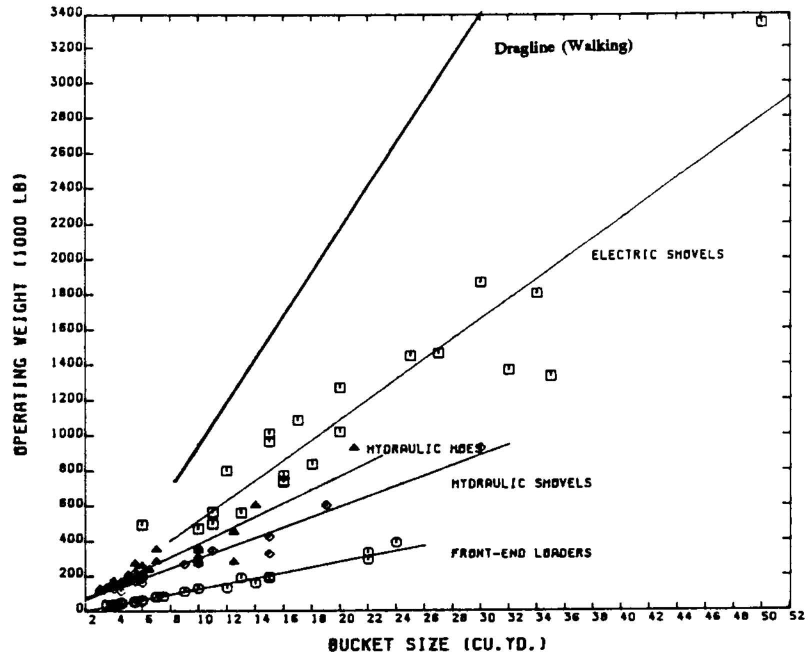



**Figure 4-7.** Power for Excavating/Loading Equipment (from Ref.11)

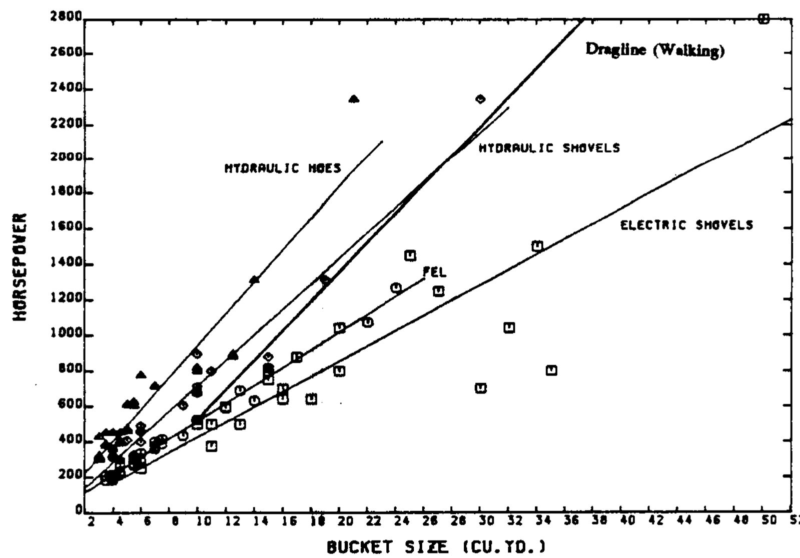


**Table 4-3.** Considerations and Comparison Factors for Construction Equipment (from Ref.11)

| Excavators/Loaders | Transport/Trucks | Preparation/Drills |
|---|---|---|
| Bucket capacity | Payload | Hole size |
| Digging capabilities: | Weight | Drilling rate: |
| - Cutting forces | Power | - Down pressure |
| - Cutting speeds | Gradeability | - Rotary torque |
| - Cutting path/action | Speed ranges | - Rotary speed |
| - Cycle time | Acceleration | - Compressor size |
| Digging height | Retardation/braking | Mast height |
| Dumping height | Traction | Max. Drilling Depth |
| Reach | Turning radius | Cycle time: |
| Ground pressures | Dump speed | - Pipe Changes |
| Swing speed/turning radius | Reliability | - Machine Relocation |
| Propel speeds | Maintenance requirements | Maneuverability |
| Gradeability | Parts inventory required | Travel Speeds |
| Tractive effort | | Gradeability |
| Reliability | | Degree of Automation |
| Maintenance requirements | | Reliability |
| Parts inventory required | | Lifetime of components (i.e. drill bits) |

**Table 4-4.** General Excavator Characterizations (from Ref.11)
(Relative comparisons made between units of same general size)

| | Front-End Loader | Hydraulic Excavator | Electric Shovel | Bucket Wheel Excavator (Medium) | Dragline |
|---|---|---|---|---|---|
| Sizes ($yd^3$) available* | 3 to 24 | 3 to 30 | 15 to 50 | 1.5 to 16 | 10 to 180 |
| Production Avg. ($yd^3$/hr)* | to 2000 | to 1800 (hoe) to 2400 (shovel) | to 5500 | to 3000 | to 7500 |
| Hard Digging capability | fair | good | excellent | limited (no boulders) | good |
| Mobility | excellent | good | poor | poor | poor |
| Reliability | medium | medium | high | low | high |
| Crew Size | 1 | 1 | 1-2 | 1-2 | 1-3 |
| Digging Path | semi-fixed | variable | semi-fixed | fixed | variable |
| Face Height (Maximum) | low | high | high | medium | high |
| Dump Height | marginal | good | good | good | excellent |
| Discharge Complexity | easy | easy | can be difficult | easy | can be difficult |
| Segregation Capability (ability to selectively extract certain materials from digging face) | good | excellent | fair | poor | fair |
| Auxiliary Equipment (often employed to remove debris from around excavator) | none | none | dozer | dozer | dozer |

* Production and size based on loaded material bulk weight density of 1,780 kg/$m^3$.

**Table 4-5.** General Characterization of Grading/Leveling Equipment (from Ref.11)
(Relative comparisons made between units of same general size)

| | Dozer | Scraper | Grader | Dragline |
|---|---|---|---|---|
| Rough leveling | excellent | fair | poor | good |
| Grading | excellent | good | good | fair |
| Fine grading | good | fair | excellent | poor |
| Lateral displacement of loaded material (m) | to 100 | to 1500 | to 5 | to 150 |
| Surface compaction | medium | high | medium | low |
| Capital Costs | low | low | low | high |
| Operating Costs | high | high | medium | low |

**Table 4-6.** General Characterization of Transportation Systems (from Ref.11)
(Relative comparisons made between units of same general size)

| | Front-end Loader | Scraper | Truck | Belt Conveyor* |
|---|---|---|---|---|
| Capacity (mt/hr) | to 725 | to 1100 | to 2300 | to 4500 |
| Distance (m) | 15-300 | 150-1500 | 300 and up | 1800 and up |
| Grades (deg.) while loaded | to 7° | to 7° | to 6° | to 15° |
| Avg. Speed (km/hr) while loaded | 8-16 | 24-40 | 30-55 | 10-23 |
| Reliability | medium | medium | medium | high |
| Crew | 1 | 1 | 1 | none |
| Handling large blocky material | good | poor | good | poor |
| Flexibility for length change | excellent | excellent | excellent | fair |
| Flexibility for route change | excellent | excellent | excellent | poor |
| Haul road condition | prepared by loader | prepared by scraper | graded | none |
| Capital Costs | medium | medium | medium | medium/high (setup costs) |
| Operating Costs | high | high | high | low |

* Shiftable and series of modular conveyors considered (180 cm wide and smaller).

## 5.0 Construction Job Description Set

The construction schedule for a remote exploration or industrial base, on Earth or the Moon, can be decomposed into a network of smaller, fundamental jobs. This set of fundamental jobs, although not all necessarily required in every construction project, could be considered a shopping list from which selections are made to build a construction plan for a large project.

The construction jobs which make up the job description set for the lunar base in this study are listed in the following sections with a brief generic description. Alternate plans and approaches for performing each job have been conceived where possible. These alternate plans are described in Section 6.

### 5.1 Anchor an Object

It is likely that numerous requirements may develop for anchoring objects to the lunar surface. Examples include crane guy wires, permanent habitat stablization holddowns, canopy tiedowns, and temporary winch/cable or come-along anchor-legs. A come-along connected to an anchor leg could attempt to move loads as large as 10 mt (such as a dry lander) to 25 mt (maximum lander cargo).

### 5.2 Unload a Lander

Section 3.2 of the baseline requirements identifies the types of cargo that may require unloading.

### 5.3 Contingency Methods to Unload a Lander

The types of contingency situations for unloading a lander include unloading the first lander, sorties to remote lunar locations, and out-of-service equipment.

The first cargo lander will, by definition, not have any pre-existing support equipment on the lunar surface to assist in unloading cargo. The cargo unloading devices will be a part of the cargo itself. Therefore, the unloading equipment must be capable of being unloaded with hand tools or of unloading itself.

### 5.4 Move Cargo

The cargo unloaded from the lander must be moved from the landing site to the work site.

### 5.5 Contingency Methods to Move Cargo

It can be assumed that the first cargo must be moved away from the area designated to become the lunar landing facility and to the general area where habitation is planned. If the first cargo includes the surface transportation equipment for cargo, this job is not unique for the first cargo and is the same as the nominal cargo transportation operation. Therefore, it is assumed in this job that no major transportation vehicles are available to support this job.

## 5.6 Prepare Landing Site Prior to Surfacing

The landing site must be surveyed, cleared of boulders, and graded according to the dimensions of the baseline requirements.

## 5.7 Prepare Base Habitation Site Prior to Constructrion

The Base habitation site must be surveyed, cleared of boulders, and graded according to the dimensions of the baseline requirements (see Section 3.4).

## 5.8 Build a Road

The primary need for a road is between the habitation area and the launch and landing facility. Another road between mining and processing areas of a resource utilization facility (such as for a lunar oxygen plant) could reduce haul time for feedstock and tailings (and thus reduce the number/size of haulers required).

## 5.9 Build Landing/Launch Site Facilities

The landing/launch site facilities could include a surfaced lander pad and a covered shelter for the waiting lander.

## 5.10 Move a Lander

It is assumed that a Lander may have to be moved away from the landing site. Reasons include disposal of a damaged lander, temporary relocation to a servicing/storage shelter, or to clear a single landing pad for the next landing.

## 5.11 Unload and Position Cargo

After transport to the work site, the cargo must be unloaded from the transporter, aligned in a mount or specified position, leveled, and secured.

## 5.12 Route Utilities

Utilities need to be routed in utility-ways between the major areas of habitation, work, and utility systems.

## 5.13 Build a Habitable Volume

### 5.13.1 Modules

The conventional approach to providing habitation volume in space is to prefabricate a module on Earth and connect the prefabricated modules at the desired location in space. For this case, the primary construction and assembly operations after offloading modules from the lander and transporting the modules to the base site are to position the modules in the proper location and orientation, connect modules, and anchor the module assembly.

### 5.13.2 Inflatables

Another approach under consideration is the use of an inflatable volume, a sphere in the LBSS study. Excavation is required to contain the lower portion of the inflatable habitat and for the anchor system required to stabilize the completed configuration. Since a spherical excavation is not possible with the lunar regolith angle of repose of 35 degrees, a hole bigger than the sphere (but of the proper depth) must be excavated. The habitat must be inflated and positioned in the proper location and orientation. Then the hole is backfilled with regolith. Finally, the interior habitation structure must be assembled and the total configuration securely anchored.

## 5.14 Assemble Structures

### 5.14.1 Canopies

An interesting concept for shielding most base activities from space radiation, solar thermal variations, and micrometeorites is to construct an expansive canopy system, under which the base facility is constructed. The canopy must be covered by a layer of regolith sufficient to provide the desired shielding. In addition the outside boundary of the canopy must have a shielded wall and access driveways must have at least one 90° turn (to prevent radiation penetration).

### 5.14.2 Landing Aids

Pad markings and navigation aids are used to assist flight crews and automated landers in locating the landing pads and in adjustment of trajectories to insure precision landings. Pad markings provide visual identification for piloted missions while navigation aids provide visibility to automated guidance systems. A light-weight marker that combines both functions, and is easily deployed is preferred. One concept consists of a transponder, 2 m diameter (foldable) visual marker disk, 150 W light, and a retroreflector for laser range finding, all mounted on a tripod (4). Two navigation aids are required 1.5 km downrange and 1.5 km cross-range from the landing site while 3 more are stationed at 120° positions around the periphery of the 100 m diameter pad. The navigation aids must be accurately positioned. Their true location in global terms (latitude, longitude) must be well known to allow automatic landings by unmanned cargo missions. Each marker/navigation device has stowed dimensions of 0.5 m x 0.5 m x 0.1 m and a mass of 10 kg.

### 5.14.3 Communications Towers

A lunar base may utilize an antenna elevated on a tall tower to extend the distance to which communications can be established with remote vehicles or locations. A 600 meter tall tower enables line of sight contact with a remote antenna of 5 meter height at a distance of 50 km assuming no hills or valleys are in the path.

## 5.15 Emplace Radiation Shield Material

Lunar regolith will provide shielding from space radiation. Lunar soil may be used in loose, bagged, or block form. Blocks can be made from either sintered (hot-pressed) or melted soil. In loose form, it must be dumped on the surface or conveyed over the top of a structure to become the radiation shield. In the bagged and brick forms, the material must be stacked to become the radiation shield. Lunar materials may be used as radiation shielding in its natural form if a lava tube or other natural cavern can be found convenient to the base.

## 5.16 Assemble External Systems

Systems supporting the base but external to the habitation volume include the electrical power and thermal control systems. This equipment must be positioned, oriented, and assembled very early in the base buildup process.

## 5.17 Excavate Regolith

The need to excavate regolith is certain to occur in various different areas and phases of the lunar base construction. The excavation may require blasting or it may all be accomplished by excavation equipment in some jobs.

## 5.18 Move Regolith Bulk

Regolith is required to be moved in the lunar base construction for grading and leveling purposes, to dispose of it in one area or to deposit it as fill in another area.

## 5.19 Deposit Regolith Bulk

In numerous construction jobs, regolith must be deposited to fill a natural void or one previously excavated.

## 5.20 Prepare Lunar Lava Tube

If a lunar base site can be located adjacent to a lava tube, the lava tube can be used as a natural shield from meteorites and impact ejecta, solar thermal variations, and space radiation. The approach to the tube entrance may have to be graded to allow access, the lava tube floor may require preparation, and lunar base equipment must be transported into the lava tube. A closing structure may have to be constructed in the mouth of the lava tube.

## 6.0 Lunar Equipment Options For Accomplishing Job Set

Alternative approaches for implementing a particular construction job have been conceived where possible, and are described in the following sections.

### 6.1 Anchor an Object

Many static objects will utilize their own lunar weight and will not require an external anchor to stablize themselves. When anchoring is required, the preferred terrestrial practice is to anchor into bedrock. Anchor options for the Moon include:

- Standard Earth practice. Dig or drill down to bedrock, drill rock, then fill hole with reinforced concrete or grout and a large diameter rebar to form an anchor. The object to be anchored can be mechanically fastened directly to the anchor, or secured indirectly by attaching a cable from the object to the anchor (assuming the end of the anchor is equipped with an eyebolt ring or cable attach point).

- Deadman. Excavate hole, place large inert mass (deadman) attached to cable in hole, rebury deadman, attach other end of cable to object to be anchored. An alternative deadman could be a large piece of fabric or sheet metal with attached cable, spread flat, then buried.

- Spike. Drive straight or cork-screw spike into regolith. Use spike as tie-down point. This technique could be accomplished by an EVA crew member using a hammer, but would only be applicable for low loads.

- Pile-Driver. Pound pointed pile anchor into surface using a crane with pile-driving weight (ram) and mechanism attached, or use other pile-driving machines (power hammers, vibratory drivers, etc.). In-situ materials (lunar soil, rocks) could be used to weight the pile-driver ram. A cable attach point (eyebolt) or other mechanical anchoring mechanism would be mounted to the sides of the pile to avoid being crushed during the pile-driving operation.

- Natural anchors. Large lunar boulders or the fissures between exposed rocks could be used as natural anchor points. An anchoring cable could be attached to the boulder by placing a loop of the cable around the boulder, or by driving a piton into the boulder and attaching the cable to the piton. A fissure can be used as an anchor point by attaching a cable to a rod or wedge and placing the rod across the fissure.

### 6.2 Unload a Lander

Various unloading systems and techniques for off-loading cargo from the lunar lander have been investigated. Different concepts and associated equipment and labor requirements have been considered. The off-loading methods are separated into three categories; equipment intensive methods which use conventional mobile equipment, labor intensive methods, and hybrid methods which are not adequately described by the previous two categories. The labor intensive method is presented under the section (Section 6.3) for contingency methods of unloading a lander.

The equipment intensive methods employ the use of conventional equipment, such as a mobile crane, and a minimal amount of manual labor. The minimal amount of manual labor is considered to be the labor required for connecting and disconnecting the component to be moved to the lifting device.

The labor intensive methods are those in which the predominant resource that is required is manual labor. These methods do not require major pieces of equipment but they do require temporary structures to be built in order to support lifting devices and the load to be moved. These temporary structures require a relatively high amount of manual labor to construct and dismantle.

The hybrid category consists of methods which are dependent upon both major equipment and manual labor. However, these methods require less massive equipment than the equipment intensive methods and less manual labor than the labor intensive methods.

### 6.2.1 Conventional Mobile Crane Method

The types of cranes investigated here are the mobile boom-type cranes and gantry cranes. The major disadvantage of the mobile crane is the mass required to act as a counter weight to prevent overturning during lifting operations. This mass can be integrally built into the crane or it may be obtained from in-situ material (regolith). Therefore, the mass of the mobile crane can be described as being made up of two components; the mass required for strength and the mass required to prevent overturning of the crane during lifting operations. The mass required for strength is determined by the strength of the materials used in the design of the crane and the design requirements of load and lift geometry. The scope of this report is limited to relative comparisons of mass required for counter weight and does not consider other design requirements.

Figure 6-1 is a schematic diagram of a mobile crane utilizing a straight boom. The figure illustrates two important items. First, the required mass of the crane plus counter weight is inversely proportional to the distances between the crane pivot point and the centers of gravity of the crane and the load to be lifted. Second, the distance between the centers of gravity of the crane and the load to be lifted is limited by the interference between the boom and the lander frame. The required mass of the crane plus counter weight (to lift the largest load of 25 mt), as shown in Figure 6-1 would be 50 mt (excluding considerations of safety factors, soil bearing capacity, and load acceleration factors). The use of lunar materials (soil or rocks) to provide the counterweight mass appears to provide a good balance between operational efficiency and utility while lessening the amount of Earth launch mass required for a robust mobile crane.

One method to reduce counterweight requirements is to reduce the distance between the end of the crane and the center of gravity of the load to be lifted by using a jib as shown in Figure 6-2. If a jib is used, the required mass of the crane plus counterweight, as shown in Figure 6-2, reduces to 25 mt (for the 25 mt load). Further information regarding overturning calculations can be found in the literature (5).

The gantry crane, as illustrated in Figure 6-3, has greatly reduced counter weight requirements. It also has somewhat reduced maneuverability capabilities, it requires two mobile platforms which add to the mass requirements, and it is more difficult to transport to different locations. A preliminary mass estimate of the gantry crane is beyond the scope of this report.

Other ways to reduce counterweight requirements are to employ very long crane stablizing outriggers or to lengthen the crane by placing the crane counterweight far from the load to be lifted. However, these generally limit crane maneuverability.

Another method to reduce counterweight requirements, is to place the cargo near the periphery or on the sides of the lander. Conceivably, cargo elements could be secured by trunnions in cradles positioned symmetrically along the outside edge of the lander; lowered to the lunar surface or transporter bed by a simple rack and pinion gear-drive integral to the lander's cargo cradle; and finally released from the cradle after being secured to the transporter. In a way, this approach has already been demonstrated. The Apollo lunar module (LM) carried much of its (limited) cargo load to the lunar surface on the sides of the lander. Manifesting the scientific experiment packages and lunar rover vehicle on the sides of the LM simplified unloading and deployment of these elements by the crew during EVA. Placing cargo near or at the sides of a current lunar lander conceptual design (3) does not seem to be a particular problem (except for possible reaction control system. plume impingment interaction which could be protected against) as long as the total cargo center of gravity is not greatly effected. However, the major problem with this approach is that it places limitations on the maximum allowable <u>individual</u> cargo size since the cargo has to be split into two or more equal units to balance the lander. It also makes it more difficult to reduce lander/cargo interfaces and have a general purpose lander. While this approach makes sense for a very few missions, it probably is not a good long-term solution.

### 6.2.2 Hybrid Method

Other methods which represent a compromise between the equipment intensive and labor intensive methods are the tower-crane system, bridge/pivot-crane system, and a system which utilizes a mobile crane plus an assist from a fixed support. A tower crane will operate effectively once erected. However, it does require a counter weight, the process of erecting the crane may prove time consuming, and a foundation should be constructed for the support base. A bridge/pivot crane, as shown in Figure 6-4, would require less massive equipment than the gantry crane discussed previously, but it would require more labor to construct the pivot. Also, this method would require more effort to position the lifting device over the load and to place the load over the surface transporter. The use of a smaller mobile crane (smaller than the mobile crane previously discussed), plus the aid of a fixed support for lifting large loads, is illustrated in Figure 6-5. The mobile crane could be utilized to off-load all but the largest of components without the fixed support assist. Therefore, the material handling operations of off-loading the lander, loading the surface transporter, off-loading the surface transporter, final lifting/positioning of the components, and other base lifting/moving operations would require a minimal amount of EVA manhours except for the handling of the most massive components.

Figure 6-1. Representation of Boom Crane Cargo Unloading Variables

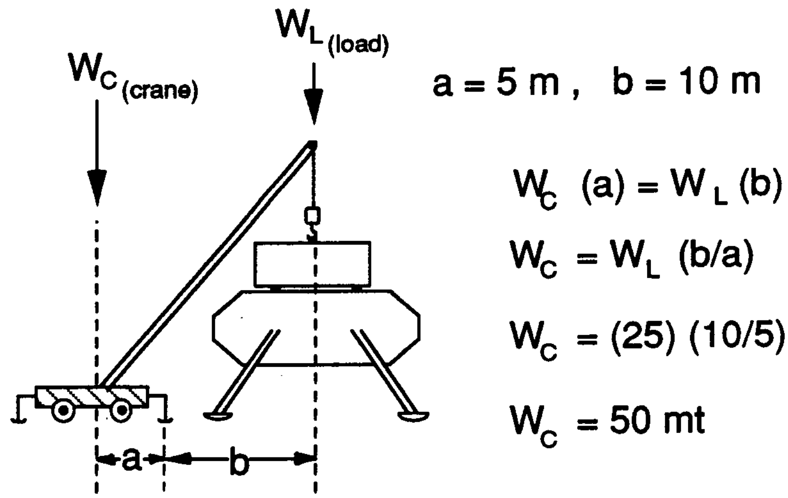



**Figure 6-2.** Use of Jib to Reduce Counterweight Requirements

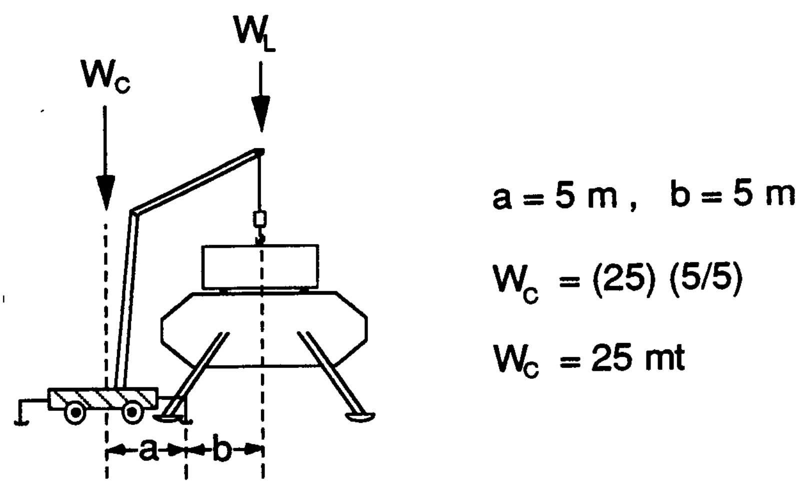



**Figure 6-3.** Gantry Crane

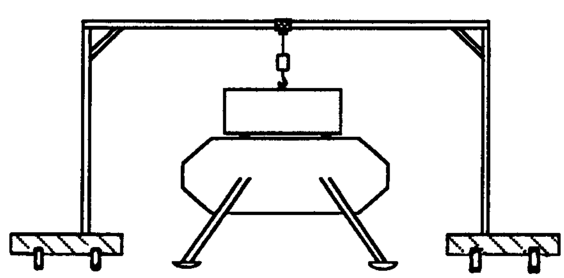


**Figure 6-4.** Bridge/Pivot Crane

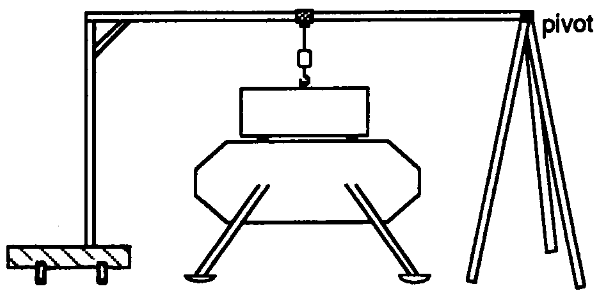
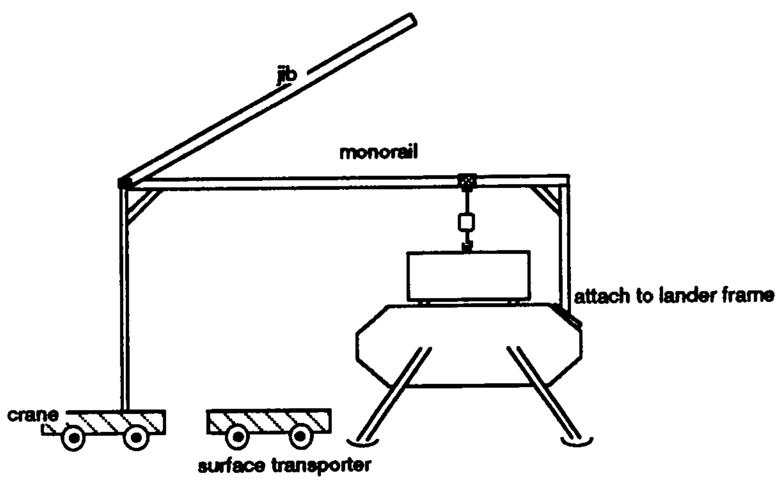



**Figure 6-5.** Mobile Crane Plus Fixed Support Structure



## 6.3 Contingency Methods to Unload a Lander

The nominal approach to unloading the lander uses equipment intensive methods. However, there are contingency cases where the nominal equipment may not be available. In these cases, the unloading is based on the use of more simple mechanisms with extensive crew participation. Three cases can easily be foreseen for contingency methods. They are:

1) Unloading the first lander, when the nominal equipment is not on the surface and ready to perform,

2) Special sorties to remote lunar sites where no support facilities or equipment exists, and

3) Contingency situations where the nominal equipment is broken or out of service.

For discussion purposes, case 1 (which will definitely occur) is used as the example for synthesizing and evaluating a labor intensive scenario.

The recommended plan is for the payload of the first lunar cargo lander to be the operational cargo unloading and transporting devices (2). Since the devices will not be available to unload themselves, methods need to be formulated to enable unloading the cargo handling devices with a minimum amount of specialized equipment and labor. Once this recommended first cargo is unloaded, the subsequent lunar cargo landers will be unloaded with the benefit of the planned operational cargo handling equipment.

Since the cargo unloading device is mobile (Section 6.2), the recommended method to unload the cargo unloading device is to roll it down a ramp. The first step of the unloading procedure is to release the cargo unloader from its lander tie-downs, to power-on the unloader, and to function check its systems. The next step will be to deploy the ramp which could be motor-operated to facilitate the deployment. The unloader would drive itself to the top of the ramp. The ramp could be either a solid sheet or rails. The most important part of rolling the unloading machine down the ramp will be to maintain control of the deployment. This is best served by maintaining a low speed on the ramp. Low lunar gravity helps in this situation but additional measures to consider include keeping the slope of the ramp low (a hinged rail or solid ramp system could be used to lengthen the ramp), increasing the friction of the ramp surface (by roughening it or making it sticky), and putting the unloader in low gear or applying the unloader's brakes while descending the ramp. Another option is to use a winch/cable system attached to the unloader and to the lander to help control the unloader's speed on the ramp. Since all cargo unloading devices described in Section 6.2 contain winch and cable systems, the unloader system could perhaps lower itself down the ramp.

After unloading the cargo unloading device, all other cargo can be unloaded by it instead of using the ramp system, unless the cargo unloading device uses lunar soil or rocks as a counterweight. Since machine excavation is preferred to hand-excavation for filling the unloader's counterweight reservoir (if required), an excavator device could be unloaded from the lander in a manner similar to the unloader. It would then be used to collect and load the unloader's counterweight prior to starting the remaining unloading tasks.

Another solution to the problem of unloading a crane from the first lander is illustrated in Figure 6-6. Parts of the crane can be used to construct a frame and, if the crane is designed as a hydraulic crane, it may be possible to design it so that it will unload itself.

If the normal cargo handling equipment fails and cannot be repaired, or is unavailable because of a landing at a remote site, the cargo unloading operation is likely to be a labor intensive job. The labor intensive methods can be divided into two categories; methods which require lifting and methods which require sliding, rolling, or conveying. The lifting methods require the construction of temporary structures to support the lifting device and the load to be moved.

One such method requires the use of a gin pole. A gin pole is pictured in Figure 6-7a. The gin pole method makes use of a compression strut (pole) and several cables (guys). The cargo is lifted off the lander by a winch/cable system and then placed on a transporter. A tripod alternative made from rigid struts is shown in Figure 6-7b. Gin poles can be used effectively in lifting operations but are not suited to horizontal movement of the load. The lander will have to be moved out of the way before lowering the cargo onto a transport vehicle. This could present a formidable task for the crew. It may also be difficult to anchor the guys securely in the regolith. Positioning of the lifting device over the center of gravity of the load may prove difficult and it would be necessary to move the lander and replace it with the surface transporter once the load is lifted.

Another labor intensive method is one in which a scaffold or temporary framed structure is constructed to support the lifting device and the load. Possible structures are shown in Figures 6-8a and 6-8b. A framed structure is built to support a bridge crane or a monorail lifting system. Once constructed, the unloading operations would require a minimal amount of labor for off-loading the lander.

Both the gin pole and the temporary frame methods have two major disadvantages. Relatively large amounts of labor are required to construct and dismantle the system and worker accessibility to the structure being constructed is limited. However, they do not require major equipment support.

Other labor intensive methods include sliding on skids or rolling (for wheeled or cylindrical objects) down a ramp or chute, and conveying. These methods are illustrated in Figure 6-9. While these methods are possible and do not require major equipment, there are some problems that must be overcome if they are to be used, such as:

1. Maneuvering the load to the ramp, chute, or conveyor.
2. Positioning the load onto the surface transporter.
3. Unloading the surface transporter.
4. Lifting and repositioning the components to their final location.

Note that these issues do not apply to the ramp operation recommended for unloading the first lander because these operations are assumed performed on self-propelled mobile equipment. The potential for requiring these methods due to equipment failure can be reduced by providing adequate spare parts and eventually delivering redundant equipment.

Figure 6-6. Unloading Crane by Constructing Frame from Cannibalized Crane Parts

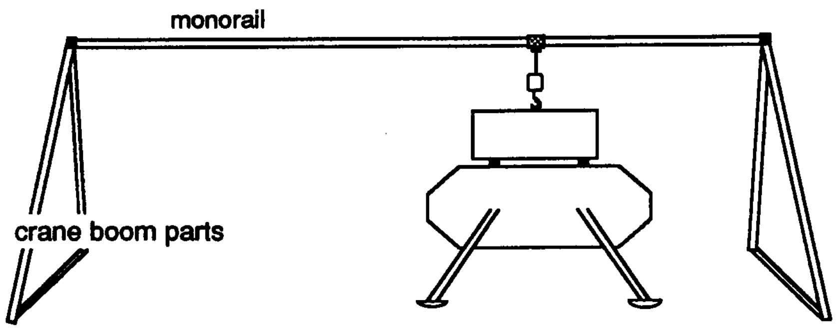



**Figure 6-7a.** Unloading Lander using Gin Pole

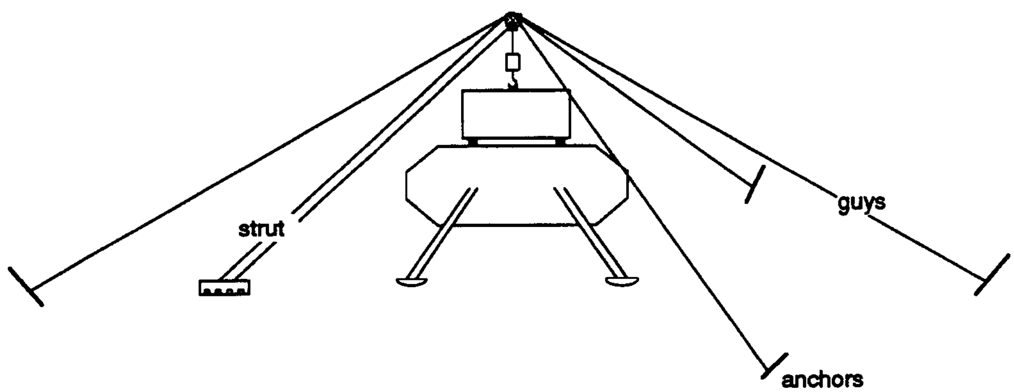
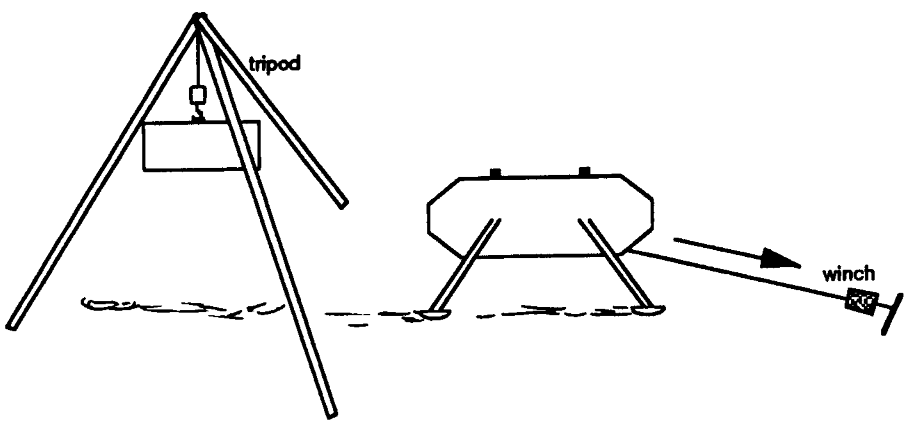



**Figure 6-7b.** Unloading Lander using Tripod






C-2

**Figure 6-8a.** Unloading Lander using Temporary Frame to Support Bridge Crane

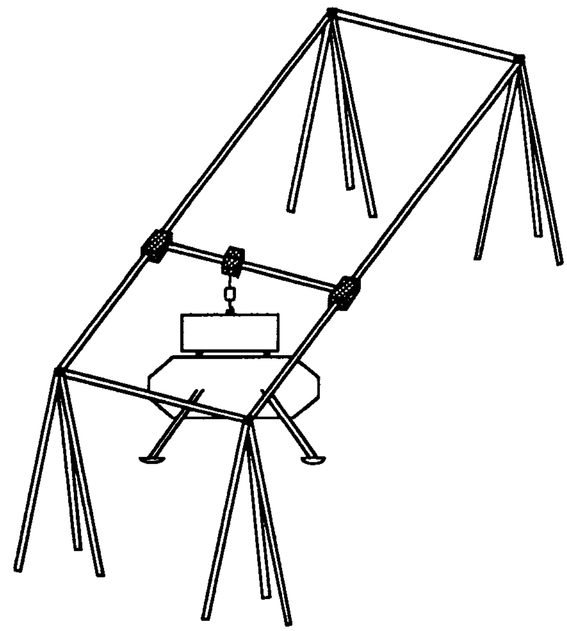


**Figure 6-8b.** Alternative Bridge-Crane Lander Unloading Operation

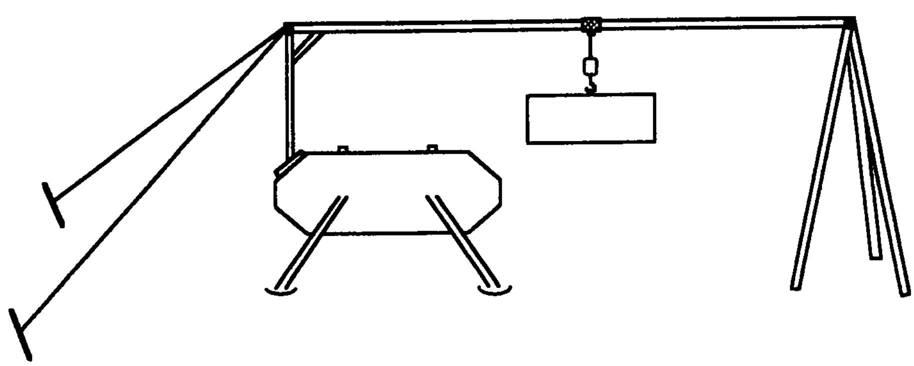
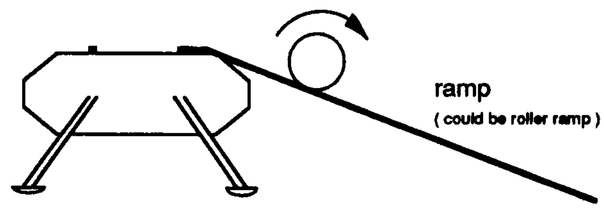
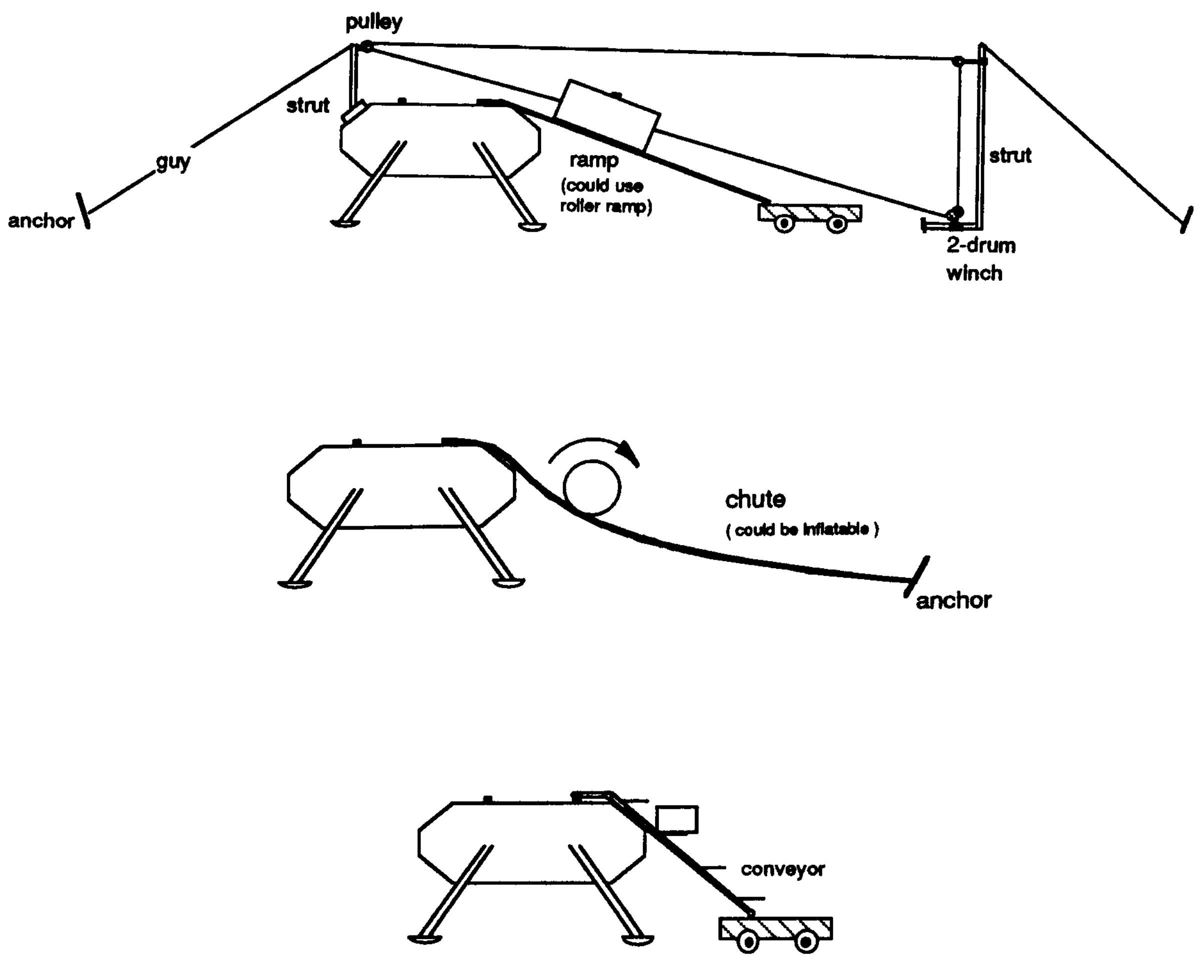


**Figure 6-9.** Unloading Lander Using Ramp, Chute, or Conveyor




An illustration of one technique using cable/winch system to control deployment of cargo using a ramp (or chute) in a contingency unloading operation.



## 6.4 Move Cargo

Cargo transportation will be needed from the landing pads to the base area (250 m to 3 km). Some remote deployment of scientific and resource utilization equipment may also be required (2). As described in Section 3.2, maximum cargo size is 4.5 m diameter x 14 m long with a mass of 25 mt. Smaller cargo elements will also be delivered (3.7 m diameter x 3.4 m long, 3 mt airlocks), but very small elements such as spare parts and resupply items will probably be manifested in pressurized and unpressurized logistics modules and pallets (48). Alternatives for providing cargo transport capability include:

- Self-propelled truck or pulled trailer. Flatbeds are likely because of their volume flexibility, provided some method to secure the cargo on the transport is available (trunnion and cradle, flatbed with sides, etc.). A similar method as used on the lander is possible. The transport trucks could be manned or unmanned (remotely controlled or supervised near-autonomous operation).

  Trucks or trailers for lunar cargo transport is a common option described in the literature (2, 43, 49). One concept of a trailer is depicted in Figure 6-10. This concept illustrates a common securing feature used on both the cargo transport trailer and on the lunar lander. In this concept, the cargo (a module) is outfitted with mounting pins that fit into inserts on the lander and which are duplicated on the flatbed trailer. The crane in this concept pulls the loaded trailer to the base site.

- Forklift. A forklift truck could provide a means to unload smaller cargo on pallets from the lander (without a crane) and to transport the cargo to the base or work site. A very large forklift and special attach points on the cargo would be required to off-load a cylindrical habitation module from the lander and transport it.

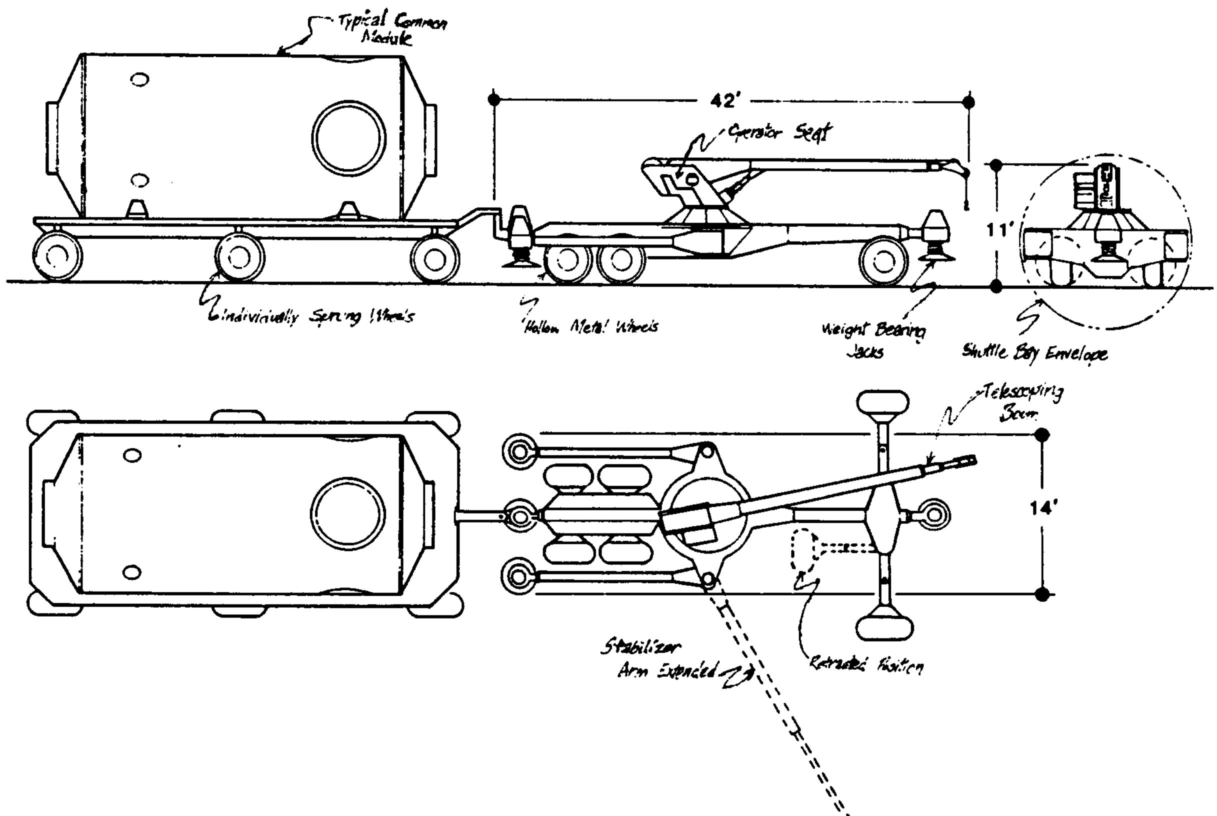
- A wheeled mounting cradle could be attached to each cargo element delivered by the lander. After unloading from the lander, the cargo could be pulled to the base. This approach has the advantage of speeding and simplifying unloading (i.e. because no alignment is necessary between cargo carrier and unloader at landing site, no time is lost to secure cargo to transporter vehicle), but the expended carriers represent a mass penalty loss that is paid on every mission. This penalty may not be significant if permanent mounting cradles or platforms are required for most cargo elements anyway to provide an adequate foundation and to insure proper alignment/fitting with other elements at the base emplacement.

- A large, mobile bridge-crane could be used to move a cargo. The advantage with this scheme is that the same device could be used to unload the lander, transport the cargo, and place it at the final position. A large bridge crane is necessary since it will have to go over the cargo on the lander. For lifting a 4.5 m diameter x 13.6 m long module off the lander, the crane would need to be at least 13 m high x 14 m long x 10 m wide. This will be a difficult machine to maneuver during transport. Because it is so big, it will be hard to get near the desired final position if there are other nearby base elements (such as other modules) already emplaced. Precise final positioning of the crane relative to the payload during loading and unloading operations is more difficult.

- A belt conveyor system could be installed from the landing site to the base site. This would be only appropriate for a permanent landing pad site and if high volume cargo delivery is expected.

- For an infrequent, large cargo element, it may be possible to land close to the cargo element final resting place. Any nearby (<400 m) structures should be protected from engine blast/debris damage using blankets or other barriers (4).

**Figure 6-10.** Crane and Flat-Bed Trailer Cargo Transporter (from Ref.49)



## 6.5 Contingency Methods to Move Cargo

Methods are needed to move cargo when planned equipment (such as trucks or trailers) are not available because of equipment failure or remote site visit. These will be labor intensive and limited in terms of maximum mass moved capability. Possibilities include:

- Manual methods similar to those employed during Apollo such as:

  - Balance Pole with equipment slung from either end that a crew member could take in hand or put across a shoulder. A similar version (4 kg) was used on the lunar surface missions to move Apollo Lunar Surface Experiments Packages (ALSEP).

  - Wheeled tool/equipment carrier pulled by a crew member. This could be a flatbed version similar to the Modular Equipment Transporter (MET) used on Apollo 14.

- An unpressurized rover, similar to the "LOTRAN" (local transportation vehicle) described in Section 3.2.2, which could be used to transport 490 kg of cargo with 2 crew.

- A winch and cable support attached to an anchor could be used to pull a cargo (preferably after it is mounted onto a wheeled flatbed trailer). The anchor and winch pull cycle could be repeated as often as necessary to move the cargo the desired distance.

Because of the severe constraints in productivity and capability imposed by these contingency moving methods, the preferred contingency option is to repair the transport equipment if equipment failure has occured. This will require adequate stores and tools, or a redundant backup vehicle. For remote sites, operations will be constrained to the capability of available transport systems; only small cargos can be moved quickly by the LOTRAN while more massive objects can be moved more slowly by the winch/cable system.

## 6.6 Prepare a Landing Site Prior to Surfacing

As described in Section 3.4, several (perhaps six or more) 100 m diameter landing sites will be needed. Each pad will be separated by 250-400 m from each other. Although the lander is likely to be robust, strict requirements are anticipated to minimize landing risks and ensure compatibility with unloading equipment. Requirements specifically address overall grade (less than 6° slope) and roughness (no humps or craters greater than 1 m in relief, all rocks greater than 0.5 m removed). The required number of landing sites must be selected, marked, and, if necessary, the surface prepared by grading and leveling. It may also be necessary to stabilize the surface of the landing pads by one of the options described in Section 3.4.2 and illustrated in Figure 3-11. The equipment needed to prepare landing sites without surface stabilization is discussed below.

- Site Selection. A primary goal will be to search and find a location that does not need much preparation. Much of this selection activity can be performed by unmanned spacecraft and rovers prior to establishing a lunar base. However, final site evaluation and selection will likely involve humans. This will require a LOTRAN-type vehicle (see Section 3.2.2) that can perform the on-site selection and evaluation task rapidly.

- Survey and Mark. Using surveying equipment (Section 4.3), the crew will need to map the exact locations of the selected landing sites (distance and direction from each other, the base site, and any major natural features). The major reason to survey is to precisely locate navigational aids so landing trajectories, particularly unmanned ones, can be planned. Mapping of the landing sites themselves will be needed to determine the nature and type of obstacles that must be removed. The crew will need to indicate the boundary of the areas to be cleared and leveled with stakes or other markings.

- Clear Boulders. All oversized rocks within the landing area must be removed. This operation can be performed by one or a combination of the following methods.

  - Pushing the boulders/rocks out of the way with a dozer. There is a certain maximum force that can be applied by a dozer (depending on the power developed by the machine, traction, and other factors) and therefore a maximum boulder size that can be removed by this method.

  - Picking the boulders/rocks up with a front-end loader (FEL) or other excavator and carrying them away with the excavator or with a truck. Again, due to machine limitations, there is a certain boulder size that can be treated in this way.

  - Using explosives or expanding material to break boulders. A hole or holes will need to be drilled into the boulder to contain explosives or expansion material. Placing explosives on or below the rock instead of in a drilled hole would produce inefficient fragmentation and would tend to laterally displace the rock instead of breaking it up. In using the explosive technique, the amount of explosives needed will require knowledge of the fragmentation characteristics of the rocks to be blasted. This technique would also be relatively time consuming. For each rock needing to be removed, the procedure would be: 1) identify rocks to be blasted, 2) drill holes, 3) load explosive and wire, 4) clear area, 5) detonate explosives, and 6) remove or blast any remaining oversize rocks.

  - A combination of the above might be the best approach. First, explosives would be used to remove any large boulders beyond the capability of the rock removing machines. Then, a dozer or front-end loader (FEL) would be used to remove the remaining oversized rock and explosion fragments. A FEL can usually outperform a dozer of equivalent size in terms of maximum boulder capability because the dozer must overcome the frictional resistance of larger boulders, but a dozer is more productive than a FEL in removing many smaller rocks.

- Grade and Level. First, any necessary grading of the general slope of the site to satisfy requirements (no greater than 6°) can be accomplished by dozer or scraper, or excavaator if the volume of soil to be moved is great. Then, any large (> 1 m deep) craters or depressions could be filled in by truck, trailer, scraper, or dozer. The truck or trailer would need to be filled by soil excavated by FEL, scraper, shovel/hoe, or bucket wheel excavator. After major depressions are filled, a dozer with angle blade or scraper could be used to remove rises, level and grade the entire site, and compact the surface. Vehicle weight will compact the surface to a certain extent. A weighted roll implement can be attached to the dozer to provide additional compaction if necessary. The compactor roll could be filled with lunar regolith to reduce Earth launch mass.

### 6.7 Prepare a Base Habitation Site Prior to Constructrion

A similar procedure as described in Section 6.6 can be used to level and grade a site for the habitation modules. The size of the area to be cleared and leveled was defined as a 50 m x 50 m site in one report (2), but this would be highly dependent on the eventual size of the base. The slopes within this area should be as close to 0° as practical. The most important goal will again be to search and find a location that does not need much preparation.

### 6.8 Build a Road

The requirements for lunar roads have not been firmly established. Road construction on the Moon will not be analogous to Earth construction which is defined more by local climate and the need for drainage than by soil bearing strength. A lunar road will only be needed for heavily traveled paths where a natural course cannot be found that is free of substantial risk. Roads would also increase allowable transport speeds and could simplify the design of transport vehicles. The amount and type of traffic will depend greatly on base objectives. More study is required to determine if the costs for road construction are outweighed by its advantages after lunar base objectives and traffic are better defined. A road is assumed required for this study.

As defined in Section 3.4.2, an approximately 3 km long and 10 m wide road connects the landing site to the base area.

Tasks and equipment to plan and prepare the roadway is the same as that used for preparing the landing and habitation sites. The tasks include:

- Survey using LOTRAN and surveying equipment.
- Plan grades (cut and fill) using dozer with universal blade, or excavator and truck.
- Remove boulders using combination of drilling and explosives, dozer, and/or excavator with trailing truck.
- Grade using angle dozer.
- Compact road bed using compactor.

Surfacing the road will reduce road wear and maintenance. Surfacing options include simply compacting, using sized lunar gravel, or using paving tiles. These are described in Section 3.4.2. Other options include melting the surface or using Earth supplied materials such as the metal grating used by the military to make remote runways.

The following steps and construction equipment are based on a roadbed consisting of a coarse gravel base (greater than 1 cm diameter) and a fine gravel finish (4 mm to 1 cm).

As given in Section 3.4.2, a 3 km x 10 m road would require 4,500 $m^3$ (7,200 mt) of coarse gravel for a 15 cm base and 300 $m^3$ (540 mt) of fine gravel for a 1 cm thick finish. Assuming that the gravel is separated from a very coarse soil feed (30 weight percent greater than 4 mm particles and 20 weight percent greater than 1 cm particles), a minimum of 36,000 mt of soil must be processed. The following steps and equipment would be involved in the road surfacing operation.

- Coarse soil collection. Coarse soil can be collected by bucket wheel excavator (BWE), front-end loader (FEL), hydraulic hoe or shovel, dragline, or by other types of excavators described in Section 4.2. If an area of coarse soil or small rock is found on or near the surface, scrapers or bulldozers can be used to collect it. An alternative approach would be to crush stone to produce the required gravel (often the approach on Earth).

- Coarse soil transport. The coarse soil needs to be transported to the gravel separator. This job can be performed by self-propelled trucks, dozer tractors pulling trailers, scrapers, or draglines, or more slowly by a FEL excavator.

- Gravel separation. Coarse and fine vibratory screens can be used to separate a greater than 1 cm fraction, a 4-10 mm fraction, and discards.

- Fines discard. The same options as used to transport coarse-soil can be applied in moving the fines from the gravel separation step to a discard area.

- Spread coarse gravel. A truck, pulled-trailer, or scraper can be used to transport the sized coarse gravel to the road and spread the coarse gravel base.

- Grade and compact. Dozers with angle blade or scrapers can be used to grade the coarse gravel base. Compaction can be done with the weight of the machines used to grade, or by using a compactor roll implement attached to a grading machine, or by using a dedicated compactor machine.

- Spread fine gravel. A truck, pulled-trailer, or scraper can be used to transport the sized fine gravel to the road and spread it as a top-cover finish.

- Compact finish. Final grading will probably only require compacting if the fine gravel spreading operation is controlled. Same options as with coarse gravel base.

### 6.9 Build Landing Site Facilities

The major construction activities that are involved in providing surface facilities capable of refurbishing lunar landers and supporting cargo loading operations (4) are to provide a stablized surfacing to the 100 m diameter landing pads and to provide the ability to move an entire lander to a servicing building.

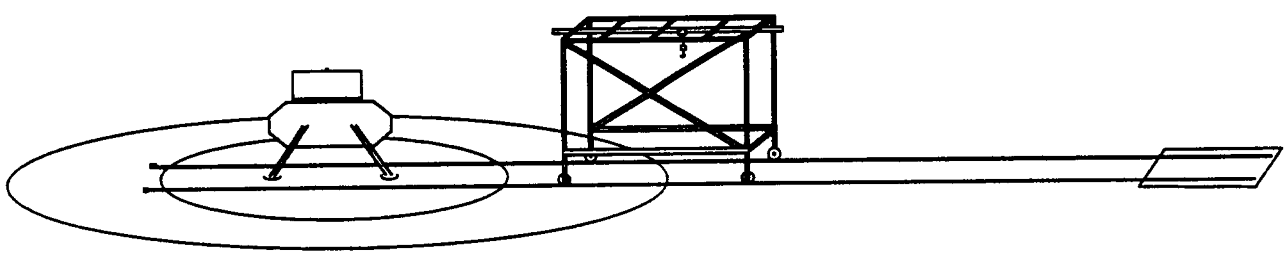
Surface Lander Pad

The tasks and equipment to surface the landing pads is the same as for surfacing a road (Section 6.8).

Provide Servicing Hangar

One way to provide access to a hangar for lander servicing is to move the entire hangar to the lander. A concept with the hangar placed on rails, which could also serves as bridge crane for loading and unloading cargo, is shown in Figure 6-11. Methods to move the lander to the hangar are described in the next section (Section 6.10).

**Figure 6-11.** Lander Servicing Hangar on Rails



## 6.10 Move a Lander

As given in Section 3.1, an empty lander stage is 8.2 m high by 9.8 m maximum on a side (13.0 m diagonally) and mass of 9,800 kg. If a 4.3 m diameter by 2.7 m high crew module is mounted to the top of the vehicle, the total lander mass is 15,800 kg.

If lander has to be removed from a pad to clear it for the next landing, the best way to move it off the pad is to fly it away. Other options for moving a lander to a hangar for servicing, or disposing of a damaged lander, are listed below.

- Load on flatbed truck. A large flatbed truck is required (10 m x 10 m) to transport the lander to the hangar. Several options to load and unload the truck are:

- Jack up each leg of the lander and put a wheeled dolly under each. Then pull lander by winch/cable system up ramp onto flatbed. Reverse process to unload.
- Pull lander onto flatbed by same process (via cable/winch and ramp) except with skids under each footpad, or if footpads do not bulldoze badly, directly onto truck without skids.
- Hoist lander onto flatbed with a mobile crane.

• Gantry. A mobile gantry or bridge crane on wheels could pick up and transport the lander to the hangar.

• Tow. A prime mover (tractor) is used to tow the lander. The lander is made mobile by:

  - Jack up each leg of the lander and install wheel.
  - Jack up each leg of the lander and attach skid.
  - Jack up whole lander with a large wheeled jack.
  - Land on a mobile pad or platform (helicopters do this).

• Disassemble. The lander could be disassembled into major pieces which are then separately hoisted or loaded onto a flatbed and pulled to the hangar.

• Miscellaneous.

  - Install ground effects skirt around lander and either use compressed gas or idle lander's engines and slide away.

The major problem with all these options, except the disassemble option, is that the large size of the lander's transporter will limit maneuverability and mobility across the lunar terrain. A 12 m wide road or path free of obstacles is barely adequate for this size vehicle.

### 6.11 Unload and Position Cargo

The cargo transporter can be unloaded at the habitation or work site using the same methods as for lander unloading described in Section 6.2 including:

- Mobile boom crane.
- Mobile boom crane with jib.
- Mobile gantry or bridge crane.
- Erectable Tower crane.
- Mobile boom crane with fixed support.
- Erectable gin-pole hoist.
- Erectable frame and hoists.

As discussed, the mobile boom crane with lunar derived counterweight offers good versatility and efficiency while minimizing Earth launch requirements. For smaller cargo elements, unloading could be accomplished by the above or:

- Smaller winch/cable and boom system mounted on another vehicle.
- Forklift.
- Power roller conveyor.

The positioning requirements will vary depending on the nature of the cargo. One of the toughest will be in positioning a second pressurized module prior to docking/connecting with a previously installed module. Cradles or module mounts could be pre-aligned on the surface prior to placing the module in/on or them, or the module with cradle could be properly orientated by the crane while suspended. Final orientation adjustments could be made with come-along pullers during the mating and bolting operation. On-site human support and supervision is indicated. Manual sighting and leveling tools and devices will be needed.

## 6.12 Route External Utilities

Utilities consist of cables, pipes, and tubing that carry power, thermal control system fluids and gases, and data and communications channels. Nitrogen for experiments and other pressurized gases might also be routed in the utility ways. Utilities will need to be routed between the habitation, work, and utility areas. The following describe techniques to route utility ways:

- <u>Buried</u>. The utilities could be buried beneath the surface. The utilities might be contained in one or two trays or conduits to keep soil away from connectors and to make it easier to feed new utilities through at a later time. Buried utilities have the advantage of good thermal control because of the insulating quality of the soil. This plan also gets the utility lines out of the way of surface activities. A bucket wheel trenching machine or a backhoe could be used to produce the trench. A dozer with angle blade could backfill the trench after utilities were installed. The backfill should be compacted to keep heavy vehicle traffic from re-excavating the trench and possibly exposing utilities. The trench might also be dug and filled by hand.

  A relatively shallow trench might be adequate. Beyond 10 cm deep, little variation in temperature is detected from the diurnal cycle (37). For one Space Station concept, the utility trays are 1.778 m wide x 0.0965 m deep (50). If the same size utility tray is selected for a lunar base, and allowing 5 cm additional space on top and sides for margin, a trench 0.25 m deep and 1.83 m wide at the bottom should be dug. Since the angle of repose for lunar soil is 35°, the top of the trench would be about 2.5 m wide.

- <u>Surface</u>. The utilities could be laid directly on the surface. This would be the easiest to set-up and added to when needed, but not necessarily the lightest option. Although the vacuum and soil are electrical insulators, the power lines would still need to be provided insulation (i.e. mass) to avoid electrocuting crew or short-circuiting equipment that might come in contact with them. Bridges over the utility ways would be needed for foot and vehicle traffic to avoid crushing tubing or cables. The only equipment needed is a vehicle to carry the cable drums and pipe sections (or deployable utility trays as proposed for Space Station) for the utilities, and the tools to connect them together.

- Overhead Utility Trays. All utilities but power could be placed in trays and carried or suspended from poles or pipe-bridges. An advantage with overhead utility ways is that the power lines would not need to be insulated, saving weight. Keeping the utilities out of the way of traffic is another advantage. Equipment needs for this option depend on the type of overhead bridge used to carry the utility ways that is selected. For a single pole with horizontal cross-piece, the pole can be fixed by:

  - placing the pole in a hole drilled by a mobile rotary drill, or
  - anchoring guy-wires to support the pole using equipment described in Section 6.1, or
  - placing a pole in a hole excavated by an backhoe excavator and backfilling.

  Free-standing utility poles are another option. They could be erectable or deployable frame structures that would be situated at intervals to carry the utility ways.

  The utilities could be run several meters off the ground to keep them away from all traffic, or set on supports close to the ground (~1 m) and run underground as required for vehicle transit.

  For high-overhead utilities, utility trays will have to be placed on the supports using either a mobile boom crane or manually by a crew with ladders. If the trays do not have pipe and cable for the utilities already installed, than additional crane or manual effort will be needed to pull cable and pipe through the trays.

### 6.13 Build a Habitable Volume

The two types of habitats considered in this study were prefabricated modules and inflatable habitats.

#### 6.13.1 Module

Two options exist for establishing a prefabricated module:

1) Living out of a module still attached to a lander without unloading it (42-44). A major construction activity for this case will be to provide radiation protection (43). Other activities include providing access to the module from the surface (platform and stairs) and perhaps to set-up flexible (but pressurizable) connections from this module to other pressurized base habitats.

2) Unloading the modules and moving them to a central base area. Setting up the habitation module in this case will involve:

- Base site preparation activities (Section 6.7).
- Habitat module unloading operations (Section 6.2).
- Transportation to the base site (Section 6.4).

- Transport unloading and habitat module positioning (Section 6.11).
- Providing radiation protection (Section 6.15).
- Providing power, thermal control, and other utilities (Sections 6.12, 6.14, and 6.16).

### 6.13.2 Inflatable

The inflatable habitat considered here is illustrated in Figure 6-12 (42-44). This inflatable is a 14.3 m diameter sphere that is covered with 1 m of bagged regolith (43). After site selection, steps in emplacing the inflatable are:

- Explosively Form Excavation. A 5 m deep crater is formed to contain the lower portion of the inflatable using explosives. 7 m deep cores are drilled using mobile rotary drill, packed with a sufficient amount of explosives, and detonated after personnel have cleared the area. The desired crater size is one that exactly fits the lower third of spherical inflatable and is 5 m deep by 13.6 m diameter at the surface (430.7 $m^3$). The actual crater size produced by the explosives probably will not exactly conform to this shape. In the worst case, it would resemble craters produced by meteorite impact which have a diameter to depth ratio of approximately 5. The crater could then be 5 m deep by 25 m in diameter (1293 $m^3$).

- Prepare Crater. The crater might require shaping and rock debris from the crater bottom and sides should be removed. This job could be accomplished with a clamshell on a boom crane, dragline, or hydraulic excavator working from the rim of the crater, or by removing the debris with front-end loaders or other excavators operating on the floor of the crater. A crew working with a portable rock drill and explosives or expansion material might also be capable of breaking up large obstacles. The steep sides of the crater will make access to the floor difficult for both machines or people however.

- Install Inflatable. A boom crane could swing the inflatable (deflated) into the crater. The inflatable can be attached to a support frame to orient it properly on the bottom of the crater (the support may itself be inflatable). The inflatable is inflated and leak checked. Anchor tie-downs are made if necessary.

- Backfill Crater. The crater is backfilled using a dozer or excavator and truck. Up to 860 $m^3$ of soil will need to be moved.

- Place Airlock. An airlock external to the inflatable is unloaded, positioned, and leveled near the inflatable. The airlock is connected to the inflatable. This airlock may need to be deployed and flexible connections made with the inflatable prior to inflating the inflatable to enable earlier access to the interior of the inflatable (42).

- Install Internal Systems. Internal elements (including structural floors and walls, equipment, consumables) need to be transported and installed. A tower crane working inside the 14.3 m high inflatable could assist the erection of internals.

- Provide Radiation Protection. 1 m of radiation protection is provided by 710 $m^3$ of regolith filled bags (43). A soil excavator, regolith bagger, and bag conveyor are required.

**Figure 6-12.** Inflatable Habitat (Ref.44)

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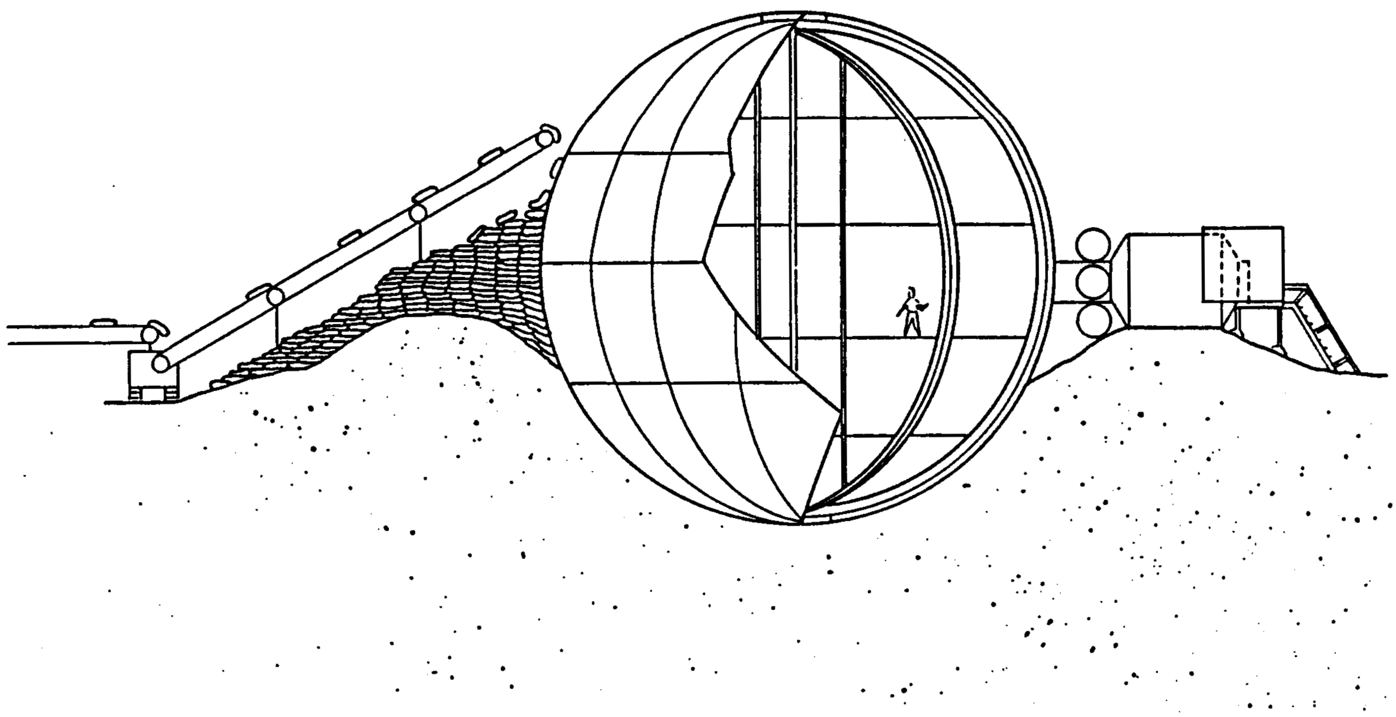


## 6.14 Assemble Structures

Erecting structures on the Moon using conventional assembly techniques of bolting and riveting structural components and preassemblies together might be time consuming but less risky than using more mechanically complex deployable structures. Several deployable truss structure concepts have been developed during Space Station development, but an erectable option was finally baselined because of the program risk and cost associated with the deployable versions. Simple attachment fittings and procedures were developed for the erectable method to ease assembly. It is therefore likely that erectable structures will be employed on the Moon, although foldable, deployable structures would be used to save time if similar concepts were implemented during operational phases of Space Station. For instance, utilizing Space Station derived deployable solar array and array boom assemblies might simplify a lunar power plant deployment.

For erectable structures, access to work areas at elevations above ground-level can be provided by one or more of the following options:

- Cherry-picker on boom crane.
- Scaffolding.
- Ladders.
- Tower crane.
- Inflatable work platform.

### 6.14.1 Communication Tower

As given in Section 5.14, a 600 m high tower would allow communication with lunar surface vehicles (having a 5 m tall antenna) to distances of 50 km. The low lunar gravity and lack of climate effects (wind) would allow significant reductions of mass over an equivalent height Earth tower. Several tower options are:

- Guy-wire supported truss or pole that is erected by crew with winch/cable systems.
- Free-standing truss that is erected by crew or deployed from folded configuration.
- Inflatable or space-rigidized inflatable similar to those used for some thermal shields and communications satellite antennas (51).

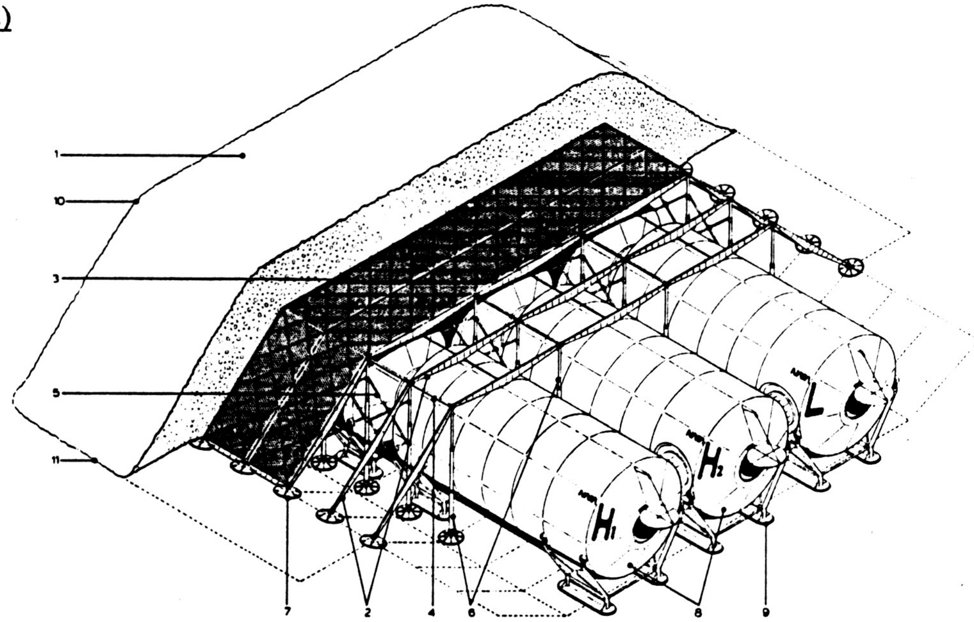
### 6.14.2 Canopy

Two views of a canopy structure are given in Figure 6-13. The canopy provides an unpressurized envelope over the habitats and other base structures. This structure carries the load of lunar regolith which provides protection from radiation, meteoroids, and thermal variation. The volume under the canopy allows for direct inspection of the exterior of the habitation modules. Without the canopy, the module would have to be designed to sustain the load of soil without being crushed when depressurized. With the canopy, a depressurized module will not have to sustain this load, thus reducing module weight (and increasing the chance direct derivatives of Space Station modules could be used for lunar application).

The canopy configuration shown at the top of Figure 6-13 is 26 m long x 21 m wide and contains 546 $m^2$ of membrane panels (65 elements) held up by a frame consisting of 56 telescoping columns, 70 main beams, 143 lateral beams, and 84 footpads (52). Total mass is estimated as 5000-7500 kg (52). The canopy is open at one end to allow modules to be slid in. It would probably be better to build the canopy over a module that is already emplaced because it would simplify construction (slidding a module under the canopy would be difficult) and because the open end exposes inhabitants to a higher radiation flux. More study of the possible internal radiation dose is needed to assess configurations which are open at one end. Construction of a canopy would involve a boom crane or hoist, and some manual labor to connect frame components depending on the level of prefrabrication.

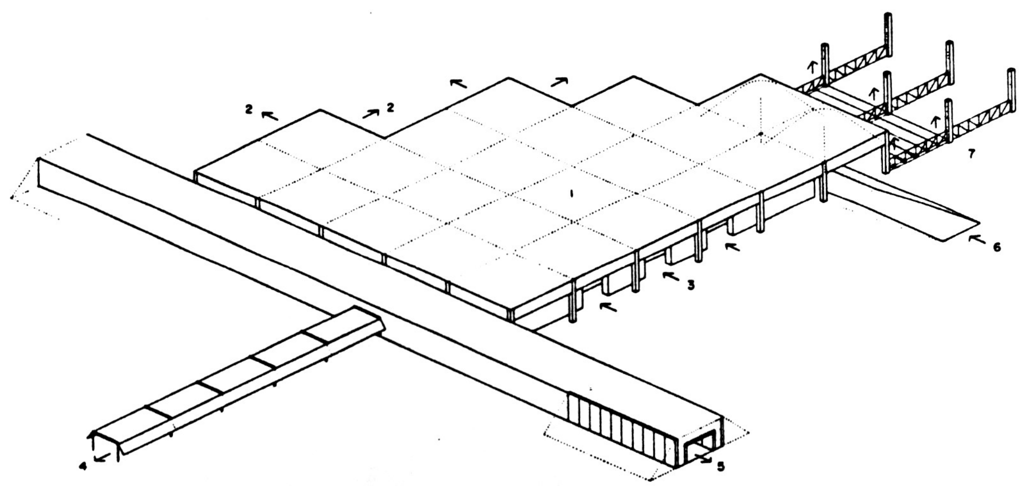
**Figure 6-13.** Canopy for Habitat Shielding

(from Ref. 52)



*Cutaway illustration of superstructure envelope system: 1—regolith mass shielding; 2—main tapered beams; 3—graphite fiber mesh; 4—longitudinal struts; 5—longitudinal bracing; 6—telescopic tubular columns; 7—circular footpads; 8—linked habitat/laboratory/workshop modules; 9—module ground support cradles; 10—crest of slope; 11—base of slope.*

(from Ref. 53)



BASE CONCEPT I. Flat shield raised in sections, pressurized enclosures beneath. *Overall view of base. (1) Regolith shielding. (2) Perimeter expansion. (3) Base entry through overlapping radiation barrier walls, from lunar surface equipment and installations "park." (4) Solar shaded links to other parts of base. (5) Shielded links to other parts of base. (6) Ramp access to lower levels. (7) Initial erection sequence.*

## 6.15 Construct Radiation Shield

The radiation protection requirements for lunar habitation elements need additional definition work. However, a recent study (47) recommended that 785 g/cm$^2$ of shielding (assuming siliceous materials) is needed for permanent lunar shelters to reduce radiation exposure to Earth's natural background (for people living at 9000 ft. above sea level). This would allow the maximum amount of EVA operations where dose rates will be higher of necessity. Shielding thickness requires that the density of the lunar material as placed on the structure be known. For an in-place shielding density of 1.66 g/cm$^3$, which is the average bulk density of the top 60 cm of lunar regolith (see Table 3-3), 4.7 m of soil would be needed. Hot-pressed sintered blocks made from lunar materials might have a density of 2.7 g/cm$^3$. A radiation shield constructed from such blocks would need to be 2.9 m thick.

Assuming radiation protection is to be provided for a 4.5 m diameter x 13.6 m long habitation module, there are a number of construction options:

- Excavate and bury module. Excavator, dozer, and crane would be used. Explosives might also be used. Access to surface must be provided.

- Surface installation and cover module. Several additional options are possible:

  - Cover module without using canopy and without bulkheads. Let soil settle into its natural angle of repose. Excavator, truck, and conveyor or crane would be used.
  - Use canopy to keep soil off the module. Excavator, truck, conveyor, crane, and canopy frame would be needed.
  - Use bulkheads (retaining walls around module) to reduce the amount of soil needed to cover the module (2). Excavator, truck, conveyor, crane, and retaining walls would be needed.

- Alternatives to soil covered module.

  - Cover module using bags filled with regolith (42-44). Equipment needed for this option includes a excavator and soil transporter, screens to remove larger rocks, bagging equipment, trailer or bag conveyor, and a scaffold or crane with precision end effector for stacking the bags.
  - Use blocks made of hot-pressed sintered soil (54) to protect from radiation, stack for protective walls, then erect a frame/canopy structure to hold blocks used for overhead protection. Equipment needs include a soil sintering device, block handling device (forklift derivative), flatbed truck or conveyor, and crane with grapple for frame assembly and to place overhead blocks.

Figure 6-14 shows the effect of burying or covering a module on the total amount of soil that needs to be moved. A full sized module (4.5 m diameter x 13.6 m long) with a 0.5 m high cradle is assumed covered on all sides by 4.7 m of soil. The soil is not confined by a bulkhead (or canopy) and a 35° angle of repose is used in the calculations. As shown, the minimum amount of soil to be moved (3,100 m$^3$) occurs when the excavation depth is approximately 3.5 m which leaves 1.5 m of the module above ground level (a 0.5 m high support cradle is assumed). With 4.7 m of overburden, the mound will be 6.2 m high. If the module which is placed directly on the ground, no excavation is necessary but the soil covering will be 9.7 m high and will require 5,300 $m^3$ of material. The base of this mound will measure 32.2 m wide x 41.3 m long (prismatoid shape assumed).

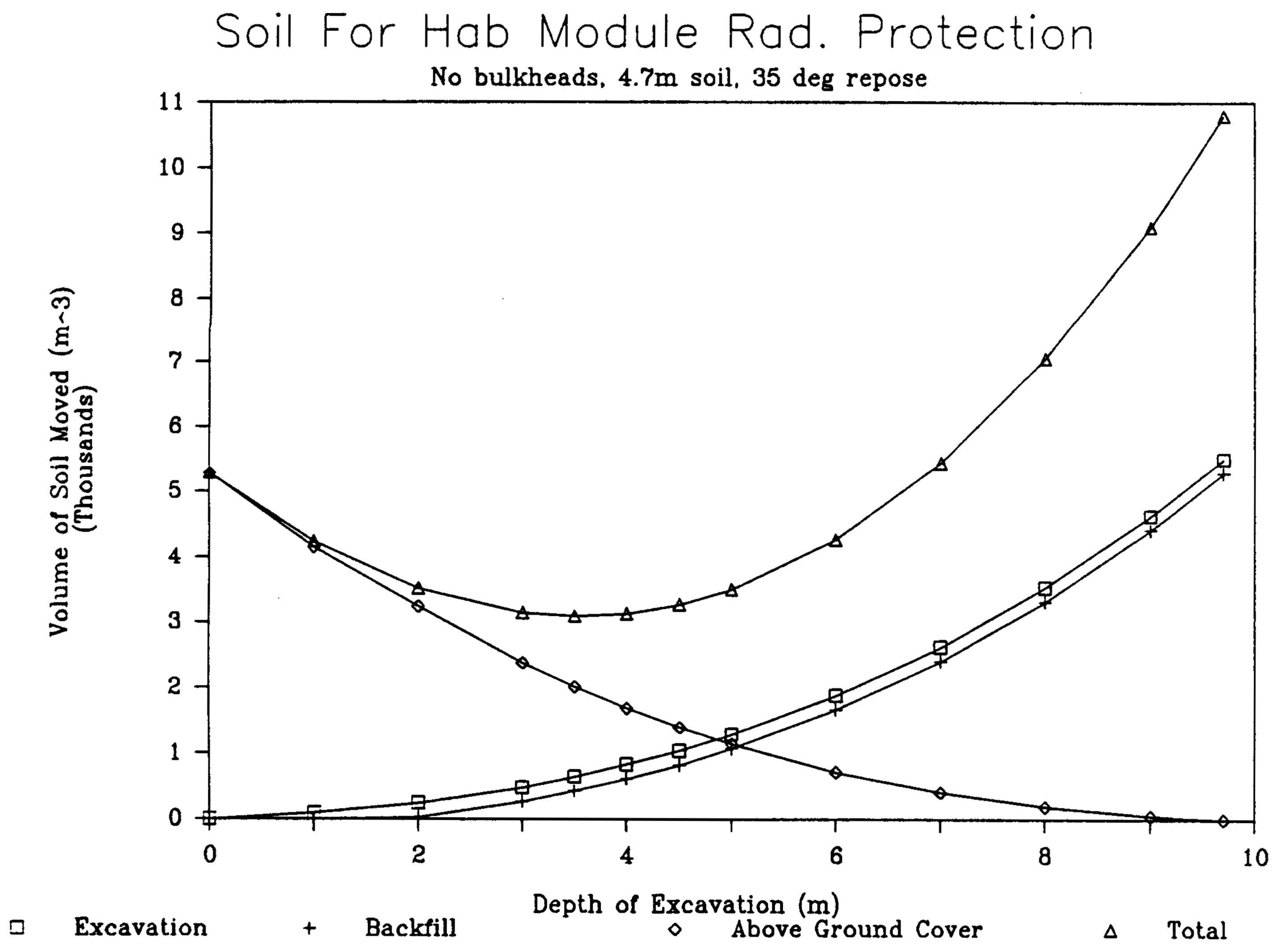
Burying the module in a deep hole is not preferred because excavating will probably be harder than collecting soil for covering the module, especially in mare regions where the regolith is only 2-5 m thick over underlying bedrock (2). It should also be noted that covering is more efficient than burying for another reason. Soil needs to be handled twice when excavating; once when digging the hole, then a second time to backfill the excavation. It is more efficient to collect soil just once to cover a module. This aspect is shown in Figure 6-14 where for a 9.7 m deep excavation, a hole 4.5 m wide x 13.6 m long at the bottom must be dug with dimensions of 32.2 m wide x 41.3 m long at the surface (5,510 $m^3$) assuming a 35° repose angle of the subsurface materials. However, 5,290 $m^3$ of soil must be used to backfill the excavation after emplacing the 216 $m^3$ habitat module. Thus, 10,800 $m^3$ of soil must be handled to completely bury a module versus 5,300 $m^3$ to cover.

Tunnels will be needed to provide access to other modules or the outside since the ends of the module are also covered, or alternatively, one end can be left uncovered until another module is emplaced.

Figure 3-12 shows an assembly sequence for covering a module on all sides using retaining walls or bulkheads (2) to minimize the amount of soil required, since it otherwise would slump into a mound inclined at its natural angle of repose (nominally 35°). The bulkhead concept reduces the required soil. For a full-sized module on the surface, a bulkhead measuring 13.9 m wide x 23 m long x 5 m high, which contains 2,165 $m^3$ of soil (including soil piled on top to provide 4.9 m of overburden directly overhead, but excluding the module volume), would provide a similar level of radiation protection as the module without bulkheads which, even with optimum conditions, still required moving 3,100 $m^3$ of material.

A combination of bulkheads and canopies can be used to both minimize the amount of soil needed for radiation protection, and to provide access to the exterior of the module for maintenance or other reasons. Two sets of bulkheads would be needed, one inside another and separated by the required soil thickness (4.7 m), to form a space which would be filled with soil. The canopy would then be attached and covered with soil.

**Figure 6-14.** Volume of Regolith Required to Provide Radiation Protection for a Habitat Module
(Habitat module measures 4.5 m diameter x 13.6 m long, 4.7 m of soil provided all around, soil angle of repose is 35°, total volume includes volume excavated + backfill + soil for above ground-level covering. Total volume is shown as a function of excavation depth. 0.5 m added for module cradle.)



## 6.16 Assemble External Systems

Systems external to the habitation modules that will require assembly include thermal control systems, solar photovoltaic power systems, and science assemblies and structures.

Thermal systems would consist of radiator panels, thermal bus, and sun-screens. Photovoltaic power systems would include structure, cabling, power conditioning equipment, energy storage, and the solar arrays themselves which could be laid flat on the ground (28), on passive upright A-frames, or on actively Sun-tracking frames. Science missions are varied (55) but some major science missions include (2): deep core drilling (200-1000 m deep), optical interferometer composed of 26 telescopes arranged in a Y-shaped array 9 km across, and life science and geochemical laboratory science.

These systems will generally require the same equipment as for module placement including equipment for site preparation; cargo unloading, transport, and positioning; utility routing; and soil collection and depositing for radiation protection in the case of pressurized science modules.

## 6.17 Excavate Regolith

A variety of equipment types are available to perform soil excavation tasks as listed below. These are described in more detail in Section 4.2. Some first-order comparisons of performance characteristics are made in Section 4.6.

- Backhoe
- Bucket Wheel Excavator
- Crane with clamshell
- Dozer
- Dragline
- Drill and Blast
- Front-End Loader
- Scraper
- Shovel
- 3-Drum Slusher

Manufacturers have combined some of these machines to offer multipurpose equipment. Backhoe/front-end loader combinations and integrated toolcarriers are common elements found on Earth construction sites (12-14). The versatile integrated toolcarrier consists of a wheeled tractor body which can be equipped with a variety of tools such as loader buckets, fork lifts, dozer blades, telescopic material handling (carrying) arms, and post hole auger (12). The boom crane is also a versatile machine capable of hoisting, post/pile-driving, magnetic lift, and excavating by using a clamshell or dragline bucket (13, 14). Front-end loaders equipped with a multipurpose bucket can perform soil loading and bulldozing chores. The multipurpose bucket can serve as a shovel, dozing blade, and also can be converted into a clamshell (14). Besides a front blade, the dozer is often fitted with a rear-ripper that is used to break-up hard ground/rock. The dozer can be fitted with a winch, cable drum, and hoist system as well. A hydraulic excavator is offered that can be quickly converted from a backhoe excavator, to a rotatable shaping shovel (or gradall, where the boom can rotate 90° or more to effectively shape side slopes), or to a boom crane (14).

Figure 6-15 illustrates a concept for a lunar excavator machine originated by NASA JSC (44). This machine uses a bucket excavator type attachment to collect soil which is held in an attached bin (43). An auger (or screw conveyor) is used to unload the bin into a more mobile truck which transports the soil to where it is needed (43). The buckets of the excavator are not attached to a revolving wheel as in a bucket wheel excavator (see Section 4.2) but rather to a continuous belt or chain as in a terrestrial ladder-type trenching machine (13, p.244). This type of trenching machine is not suitable for excavating trenches in dry unstable soil (13). However, a lunar derivative would likely be able to collect unconsolidated soil from shallow cuts into the lunar surface provided no large rocks are encountered. This concept of a lunar excavator is concieved as a multifunctional machine. The lunar excavator attachment would be replaced with a 2.2 m wide auger (with 15 cm "teeth") mounted to the front of the vehicle to perform surface leveling tasks (43). The bucket wheel excavates a 0.4 m wide trench to 0.5 m depth (43). Estimated mass of the 2 m high x 4 m wide x 6.5 m long (including wheels, excluding bucket wheel or dozer attachments) vehicle is 2,400 kg (including bucket wheel and dozer attachments) (43). Power required is 5 kW (43). Maximum speed is 2 km/hr and soil excavation production rate is 5,000 kg/hr. Maximum rock size that can be handled by a bucket wheel excavator is limited by the size of the buckets. A simple angle blade should be considered in future studies of this concept instead of the dozer auger.

Application of some of the other terrestrial soil excavating machines given in Section 4.2 should also be considered in future conceptual design studies. In particular, a conventional style dozer with blade, and a combination front-end loader/backhoe excavator machine should be considered.

The least versatile excavator is perhaps the 3-drum slusher. It cannot be easily adapted to other tasks and is constrained as an excavator as well. Although it is a low mass, high production rate machine (15) its mobility is extremely limited (since it must be moved manually) and production flow is to a point only. Several haulers are needed for a continous operation to transport the soil where it is needed. For a lunar oxygen process, two slushers might be required since fresh material flows to the process and discarded material is rejected back to the mine or to another site.

The performance of many of the excavators can be enhanced with the use of lunar materials as counterweight for better lifting capability or ballast to improve traction. Earth machines that sometimes or always use counterweights or ballast include the front-end loader, dozer, crane, dragline, and larger movable-wheel bucket-wheel excavators. Earth launch mass for lunar derivatives of these machines could be reduced by using lunar soil or rocks as counterweight and ballast.

**Figure 6-15.** Lunar Bucket Wheel Excavator and Dozer (from Ref.44)

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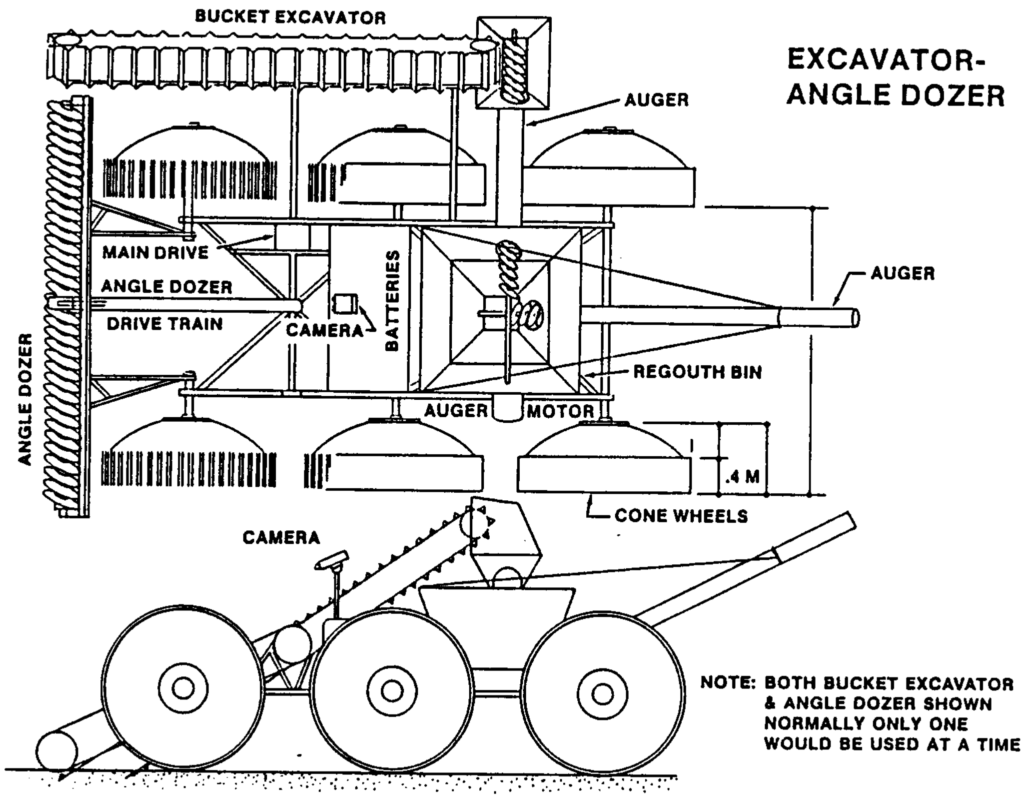


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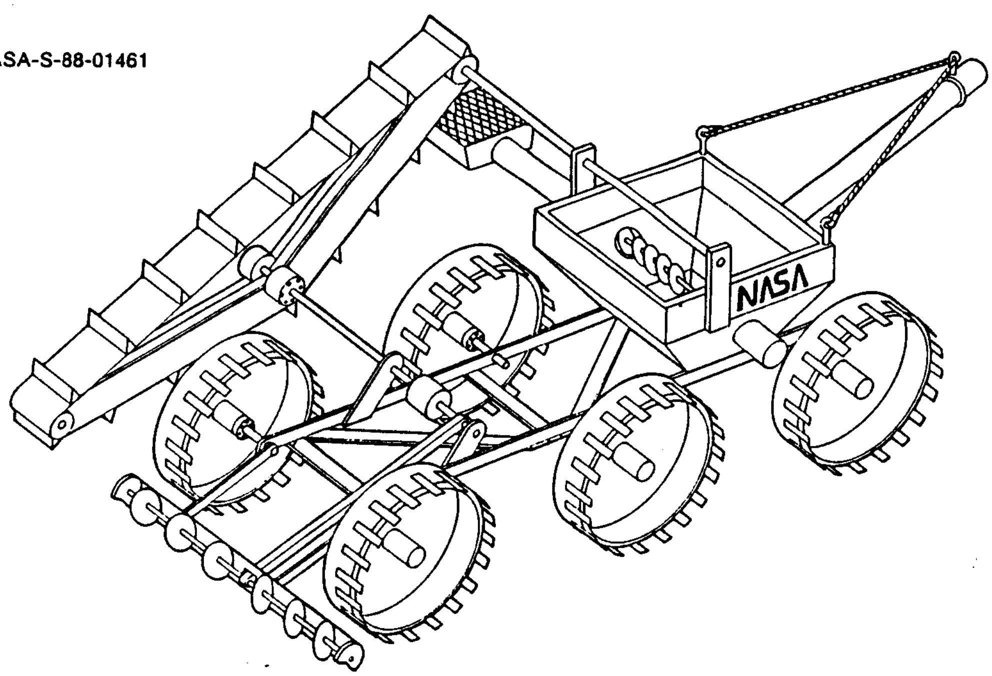


## 6.18 Move Regolith Bulk

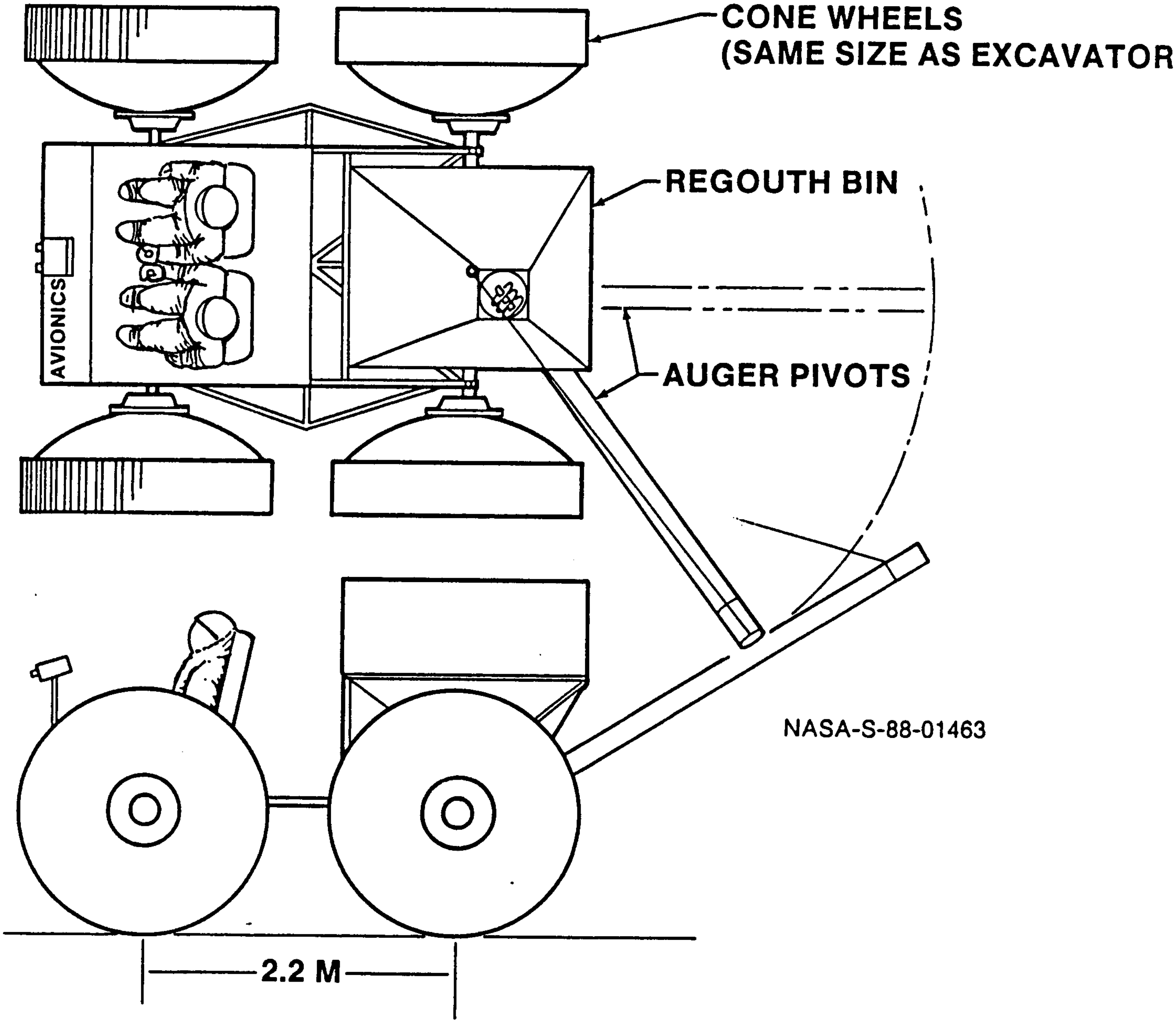
Significant amounts of soil will be needed for radiation shielding, crater fill material for surface preparation tasks, and feedstock for a lunar oxygen production pilot plant. Several methods to move regolith are listed below. They are described in more detail in Sections 4.5 and 4.2.

- Conveyors: belt, overhead tube and trolley
- Dozer
- Scraper
- Truck
- Trailer

The dozer and scraper are self-loading vehicles while the truck, trailer, and conveyors require an excavator to load them. A lunar truck concept is illustrated in Figure 6-16 (44). For comparison, typical terrestrial trucks are shown in Figure 4-5c. The lunar truck concept is a dual-operational mode vehicle (both manual and teleoperated control are possible) and is capable of 5 km/hr speeds on rough terrain and 10 km/hr speeds on smoothed roadways (43). Payload capability is 2500 kg. A movable (pivoting) auger (or screw conveyor) is used to unload the truck. The truck is able to transport 4.8 million kg of regolith per month in feed and tailings for a 2 mt/month lunar oxygen plant (43). Estimated mass of the 3.5 m wide x 2.5 m high x 4 m long truck (including cone wheels) is 1,400 kg and power required is 5 kW (43).

Variables important in selecting the most useful regolith transportation method will be the quantity of soil required over a given time period and the distance from the excavation site to where soil is needed or disposed of.

**Figure 6-16.** Lunar Truck (from Ref.44)



### 6.19 Deposit Regolith Bulk

Soil will be needed to fill craters and other natural voids in numerous leveling/grading tasks (habitation site preparation, landing pad preparation, and roadway construction). This task can be accomplished by:

- Crane with bucket
- Dozer
- Dragline
- Dump truck
- Dump trailer
- Front Loader
- Scraper

### 6.20 Prepare Lunar Lava Tubes

Lava tubes have been proposed as natural lunar features that can be used to protect habitats, crew, and equipment from the lunar radiation, meteoroid, and thermal environment (56). Potential applications include:

- Hangar for lunar lander. The landing pads would need to located nearby. A rail system connecting the landing pad and lava tube hangar could be used to transport the landers.

- Radiation protection for pressurized modules and inflatables. The floor of the lava tube would require clearing to remove debris and obstructions. The approach to the lava tube entrance should be graded to a shallow slope (to 5° or less) which would allow access to the tube with wheeled equipment. Habitation elements should be located deep enough into the tube to avoid having to close off the entrance (by sandbags) for radiation protection. Lights will be required to illuminate the interior of the tube. A low weight, reflective curtain deployed across the entrance could be used as a dust and thermal control method for equipment located near the entrance.

- Habitable Volume. A section of tube could perhaps be sealed with a bladder or sprayed on sealant, pressurized, and an airlock connected to allow the entire cross-section of the tube to be used.

Although tunneling methods were not studied extensively, manufactured tunnels may be an important method for providing radiation protection in a later base growth phase. Tunnelling machines are available that are based on one of following five basic categories that rock can be drilled (57, 58):

1) Impact
2) Abrasion
3) Thermally induced rock spalling (fragmentation)
4) Fusion (melting) and vaporization
5) Chemical reaction

## 7.0 Equipment Comparisons and Selection

Qualitative comparisons of the equipment options described in Section 6 for the construction jobs given in Section 5 were made to assess machine types suited for lunar base construction. This non-quantitative analysis approach is more suited to this stage of design where detailed definition of the construction tasks and the effect of low lunar gravity on performance is not available. Comparisons are summarized in the following sections while more detailed comparison data is given in Appendix A.

### 7.1 Lunar Construction Equipment Goals

To simplify the comparison process, the 20 jobs given in Section 5 were reduced to 9 generalized tasks as defined in Table 7-1. Equipment options for these tasks were rated on a numerical score. Performance, reliability, and versatility were considered overriding important attributes for successful lunar construction equipment. These factors are explained in more detail in the following sections.

**Table 7-1.** Construction Operations List

| | Refer to given Section number for description of: | |
|---|---|---|
| Construction Operation | Construction Job | Equipment Options |
| 1. Unload Lander (Nominal) | 5.2 | 6.2 |
| 2. Transport Loads | 5.4 | 6.4 |
| 3. Lift and Position Loads | 5.1, 5.12-5.16 | 6.1, 6.12-6.16 |
| 4. Grade/Level Surface | 5.6, 5.7 | 6.6, 6.7 |
| 5. Excavate and Move Soil | 5.12, 5.15, 5.17-5.19 | 6.12, 6.15, 6.17-6.19 |
| 6. Anchor Object | 5.1 | 6.1 |
| 7. Unload Lander (Contingency) | 5.3 | 6.3 |
| 8. Surface Roads/Pads | 5.8, 5.9 | 6.8, 6.9 |
| 9. Move Lander | 5.10 | 6.10 |

#### 7.1.1 Performance

Performance of the construction equipment is compared based on a first-order characterization of how well the system can perform the given task. Performance was rated based on consideration of the following factors:

1. Capability of the machine or system. This rating expresses how well the system can perform the required task. This comparison was made based on one or more of the following machine characteristics:
   - Adaptability to varying conditions.
   - Maneuverability.
   - Reach (across obstacles or into cracters).
   - Digging profile, ability to excavate deeply.

- Ability to excavate larger rocks.

2. Operational assessment: an assessment of the difficulty of setup and operation. This involved evaluating one or more of the following factors:
   - Work cycle time.
   - Whether setup is required or if the method is fully operational after unloading.
   - The number of requred operations crew.
   - The severity of typical operational problems in equivalent terrestrial systems.

3. Efficiency of the machine or system. A true comparison of efficiency would involve producing detailed conceptual designs to determine the mass and power for systems with comparable productivity. Because this was not attempted in this study, the efficiency comparison was limited to assessing one or more of the following:
   - Whether machine counterweight or ballast is required since it adds weight. (However, using lunar materials could eliminate this concern).
   - The relative number or size of equipment elements required for a given task.

Performance was rated on a scale from 0-4 by averaging the numerical scoring for the relative comparison of each of the above three factors. The higher the score, the better the machine performance.

| Score | Rating |
|---|---|
| 4 = | Excellent performance. |
| 3 = | Good. |
| 2 = | Fair. |
| 1 = | Poor. |
| 0 = | System not applicable to task. |

### 7.1.2 Reliability

Reliability is an important machine attitribute that reflects on the amount of time the machine will be available for doing useful work and the potential maintenance requirements for the machine. Reliability was assessed for the various construction options by averaging ratings for the following three factors:

1. Complexity of machine. Although difficult to quantify, machine complexity has been compared in the literature using the factors shown in Table 7-2 (11). Generally, the comparison made in this study was limited to mobility options; a high complexity factor was assigned to self-propelled machines, medium complexity for mobile but pulled machines, and low complexity for erected equipment. In addition, bucket wheel excavators were rated more complex than other excavators because of the rotating wheel (11).

2. Complexity of operation. Operational complexity was evaluated based on the number of functions a machine is capable of, relative to the other options under consideration for the task. For example, a mobile boom-crane was rated more complex than a

mobile gantry-crane because the boom-crane can rotate the boom section as well as hoist the load. (Of course, this same attribute increases the performance capability of the boom-crane relative to the gantry-crane as well.)

3. Complexity of setup activity. Options that require assembly, such as erectable tower cranes, were rated more complex than options that do not require assembly. In some cases, such as a large gantry-crane for unloading a lander, a device cannot be expected to be initally delivered to the lunar surface in a fully integrated and operational condition and would have to be assembled prior to use (but just one time). In such cases, a higher complexity was assigned than options that will not require much or any initial assembly.

Ratings for each of the above three factors were averaged to produce an overall complexity rating from 0-2; where the higher the score, the lower the complexity and the better the machine.

| Score | Complexity Rating |
|---|---|
| 0 = | High. |
| 1 = | Medium. |
| 2 = | Low. |

### 7.1.3 Versatility

An important design goal for lunar construction equipment will likely be the ability to perform a variety of tasks around the base (2), to provide backup (albeit limited) capability for other types of equipment, and to have a high degree of commonality with other construction equipment to reduce spares requirements. A versatility rating was assigned for the various equipment options by considering the following:

1. Flexibility. This rates the usefulness of the device in other jobs around the base. For instance, a boom crane is given a high flexibility rating because it can be outfitted with various attachments to perform a number of tasks (13, 14, 61): a boom-crane configured with a hoisting hook can unload cargo, clamshell or dragline bucket attachments allow soil excavation, and a pile-driving ram attachment can be used to place anchors.

2. Commonality. If a machine shares many subsystems with other potential equipment options, it is given a high commonality rating. For instance, a truck for moving soil will require a bed to contain the soil, but could share many of the same characteristics as a flatbed truck used to transport cargo. The wheels and suspension system for a truck would likely have many of the same features used on a mobile boom crane. However, the traction required for a bulldozer will undoubtedly require a different number of wheels or a completely different locomotive configuration than that used for the cargo or soil transporter vehicles.

3. Redundancy. A high redundancy rating is given to machines that have capabilities

which overlap with other machines. The goal is to specify a set of equipment with enough functional redundancy to provide some limited capability for contingency operations in the event of equipment failure. For instance, a boom-crane and excavator equipment set has a high redundancy rating since if the excavator fails, the boom-crane with a clamshell bucket attachment could provide some backup excavation capability.

Each of the above three factors were averaged to produce a versatility rating that ranged from 0-2; where the higher the score, the better (i.e. more versatile) the machine.

| Score | Versatility Rating |
|---|---|
| 0 = | Low. |
| 1 = | Medium. |
| 2 = | High. |

Table 7-2. Construction Equipment Complexity Ratings (Ref.11)

| | Rating |
|---|---|
| **Power Source** | |
| • Diesel | High |
| • Electric | High |
| **Primary Power Distribution** | |
| • Hydraulic cylinders, pumps (low pressure) | Low |
| • Hydraulic cylinders, motors, pumps (high pressure) | Medium |
| • Torque converter/transmission | High |
| • D.C. Motors | High |
| • A.C. Motors | High |
| • Hydraulic and electric motors | High |
| **Number of Powered Functions** | |
| • Less than four | Low |
| • Four | Medium |
| • More than four | High |
| **Control System** | |
| • Mechanical linkage, simple hydraulic valve | Low |
| • Static electric | Medium |
| • Ward Leonard electric | High |
| • Variable displacement hydraulic | High |
| **Basic Frame or Structure** | |
| • Single unit | Low |
| • Two units articulated | Low |
| • Two units rotatable | Medium |
| • Three units rotatable | High |
| • Four units rotatable | High |
| **Excavating Linkage System** | |
| • Cable and drum | Low |
| • Cylinders and arms | Medium |
| • Rack and pinion | High |
| • Digging and discharge booms | High |
| **Excavating Means** | |
| • Blade | Low |
| • Bucket | Low |
| • Fixed dipper | Low |
| • Wristing dipper | Medium |
| • Bucket wheel | High |
| **Propel Mechanism** | |
| • Wheel | Low |
| • Walking device (low speed shoes) | Low |
| • High speed crawler | Medium |
| • Independent track drive | High |

## 7.2 Summary of Comparison Results

The average performance, complexity, and versatility ratings were summed to produce an overall rating for each option for the tasks given in Table 7-1. As given in the previous sections, the performance component of the overall rating was weighted twice as much as the complexity and versatility factors. Table 7-3 summarizes the overall ratings for each option while tables in Appendix A contain the details of the individual ratings that went into the overall composite rating. Appendix A also contains data sheets that describe in more detail the rationale for the numerical ratings. As shown by comparison results given in Table 7-3, the range of anticipated lunar surface construction tasks could be accomplished by a small set of versatile machines and some auxiliary equipment.

The comparisons made here are very preliminary, serving mainly to show that a set of versatile equipment can perform multiple construction tasks. Much more work is required before making a confident choice of equipment. The following equipment set was indicated as a candidate construction system for the Phase 2 lunar base:

- Mobile boom crane. Multiple attachments would be needed including: hoisting hook for cargo, dumpable soil-carrying bucket, pile-driving ram, and soil excavation clamshell bucket (for use as a backup excavator). The boom-crane would require a counterweight. Use of lunar soil for the counterweight should be examined as a method to reduce Earth launch requirements. Using lunar materials to add weight to the pile-driving ram is also possible.

- Excavator/dozer. A prime mover tractor vehicle that could perform both excavation and bulldozing duties is a possibility. Multipurpose front-loader buckets have been employed terrestrially as a bulldozer blade or loader bucket (14). Otherwise, two separate vehicles are needed; one for leveling and surfacing, and another for excavating and collecting soil. The type of excavator vehicle finally selected will depend on the depth of excavations required by the base construction tasks. If deep excavations are required (greater than 0.5 m or so), a machine with a front-loader and a backhoe would be a good choice. For bases where only shallow excavations are required, an angle dozer and soil excavator (front-end loader or bucket wheel excavator) are indicated.

- Haulers. Flatbed cargo transporters are required. Mounting cradles will be needed for large cargo elements. Hauler trucks for soil transport are optional depending on the allowable time for completing soil excavation/transport tasks.

- Auxiliary equipment:

  - For compacting surfaces, a compactor roll attachment for a dozer prime-mover is needed. The compactor roll could possibly be filled with lunar materials (densified) to reduce equipment mass brought from Earth.

  - For unloading landers in a contingency situation (due to equipment failure or remote site landing), a ramp or inflatable chute is needed. A device to control the deployment of the cargo down the ramp or chute, such as a winch/cable system, is also needed.

- If blasting for inflatable excavation is required, drill equipment capable of drilling shallow holes (<7 m) is needed.

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# Table 7-3. Equipment Comparison

(Note: The higher the score, the better the option: 8=Best, 0=Worst. See Appendix A for details)

Operation 1: Unload Lander (Nominal)

| Option | Overall Score | Performance Rating | Complexity Rating | Versatility Rating |
|---|---|---|---|---|
| • Mobile boom-crane | 6.0 | 3.0 | 1.0 | 2.0 |
| • Hybrid: bridge assisted boom-crane | 3.7 | 2.0 | 0.7 | 1.0 |
| • Forklift | 3.7 | 1.7 | 1.0 | 1.0 |
| • Gantry crane | 3.3 | 2.0 | 0.7 | 0.7 |
| • Erectable crane | 3.0 | 1.7 | 1.0 | 0.3 |

Operation 2: Transport Loads

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Off-road truck (flatbed) | 5.3 | 2.7 | 1.0 | 1.7 |
| • Pull on wheeled cradle or trailer | 4.0 | 1.3 | 1.0 | 0.3 |
| • Forklift | 3.7 | 1.7 | 1.0 | 1.0 |
| • On-road truck | 3.7 | 2.3 | 1.0 | 0.3 |
| • Gantry crane | 3.0 | 1.7 | 0.7 | 0.7 |
| • Rail system | 3.0 | 2.0 | 1.0 | 0.0 |

Operation 3: Lift and Position Loads

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Mobile boom-crane | 6.0 | 3.0 | 1.0 | 2.0 |
| • Forklift | 3.7 | 1.7 | 1.0 | 1.0 |
| • Gantry crane | 3.3 | 2.0 | 0.7 | 0.7 |
| • Erectable crane | 3.3 | 2.0 | 1.0 | 0.3 |

Operation 4: Grade/Level Surface

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Angle dozer | 6.3 | 3.0 | 1.7 | 1.7 |
| • Dozer, front-end loader (FEL) excavator, and truck | 6.3 | 3.0 | 1.3 | 2.0 |
| • Dozer, bucket wheel excavator, and truck | 5.0 | 3.0 | 1.0 | 1.0 |
| • Dozer and rock drill for explosives | 5.0 | 3.0 | 1.0 | 1.0 |
| • Scraper (self-propelled) | 4.7 | 2.7 | 1.7 | 0.3 |

Operation 5: Excavate and Transport Soil

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Crane with soil-carrying dumpable bucket, and FEL excavator | 6.0 | 3.0 | 1.3 | 1.7 |
| • Dozer | 5.7 | 2.7 | 2.0 | 1.0 |
| • Front-end loader excavator and truck | 5.3 | 2.3 | 1.3 | 1.7 |
| • Dragline (crane with dragline bucket) | 5.3 | 3.0 | 1.7 | 0.7 |
| • Crane with clamshell bucket and truck | 5.0 | 2.7 | 1.3 | 1.0 |
| • Bucket wheel excavator and truck | 4.3 | 2.3 | 1.0 | 1.0 |
| • Backhoe excavator and truck | 4.3 | 2.0 | 1.3 | 1.0 |
| • 3-Drum slusher | 3.3 | 2.0 | 1.0 | 0.3 |

Operation 6: Anchor Object

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Piledriver: crane with pile driving ram | 5.7 | 2.7 | 1.3 | 1.7 |
| • Deadman: excavator (backhoe) and crane | 4.7 | 2.0 | 1.0 | 1.7 |
| • Standard (drill hole & cement in anchor): drill & truck | 4.0 | 2.7 | 0.3 | 1.0 |
| • Natural anchor: anchor cable tensioning devices | 4.0 | 2.3 | 1.3 | 0.3 |

Operation 7: Unload Lander (Contingency)

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Ramp and winch/cable system | 4.0 | 2.7 | 1.3 | 0.0 |
| • Chute and winch/cable system | 4.0 | 2.7 | 1.3 | 0.0 |
| • Erectable crane | 3.7 | 2.3 | 1.0 | 0.3 |
| • Lift cargo with erectable structure, then move lander | 2.7 | 1.7 | 0.7 | 0.3 |

Operation 8: Surface Roads or Landing Pads

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Compacted finish: Dozer with compactor roll | 6.7 | 3.3 | 1.7 | 1.7 |
| • Gravel finish: Excavator, truck, vibratory screens, angle dozer | 4.0 | 2.3 | 0.3 | 1.3 |
| • Melted finish: Melter, dozer | 3.0 | 2.3 | 0.7 | 0.0 |

Operation 9: Move Lander

| Option | Score | Performance | Complexity | Versatility |
|---|---|---|---|---|
| • Lift lander with jacks and lower onto several standard flatbed trucks | 5.7 | 3.0 | 1.7 | 1.0 |
| • Hoist entire lander with crane and lower onto single large truck | 5.3 | 2.3 | 1.0 | 2.0 |
| • Mobile gantry-crane | 4.3 | 2.0 | 1.3 | 1.0 |

## 7.3 Potential Cargo Unloading System

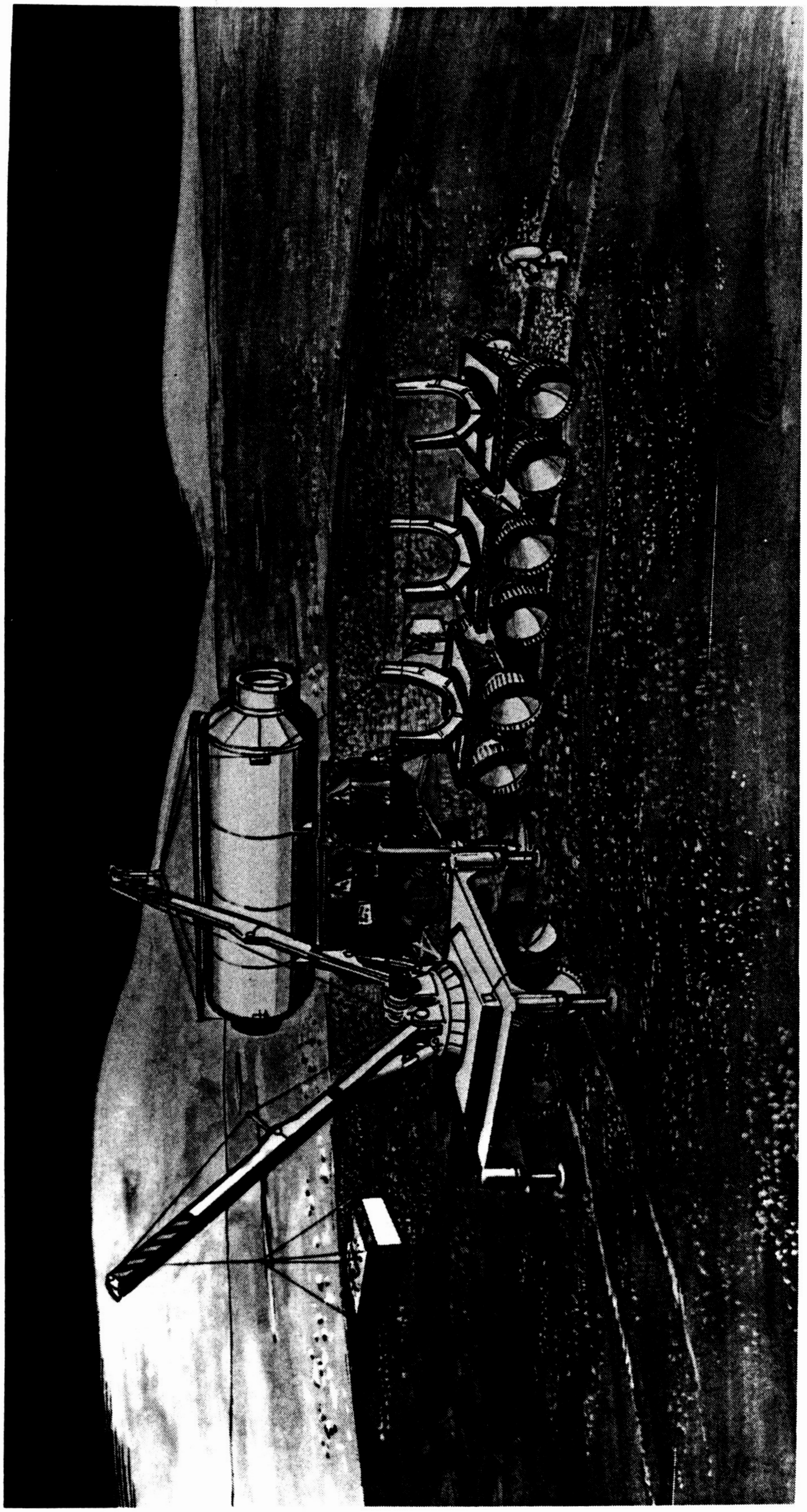
Figure 7-1 illustrates a concept for unloading a habitation module from a lunar lander. The unloader is a basic mobile boom-crane. The cargo lifting boom is 20 m long. A counterweight is provided by a 4 $m^3$ box (or bucket) filled with ~6.4 mt regolith which is suspended from another 30 m long boom. The counterweight position along the 30 m long boom can be adjusted based on the mass of the cargo lifted. For a 25 mt cargo, the 6.4 mt counterweight must be 22 m out on the 30 m boom (assuming the counterweight boom is at 30°, and the lifting boom is at 64°). Both booms can be lifted in the vertical plane and are mounted on a rotary turntable. The overall length of the crane is approximately 7 m.

Two crew are assisting the cargo loading operation. The cargo is shown suspended by a four-cable lifting sling to keep it level. Its orientation is adjusted by one crew member using a lanyard. Another crew member adjusts the crane's booms and activates the crane winch system using a remote keyboard control unit with trailing cable. The cable for the remote control unit is long enough to allow the crew member to view the operation from any angle. Eventually, these operations could be remotely controlled from the lunar base, or perhaps even Earth, as experience grows. Initial unloading operations will probably require on-site control personnel, however, to enable a better "feel" of the process and to handle unexpected problems.

The cargo is placed on a string of 3 flatbed truck carriers. Mounting cradles have been attached to the flatbeds to contain the cargo. After the cargo is placed in the cradles, but before the crane is detached from cargo, the counterweight bucket is pulled as far forward toward the crane as possible and the counterweight boom is raised. This is necessary to avoid tipping the crane after the cargo is released.

An alternative location for the counterweight is to mount the soil carrying box integrally with the crane structure, instead of on a boom. The advantage with the boom location for the counterweight is that its mass is lower for a given size cargo, since it can be placed out on a boom. However, crane mechanisms are more complicated and the counterweight bucket must be moved continuously to keep the crane in balance during certain operations (such as dumping soil) which is a major disadvantage. This movement could perhaps be automated however.

**Figure 7-1.** Nominal Cargo Unloading Operation



## 7.4 Potential System for Transporting Loads

Figure 7-2 shows three linked flatbed trucks transporting the module habitat from the landing site to the base site. The transport trucks are self-propelled, independently steerable, and remotely controlled. The mobility subsystem (unit containing cone wheels, drive mechanism, and suspension) for the transporters and crane were considered to share common features; therefore similar dimensions are shown.

One astronaut is directing the transfer vehicles using a hand-held control unit. The other crew member is in a local transportation vehicle (LOTRAN).

Both the landing site and road have a prepared surface with boulders removed, craters smoothed, and surfaced with sized gravel. A 2 m diameter landing site marker is shown at the edge of the landing field, to the right of the road.

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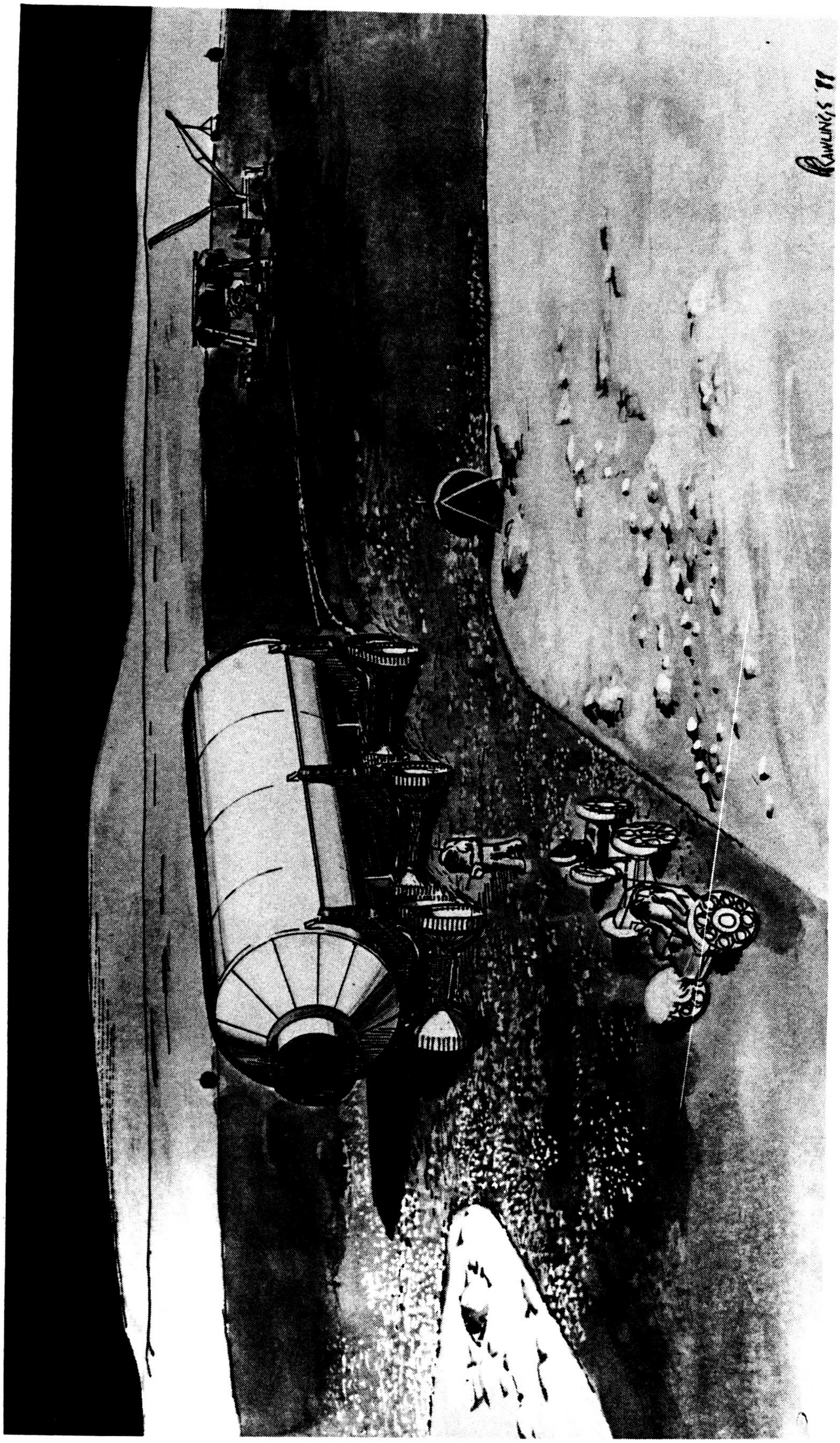
**Figure 7-2.** Transporting Cargo

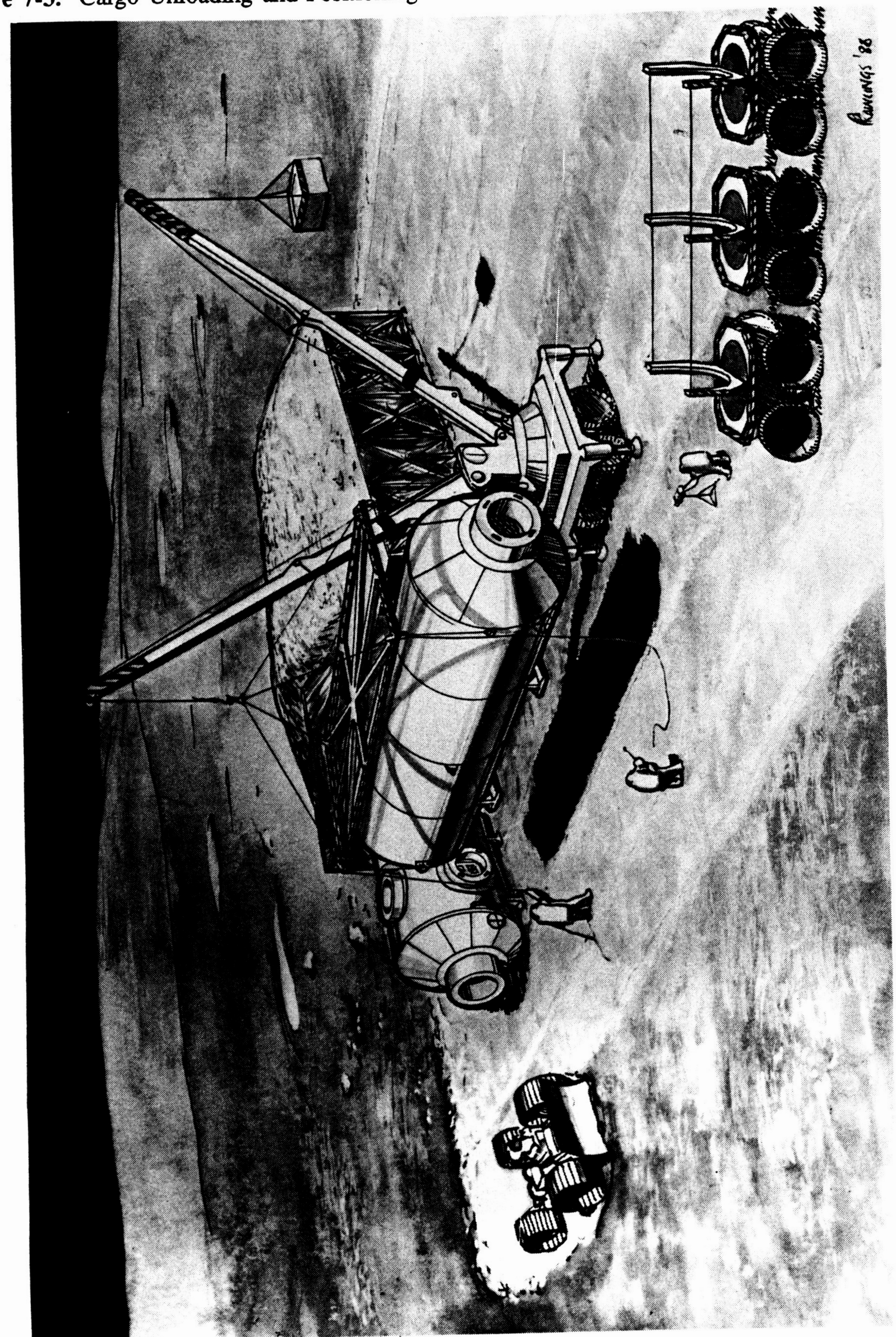


## 7.5 Lifting and Positioning Loads

Figure 7-3 illustrates cargo unloading operations at the base site. The mobile boom crane with counterweight has been relocated to the base site and has lifted the cargo from the transporters. Final positioning is conducted by two crew members orienting the cargo with remote control of the crane and by physically swinging the cargo with an attached cord. A third crew member is using sighting equipment to ensure proper placement. Final leveling of the module can be accomplished with jacks (attached to the bottom of the module in the illustration, or could be part of a mounting cradle anchored to the ground prior to lowering the module).

The base site has been prepared by the prime mover with fixed angle blade shown in the illustration. This vehicle is manually controlled but could be remotely operated. The dozer will require more traction than the transporters and will therefore probably not share common locomotion subsystems with the transporters and mobile boom-crane.

**Figure 7-3.** Cargo Unloading and Positioning

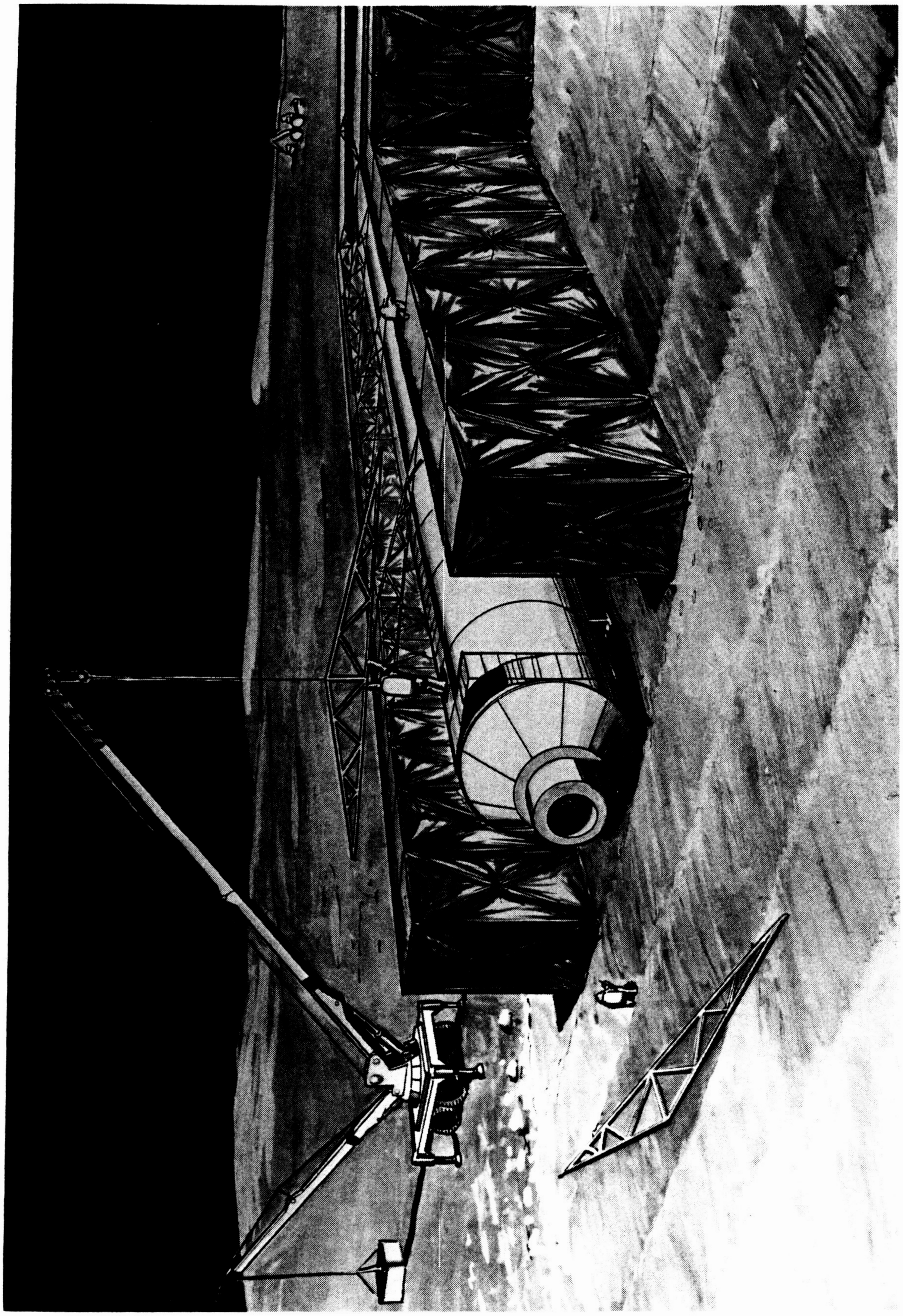


## 7.6 Assembling Structures

Framework for a canopy to support soil for radiation protection is being assembled by several crew and the mobile boom crane in Figure 7-4. One crew member is controlling the crane while another positions a frame structure, and a third is permanently attaching a previously placed frame. The walls of the protective enclosure have already been filled with regolith. The location of the counterweight along the crane boom will be adjusted for the lightweight frame elements. The framework will be covered with panels and then covered with regolith to finish the canopy structure.

A combination backhoe/front-loader is shown in the background excavating soil for covering the canopy.

**Figure 7-4.** Assembling Structures



## 7.7 Regolith Operations

### 7.7.1 Providing Radiation Protection

The canopy over a habitation module is shown being covered by soil for radiation protection in Figure 7-5. The boom crane lifting attachment has been removed and substituted with a bucket, similar to that used for the counterweight. The soil-carrying bucket attachment is used to discharge soil into and over the bulkhead wall and canopy structure (described in Section 6.14.2) for radiation protection. During the dump operation, the crane counterweight must automatically move forward to keep the crane in balance, or alternatively, the counterweight must be initially positioned close to the ground (as shown in Figure 7-5) so that the crane only tilts slightly backwards as the soil-discharge bucket empties.

The end of the enclosure is left exposed to provide a location for expanding the module set. The end module may be off-limits during a solar flare if it is determined that the open end allows too much radiation exposure. A temporary structure could be constructed and filled with soil to block the end, but would have to be disassembled prior to placing the next module.

### 7.7.2 Soil Excavation and Transport

Figure 7-6 illustrates a front-loading vehicle that could be used to collect soil from a bank or by scraping soil from a surface layer. The vehicle could then either directly deposit soil into the discharge bucket of the crane as depicted in Figure 7-6, or it could fill a soil hauling vehicle which then dumps its load into the crane's bucket as shown in Figure 7-7. The real need for a soil hauler will depend on a better definition of the quantity of soil that must be moved and the amount of time available to complete the task.

Figures 7-8 and 7-9 show the same soil moving operations for filling the crane's counterweight bucket. This bucket is being filled prior to the start of the next base assembly/soil movement operation after the crane has been positioned for work.

Figure 7-5. Providing Radiation Protection

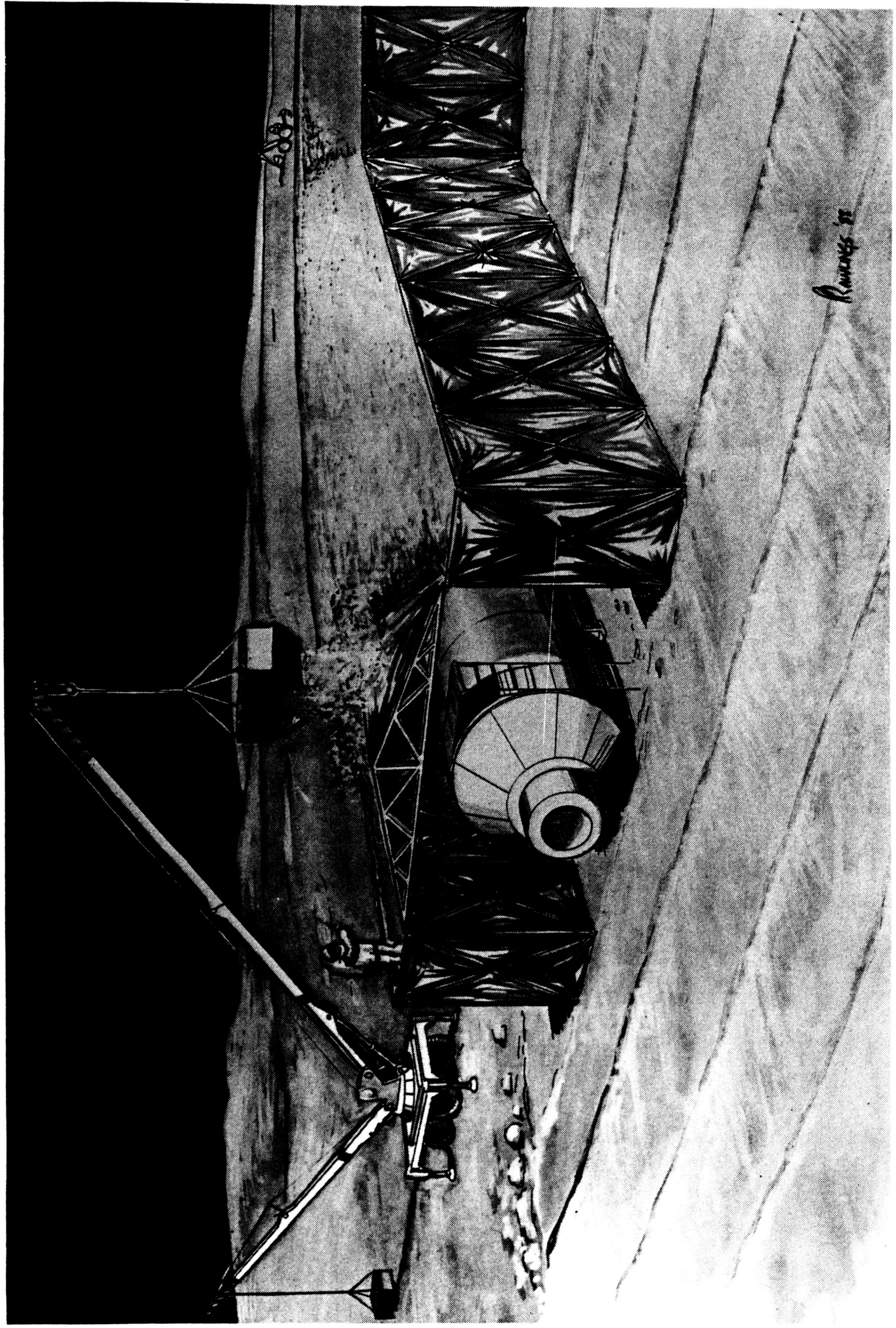


**Figure 7-6.** Soil Excavation and Transport

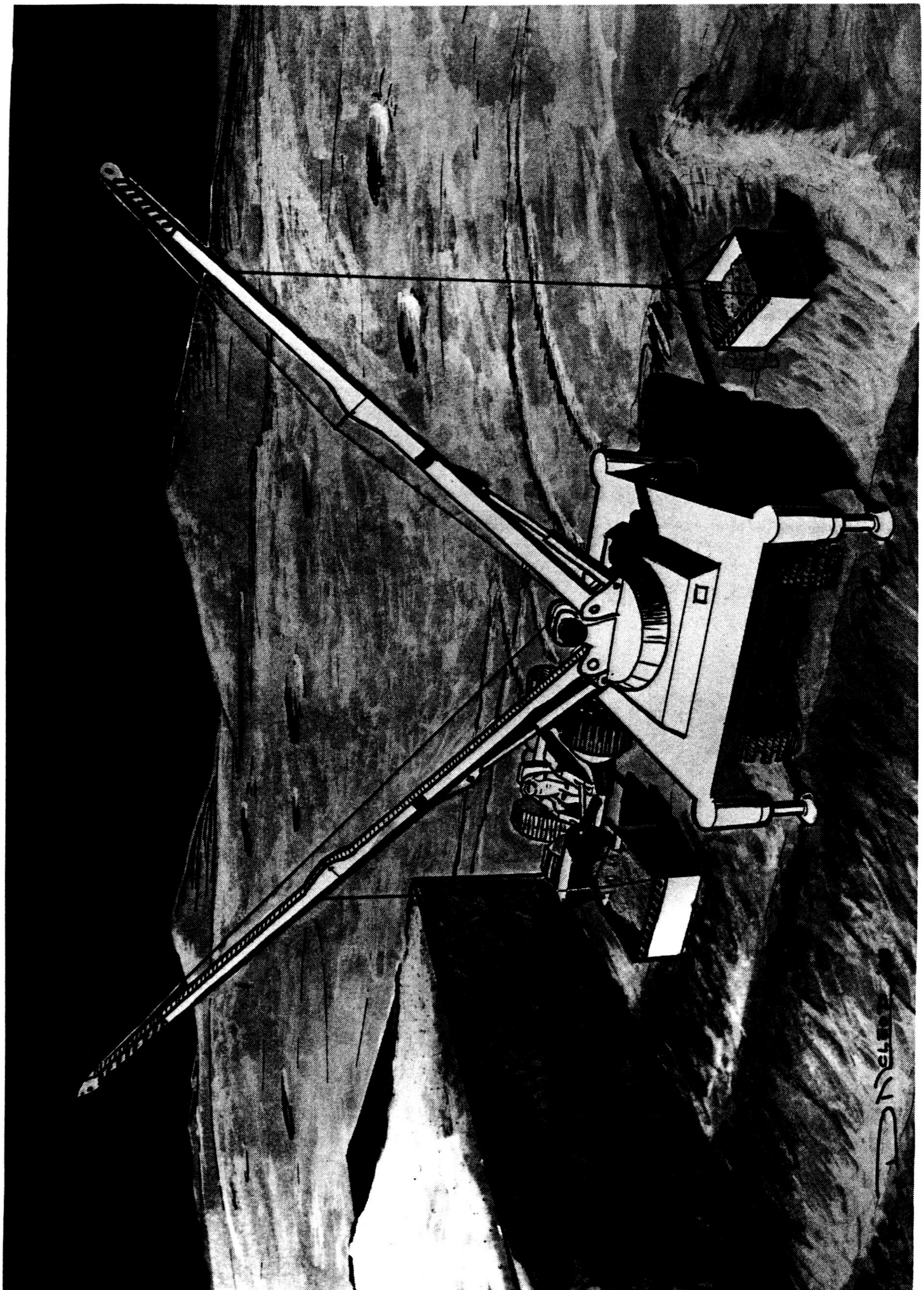
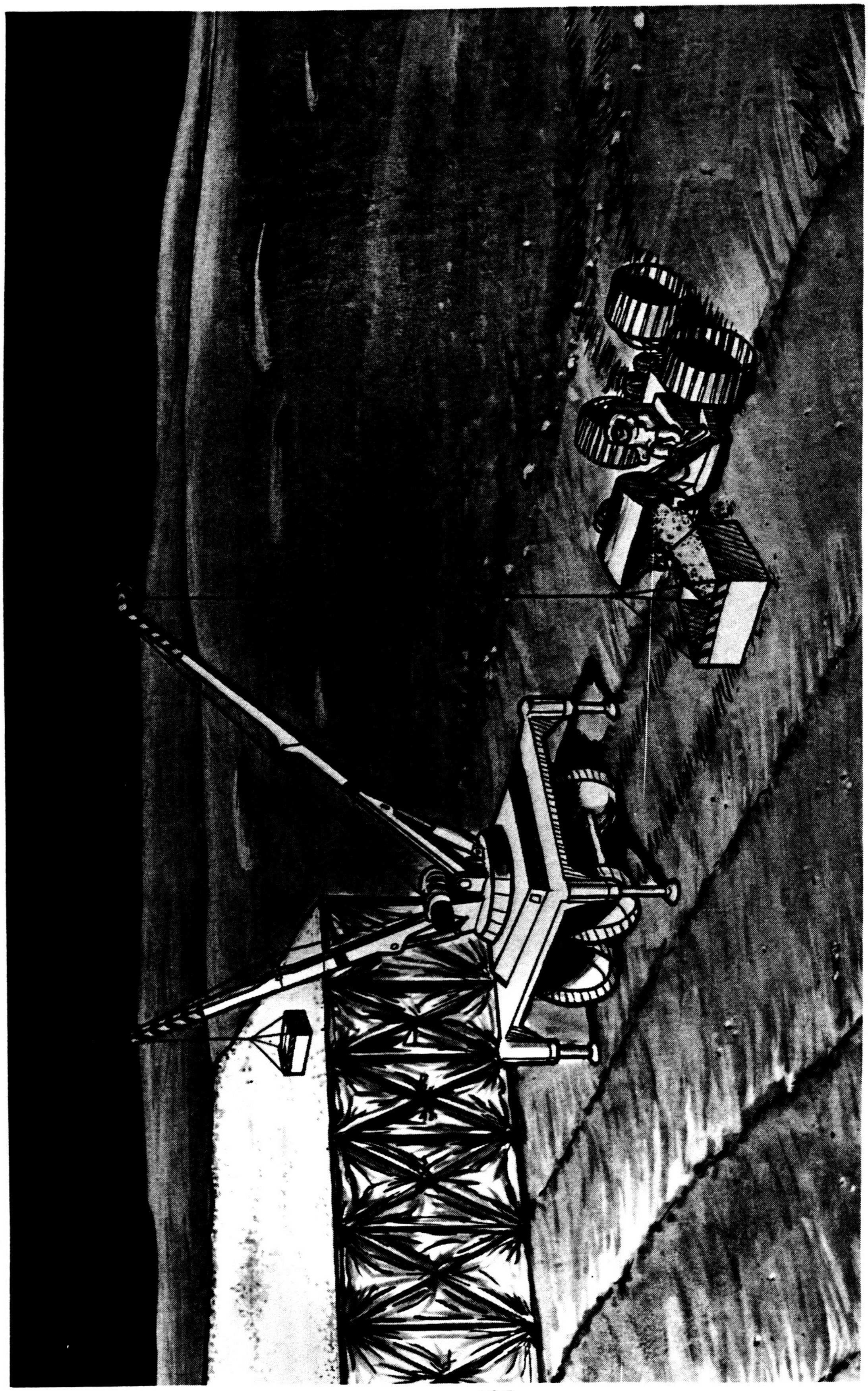


Figure 7-7. Soil Hauler



**Figure 7-8.** Filling Crane Counterweight Bucket



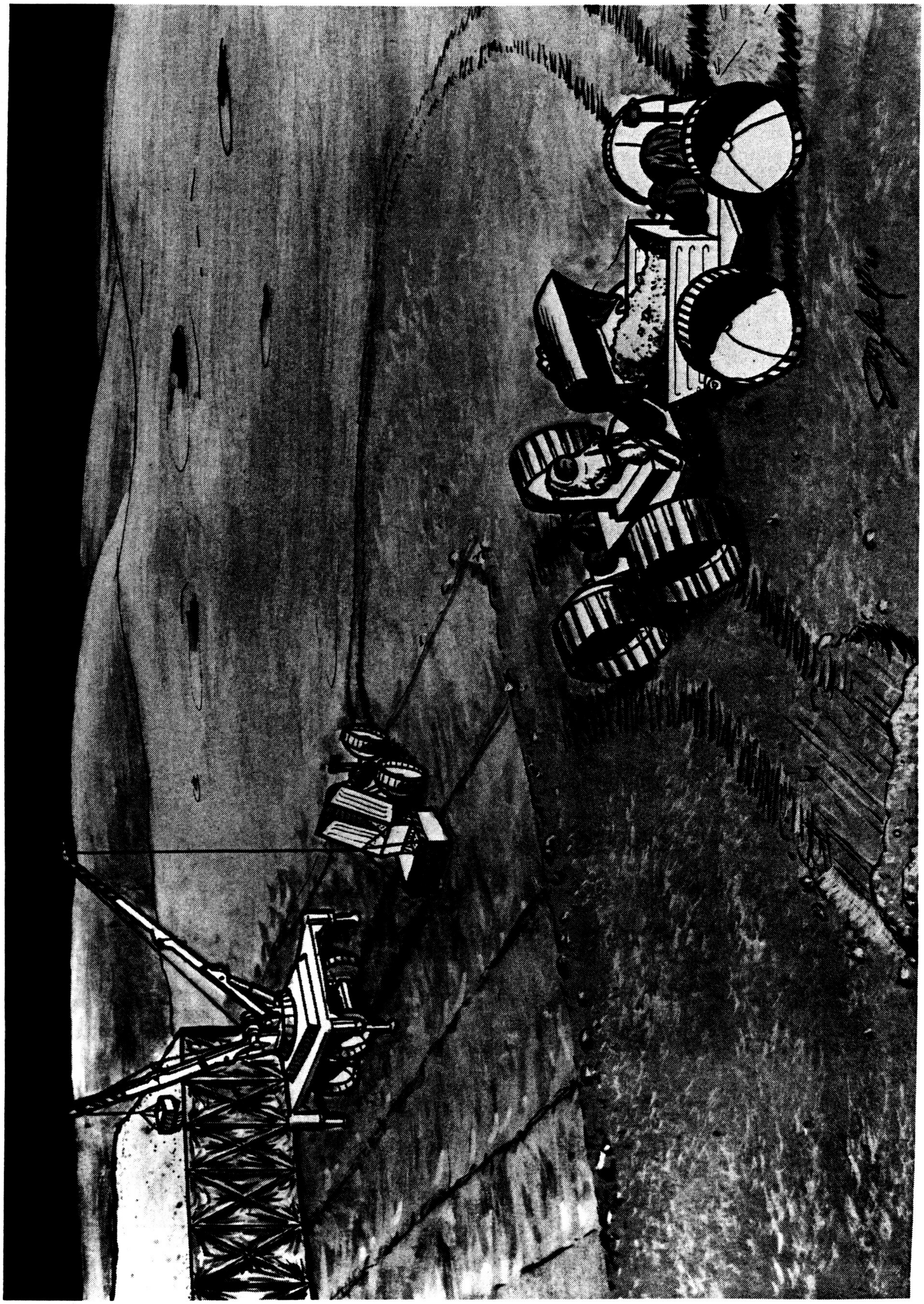


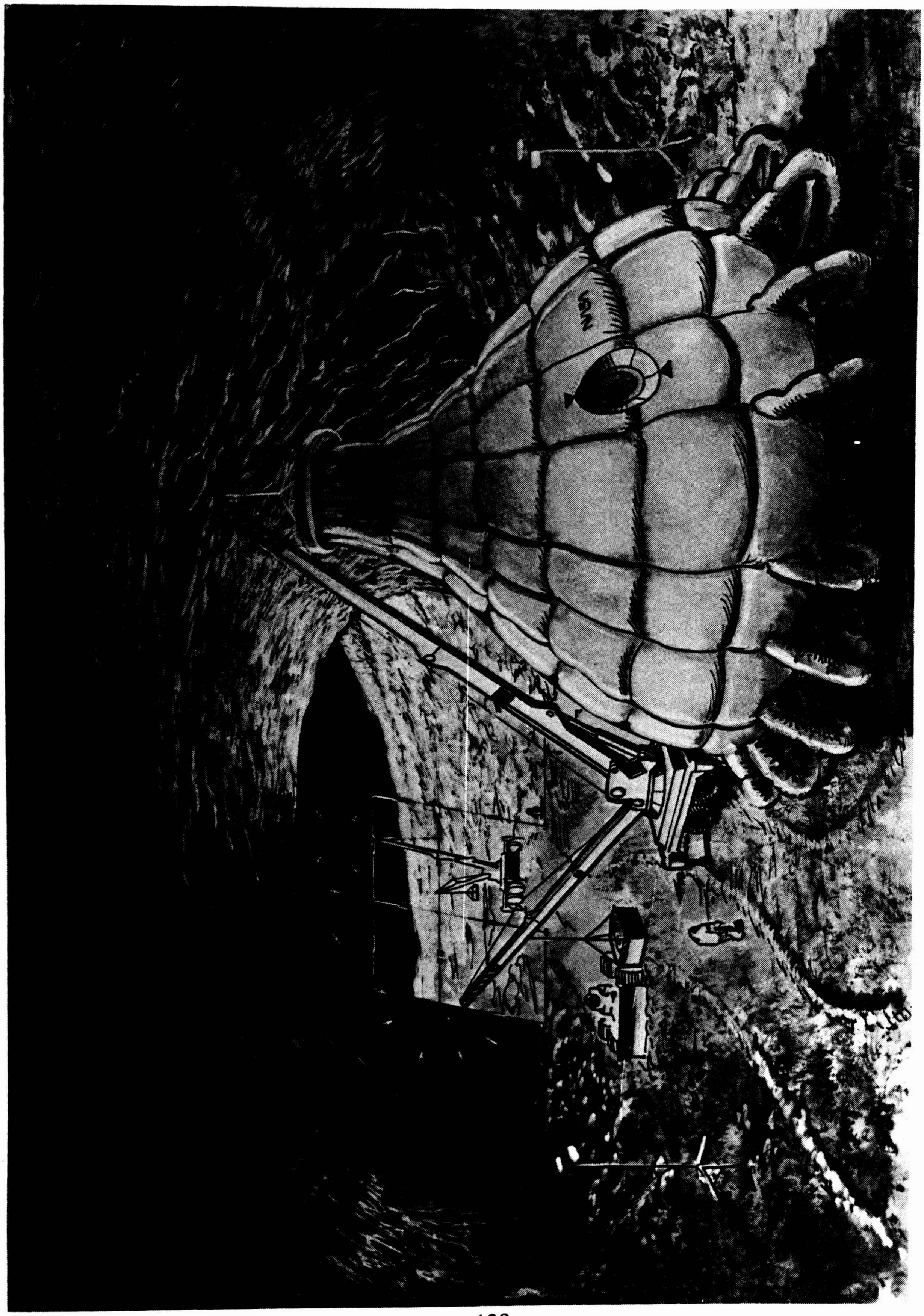
**Figure 7-9.** Alternative Counterweight Fill Operation Using Soil Hauler

## 7.8 Using Lunar Lava Tubes

Figure 7-10 shows an inflatable being inflated after installation in a lunar lava tube. The approaches to the entrance into the tube and the tube floor have been graded and prepared by the angle dozer shown. A boom crane is supporting the inflatable while it is being inflated. A support structure attached to the underside of the inflatable has already been inflated to properly orient the habitat.

Besides removing loose rock and debris from the floor of the lava tube, interior lights have been installed, and a thermal barrier is being installed across the entrance.

**Figure 7-10.** Inflatable Habitat in Lunar Lava Tube



## 8.0 Conclusions

### 8.1 Summary of Findings

Requirements, Section 3

- The type, size, and quantity of lunar construction equipment needed for building an early lunar base depends on the nature of the construction tasks which must be performed, and the required schedule and available manpower resources for completing them. A review of available information on potential construction tasks for an early lunar base described in other reports (2-4, 7, 28, 42-44, 47) indicate that major likely operations include: 1) preparing the lunar surface for landing pads, roads, and a base site, 2) unloading lunar landers, and transporting, positioning, and placing cargo elements, 3) providing habitats with radiation protection, and 4) assembling large structures that are external to the habitats such as a solar photovoltaic array and fuel cell power system. Cargo and soil handling operations are the most prominent.

- Space transportation systems influence the design of lunar cargo unloading and transport equipment. Earth launch vehicle payload dimensions determine the maximum cargo size that must be handled, maximum cargo weight is fixed by lunar lander payload capability, and lunar lander dimensions influence the size required for cargo unloading equipment. A recent lander concept places cargo on top of the vehicle (3). For this lander design, the unloader must therefore be designed to reach to the top of the cargo (8.2 m plus the height of the cargo) from a position at the outer edge of the lander (no closer than 5.5 m). Requirements could be placed on external systems to simplify the design and function of lunar construction/assembly equipment. For instance, a lander configuration that allows payload manifesting on the side of the lander could reduce lander unloading equipment design requirements.

- The lunar environment (dust, vacuum, low gravity, deep thermal cycles) presents major challenges to the design of long-life equipment. The remoteness of a lunar construction site means that equipment and access to spare parts will be severely limited. These facts indicate that lunar construction equipment should have the following features:

  - Reliability. Special emphasis will need to be applied on designing long-life bearings, seals, and lubricants for the lunar environment.
  - Versatility. A single machine can be capable of performing multiple tasks.
  - Commonality. Maximum use of common subsystems will lower spares requirements.
  - Low weight. Lunar construction equipment should be made rugged for reliability. However, use of lunar soil as ballast for increased traction or counterweight for improved stability would reduce Earth launch mass requirements.
  - Teleoperable. Since available crew time will likely be limited, construction machines should be designed for teleoperations. They will require sufficient on-board sensors and computational capability to perform some programmed tasks nearly autonomously with only human supervisory control. Teleoperations from Earth should be investigated.

Terrestrial Construction Equipment Survey, Section 4

- Equipment commonly used on Earth construction sites were surveyed. Several versatile machines are available and are often employed in terrestrial construction/assembly work: 1) A front-end loader with multifunctional bucket can perform dozer, scraper, grading, and excavating jobs, 2) a combination machine, with front-loader shovel mounted on the front and a backhoe shovel attached to the back, can perform a variety of excavating tasks, and 3) A mobile boom-crane, using a variety of attachments (including hoisting hook, clamshell bucket, and pile-driver ram) can move loads, excavate, and place anchors.

Lunar Construction Jobs, Section 5

- Complex construction operations can be broken down into a series of simplier construction tasks or jobs such as 1) unload lander, 2) transport cargo, 3) lift and position load, 4) level and grade surface, 5) excavate and transport soil, and others.

Lunar Equipment Options, Section 6

- Equipment options for performing each of the simplified construction/assembly jobs are described in Section 6.

Equipment Comparisons, Section 7

- After ranking the various options, a limited set of vehicles was identified that appears capable of completing the identified lunar construction tasks. More work is required before a optimum set of equipment can be selected with confidence. The equipment indicated by this preliminary comparison included a mobile boom-crane, a prime mover with bulldozing blade for surface grading, a prime mover with front-loader shovel and backhoe for soil excavation, and cargo transporting vehicles. All vehicles will be self-propelled, teleoperable, and capable of accepting a variety of attachments and implements. Attachments for the boom-crane include a lifting hook, cargo support sling, dumpable soil-holding bucket, and a pile-driving ram. An optional attachment is a clamshell bucket which would provide backup capabilities for soil excavation in the event of failure of the excavator. The excavator could be a front-loader or a backhoe-/front-loader combination depending on the maximum depth of required excavations.

## 8.2 Recommendations

- The tasks and required schedule and available manpower for completion are not well understood. However, these will have an important bearing on the selection of the most suitable lunar equipment options. In addition, the objectives of the lunar base influence the nature of the construction tasks and thus the required construction equipment. For instance, construction of a man-tended base for servicing an astronomical observatory may require transportation of smaller cargo elements than a permanently manned lunar base with exploration and resource utilization as primary goals, but available crew time for construction activities would probably be more limited for the man-tended base. Better definition of lunar base tasks and schedule is required to reduce uncertainity in selection of lunar construction equipment. It is recommended that prior to serious conceptual design studies, efforts should be made to better define at least a limited set of construction/assembly tasks <u>and</u> the available time (EVA and IVA) to complete the tasks. Tasks and scheduling should be established for lunar bases with a range of likely objectives, such as: 1) man-tended astronomical observatory base, 2) permanent human presence/scientific base, and 3) maximum resource utilization base.

- It is also recommended that equipment needs for scientific missions (such as drilling cores) and mining requirements for lunar oxygen production should be included in future evaluations of construction/assembly equipment since a large degree of commonality might be possible for this equipment.

- After better definition of required tasks and schedule, conceptual designs should be developed for one or more lunar construction/assembly machines. These studies should address design issues such as selection of primary power source, locomotion means, and implement control and actuation systems. The conceptual design studies should also provide a basis for evaluating the effects of lunar gravity on traction and ballast requirements, applying telerobotics, designing versatile machinery (versus simplier dedicated machines), and using lunar materials for counterweight or ballast. The role of teleoperation and the required level of automation should also be studied.

- The primary power plant of lunar construction equipment needs more detailed definition.

- Need focused, detailed study to define the best locomotion methods (e.g. wheels) and configuration for lunar construction equipment in the low gravity conditions on the lunar surface using calculations and detailed technical analysis.

- Need more detailed analysis of road requirements for a lunar base because road construction requires a large expenditure of equipment and time. Conclude what the best surfacing option is (compaction only, gravel, cement or epoxy, melt, etc.), road requirements in terms of dimensions and grade/slope, and equipment requirments in terms of type and function.

- Need focused, detailed study of hydraulic versus electric devices (motors, drums, cables, etc.) using calculations and detailed technical analysis to conclude which is best method for the implement power distribution, linkage, and control systems of lunar construction equipment.

- NASA and contractor engineers working on the problems of equipment selection and design for lunar construction and assembly tasks should get hands-on experience with available terrestrial equipment that perform these tasks. Soil handling equipment could be demonstrated in a suitable test to assist in lunar equipment selection.

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## 10.0 Annotated Bibliography

The following references concerning lunar and terrestrial construction equipment and methods are provided with a brief synopsis and a reading recommendation (definite read, read if possible, and scan).


Bekker, M.G.: Introduction to Terrain-Vehicle Systems, The University of Michigan Press, Ann Arbor, Michigan, 1969.
Recommendation: Definite Read
Bekker drew on his work with JPL, MSFC, and the Boeing Company. The book is divided into Part I, The Terrain, and Part II, The Vehicle. The part on the terrain updates Bekker's early books on the subject. The part on the vehicle begins with a discussion of the vehicle mission; ploughing by a tractor, bulldozing in construction, fighting maneuvers in a tank, and exploring the Moon as examples. For purposes of systems analysis, concepts are defined in terms of form-size-weight-power relationships. With environment, mission, and vehicle concept defined, mathematical models are used in optimization. Good data on articulated vehicles (including lunar).

Bekker, M.G.: Off-the-Road Locomotion: Research and Development in Terramechanics, The University of Michigan Press, Ann Arbor, Michigan, 1960.
Recommendation: Read if Possible
This is an old book but contains basic information about the fundamental factors involved in off-road locomotion. It attempts to demonstrate the possiblity of describing all conceivable engineering soil-vehicle relationships, in mathematical form, once a proper system of physicogeometrical values of soils and vehicles is defined and adopted. Topics discussed include train concept; properties of soil, mud, and snow; geometrical properties of terrain surface; vehicle "floatation"; draw-bar pull; soil trafficability; and development of a new concept, the spaced link track. This book represents a great deal of thought.

Bekker, M.G.: Theory of Land Locomotion: The Mechanics of Vehicle Mobility, The University of Michigan Press, Ann Arbor, Michigan, 1962.
Recommendation: Read if Possible
The purpose of this book is to provide a comprehensive source of information on the physical relation between a motor vehicle and the environment of its operation, particularly in off-the-road locomotion. Topics addressed in the book chapters include locomotion in nature; locomotion on wheels; crawlers of tracked vehicles; skis, sleighs, and toboggans; and trafficability of soils and economy of locomotion.

Bemert, R.E.: "Design of a Mars Class Radiation Shield," NAS8-5278, Avco-Everett Research Laboratory, Final Report, March 1964.
Recommendation: Scan
Looks at radiation protection for crew of ten for multiple solar proton events protection only. Uses a hybrid shield.

Christiansen, E.L.: "Lunar Surface Operations Study," NAS9-17878, Eagle Engineering, Inc., Report No. 87-172, December 1, 1987.

Techniques: Modules, Loose Regolith, Erectables
Recommendation: Definite Read
The purpose of this study was to perform an analysis of the surface operations associated with a human-tended base. The study 1) defined surface elements and developed mission manifests for a selected scenario, 2) determined the nature of surface operations associated with this scenario, 3) generated a preliminary crew activity time schedule, and 4) proposed concepts for utilizing remotely operated equipment to perform repetitious or hazardous surface tasks. Surface operations include landing site preparation, cargo handling, radiation shelter placement, construction operations, logistics activities, and contingency operations.

Criswell, D.R. and Waldron, R.D.: "Lunar Utilization," Space Industrialization, Volume II, Brian O'Leary, Editor, CRC Press, Inc., Boca Raton, Florida, 1982.
Recommendation: Scan
This study deals with economic advantages of obtaining and processing lunar material. The properties and uses of the lunar material are identified. For purposes of supporting evaluations of lunar construction, the primary value of the study is the "Lunar Bibliography" and the list of references.

Crockford, W.W.: "Lunar Surface System Concepts - Initial Lunar Base Philosophy," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, LBS-88-188, April 5-7, 1988.
Techniques: Modules, Tunnel, Canopy, Bricks, Lava Tubes
Recommendation: Definite Read
The paper addresses two types of structures: protective structures and structures to be used for transportation on the lunar surface. Within the protective structures subject area, modules, canopies, bricks, lava tubes, and tunnels are considered. The author concludes that tunneling is a viable option for relatively large span structures with a wide range of protective cover thicknesses using mechanical excavation and rock melting technology. The technique cannot be used without discretion for all lunar crust material. Need for paved roads must be proven; simple grading may suffice. Thin brittle surfaces may perform adequately.

Cummins, A.B. and Ginen, I.A.: Society of Mining Engineers Mining Engineering Handbook, The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 1973.
Techniques: Tunnel, Loose Regolith, Bury
Recommendation: Read if Possible
A mining engineering handbook presenting extensive detail definition of mining methods and equipment. The tunneling section (chapter 10) covers conventional blasting and the use of mechanical boring machines (moles). Slusher hoists and scrapers are covered in chapter 12.

DiLeonardo, G. and Johnson, R.W.: "Base Construction on Other Worlds," Advances in Space Science and Technology, Vol.7, Frederick, I. (editor), Academic Press, New York, NY, 1965.
Techniques: Inflatables, Modules, Tunnel, Masonry

Recommendation: Read if Possible
A very old, but very good overall assessment of how to construct a base on the Moon. Construction techniques include buried inflatables, rigid modules, and underground shelters. Transportation systems studied include rail systems, roads, hover flight, and ballistic systems. Construction equipment mentioned includes bulldozer, grader, compactor, dragline, crane, ditcher, mixer, truck, liquid transporter, personnel vehicle, medical aid vehicle, and emergency maintenance vehicle.

Gertsch, R.E.: "A Method for Mining Lunar Soil," Space Manufacturing 1983, American Astronautical Society, Volume 53, Advances in the Astronautical Sciences, 1983.
Techniques: Loose Regolith
Recommendation: Read if Possible
A concept design for a lunar strip mining method is presented. Known as a three drum cable-way scraper-bucket or slusher, the method specifically addresses lunar environmental conditions and meets the resource needs of a space industrialization system. Selected for its simplicity, it lessens project start-up problems, eliminates low gravity traction dependency, lowers lift (delivery) weight, and lowers capital and operating costs wighout sacrificing production flexibility. While the 3 drum slusher is particularly simple when operated in a fixed location, it is very labor intensive when it must be used in different locations.

Gill, W.L.: "Lunar Storm Shelter Conceptual Design," NAS9-17878, Eagle Engineering, Inc., Report No. 88-189, May 1, 1988.
Techniques: Loose Regolith, Modules, Inflatables
Recommendation: Read if Possible
Extended occupancy on the lunar surface requires plans for limiting crew radiation dose. Under the worst case, the total dose received by any crewman should be limited to 25 REM. The main shelter must be shielded to a level that produces an Earth equivalent background radiation level. Radiation shielding is discussed for the four approaches of 1) a buried lunar base, 2) an Earth fabricated solar flare storm shelter, 3) lightly shielded vehicles on the surface, 4) a partial protection garment. Lunar regolith density can vary from 1-3 $gm/cm^3$ causing a regolith shield layer thickness to vary from 8-3 m. A storm shelter needs 9 in. of aluminum or 2 ft. of regolith.

Hijazi, Y: "Prefraricated Foldable Lunar Base Modular System for Habitats, Offices, and Laboratories," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, LBS-88-020, April 5-7, 1988.
Techniques: Foldables
Recommendation: Scan
Proposes multi-story, prefabricated, foldable, modular, self-erecting, habitat and work station to be delivered to Moon in a cylinder 11 meters in diameter and 33 meters lond. Interesting architectural layout, but no basis in space transportation, operations, and engineering. No metion of pressurization, ECLSS, weights, or required lunar support infrastructure.

Ishikawa, N., Kanamori, H., and Okada, T.: "Possibility of Concrete Production on the Moon," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, LBS-88-268, April 5-7, 1988.
Techniques: Concrete
Recommendation: Definite Read
This paper describes possibility of concrete production on the Moon. The possible production methods are derived from results of series of experiments which were carried out taking into account the two main environmental features: the low acceleration of gravity and vacuum.

Mangan, J.J.: "The Expandable Platform as a Structure on the Moon," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, LBS-88-026, April 5-7, 1988.
Techniques: Canopy, Erectables
Recommendation: Scan
This paper appears to be very conceptual, but has some merit. Proposes tetrahedral framing for multiple applications. Its shape, with a large surface area on top, set on a truncated base, makes an excellent built-in umbrella with a capacity to hold regolith 3 meters deep, so that its top surface can provide protection from radiation, while the basic form allows for the structure to step over a surface that shows considerable undulation. Once the regolith is bermed up against the perimeter, it can provide a closed off area at the ground floor and allow for many and varied uses of the space within the platform.

Mansfield, J.M., Ed.: "Lunar Base Synthesis Study," NAS8-26145, North American Rockwell Corporation, 3 Vols., Report No. SD71-477, May 15, 1971.
Techniques: Modules, Loose Regolith
Recommendation: Read if Possible
The study describes a lunar surface base concept that has been synthesized by considering the top level program objectives and deriving hardware/operational approaches that best accomplished these objectives. From these broad objectives, the lunar base operational and design requirements were derived using a "top-down" functional analysis approach. A base configuration and surface mobility system elements were derived. A conceptual design of a lunar shelter derived from a space station module is presented. The degree of modification for the lunar environment is identified. Cost and resource estimates are presented.

Martin, J.W.: Surface Mining Equipment, Martin Consultants, Inc., P.O. Box 1076, Golden CO, 1982.
Techniques: Mutiple techniques, Loose Regolith
Recommendation: Definite Read
This manual provides an overview of equipment selection considerations based on equipment design as well as mine plan and geological constraints. Individual machine types are considered in terms of their applications, operations practices, characteristics, and basic design features. Machine selection criteria are reviewed. Detailed machine specifications are provided and comparative charts are presented to facilitate preliminary machine evaluation. Machines described include dozers, scrapers, dump trucks, front-

end loaders, hydraulic backhoes and shovels, electric shovels, draglines, bucket wheel excavators, and blast hole drills. A valuable, easy-to-understand manual.

Matsumoto, S.: "Concrete Structure Construction on the Moon," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century," LBS-88-269, April 5-7, 1988.
Techniques: Concrete, Erectables
Recommendation: Definite Read
This paper describes a precast, prestressed concrete structure system on the moon and its erection methods. The horizontal section on the structural module is hexagonal, so that various layouts of the modules are possible by connecting the adjacent modules to each other. For erection of the modules, specifically designed mobile cranes are used. Connecting works of joints and grouting gaps can be operate in a pressurized environment.

NASA: "Conceptual Design of a Manned-Unmanned Lunar Explorer (MULE)," NASA-ASEE Engineering Systems Design Institute, NASA Grant NGT 44-005-114, University of Houston/NASA Manned Spacecraft Center/Rice University, September 1970.
Recommendation: Definite Read
The MULE has a gross weight on Earth of 9,705 pounds and mission capabilities of 36 hours, 250 km in the manned mode, and 1,500 km in the unmanned mode. It employs a two-man crew, uses tracks for locomotion, and transports a science payload of 2,000 pounds. Interesting systems engineering and parametric tradeoff analyses were performed. Concepts considered include crawlers, screw drive, snowmobile, flyer, ground effect machine, hopper, and mechanical horse.

Peurifoy, R.L.: <u>Construction Planning, Equipment, and Methods</u>, McGraw-Hill Book Co., New York, NY, 1979.
Recommendation: Read if Possible
This book includes an expanded and updated coverage of construction project planning and management including time value of money, discounted present worth analysis, rate of return analysis, precedence diagramming, and PERT. Also included are sections on construction equipment selection, earth-moving fundamentals, soil stablization and compaction, tractors and related equipment, scrapers, excavating equipment, trucks and wagons, belt conveyors, compressed air, drilling and blasting, tunneling equipment, grouting, piles and pile-driving equipment, pumping equipment, crushed-stone aggregate production, and methods and materials used in concrete construction.

Phillips, P.G.: "Lunar Base Launch and Landing Facility Conceptual Design," NAS9-17878, Eagle Engineering, Inc., Report No. 88-178, March 25, 1988.
Techniques: Loose Regolith, Rocks
Recommendation: Read if Possible
The emphasis of this study is on the landing facilities needed from the first manned landing until permanent occupancy. Spacecraft that require extensive surface-based servicing will require leveled, permanent landing areas. Landing pads should be about 100 meters across. Lunar derived gravel may be used to stabilize landing pads. More design definition is needed for surface stabilization methods, cryogen storage and transfer facilities, and servicing and maintenance equipment.

Roberts, M.L.: "Inflatable Habitation for the Lunar Base," 2nd Symposium on Lunar Bases and Space Activities in the 21st Century, LBS-88-266, April 5-7, 1988.
Techniques: Inflatables
Recommendation: Definite Read
For providing lunar habitation, inflatable structures have advantages over rigid modules, in packaging efficiencies, convenience of expansion, flexibility, and psychological benefit to the crew. The relatively small rigid cylinders (conventional modules) fitted to the payload compartment of a launch vehicle are not as efficient volumetrically as an inflatable structure that, when packaged, fits into the same space but when deployed is much larger. The disadvantage of the inflatable is that one will collapse of its own weight when pressure is removed. The large inflatable volume facilitates interior rearrangement to meet evolving needs.

Rowley, J.C. and Neudecker, J.W.: "In-Situ Rock Melting Applied to Lunar Base Construction and For Exploration Drilling and Coring on the Moon," Lunar Bases and Space Activities of the 21st Century, W.W.Mendell (Editor), Lunar and Planetary Institute, 1985.
Techniques: Tunnel, Melted Regolith
Recommendation: Definite Read
An excavation technology based upon melting of rock and soil has been extensively developed at prototype levels for terrestrial conditions. Laboratory and field tests of rock melting penetration have conclusively indicated that this excavation method is insensitive to rock soil types and conditions. Especially significant is the ability to form in-place glass linings or casings on the walls of boreholes, tunnels, and shafts. These factors indicate the unique potential for in-situ construction of lunar base facilities. The most important parameter in the rock penetration process is the viscosity of the material. Implementation requires a lot of development.

Sasakawa International Center for Space Architecture (SICSA) Outreach: "Inflatable Space Structures," The University of Houston College of Architecture, Vol.1, No.7, May-June 1988.
Techniques: Inflatables
Recommendation: Definite Read
Inflatable space structures include single and multiwall bladders made of pliable composite material. A key advantage is the ability to transport large habitats in a compact, launch efficient form. Exterior surfaces must be able to withstand long-duration exposure to molecular oxygen, ultraviolet rays, and temperature extremes. Interior surfaces must be nonflammable and must not outgas toxic materials. A lunar hab is described which is a 70-foot diameter sphere. A hemispherical surface hole must be constructed to provide a stable base foundation. The upper hemisphere of the vessel might be covered with 2 meters of regolith for radiation shielding.

Sheppard, D.J.: "Concrete on the Moon," Spaceflight, Vol.17, March 1975.
Techniques: Concrete, Erectables
Recommendation: Definite Read

From the viewpoint of the structural engineer, the creation of the lunar colony will pass through three phases: 1) Importing operation modules from the Earth, 2) Assembling larger structures from imported components, and 3) making structures form lunar resources. In the 2nd and 3rd phase, concrete is a serious contender as a major structural material on the Moon. Metals are strong in tension but weak in compression because of buckling. Concretes are strong in compression but weak in tension because of brittle fracture. The most efficient shape for concrete is concave compressive arches. It will be possible to build most structures from concrete.

Stump, W.R.: "Lunar Lander Conceptual Design," NAS9-17878, Eagle Engineering, Inc., Report No. 88-181, March 30, 1988.
Recommendation: Read if Possible
This study is a first look at the problem of building a lunar lander to support a small lunar base. One lander which can land 25 metric tons one-way or take a 6 metric ton crew capsule down and up is designed. Unloading the lunar lander will be required upon arrival on the surface. The LOX/$LH_2$ reusable lunar lander design has the following approximate dimensions: 8.2 meters from the lunar surface to the cargo platform (landing stage top), 12.2 meters from surface to top of crew capsule when installed on lander, 13 meters from one landing pad to diagonally located pad, 10 meters from one landing pad to adjacent pad.

# Appendix A - Equipment Comparison Data Sheets

## Appendix A - Equipment Comparison Data Sheets

Equipment options were compared in Section 7 for nine lunar construction and assembly tasks based on a composite rating of each options performance, complexity, and versatility. The rationale for the ratings given each option are described in more detail in this Appendix.

The first 10 pages of this appendix give a breakdown of the ratings given the factors that went into each average rating for performance, complexity, and versatility. The numerical ratings are given here while Section 7 describes the factors in more detail.

Data sheets included in the last half of this appendix comment on and explain the reasoning for the ratings.

Operation 1: Unload Lander (Nominal)

Option 1: Mobile boom crane.

Option 2: Gantry crane.

Option 3: Hybrid structure. Bridge assisted boom-crane.

Option 4: Erectable, temporary crane structure

Option 5: Forklift.

| Attribute \ Option: | 1.Boom | 2.Gantry | 3.Hybrid | 4.Erect. | 5.Fork | |
|---|---|---|---|---|---|---|
| Reach. Adapt. | 4 | 2 | 1 | 2 | 1 | 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Cycle Time | 4 | 2 | 2 | 0 | 3 | 4=no setup required & easy ops (low cycle time), 2=some setup or more difficult ops, 0=much setup. |
| Counterweight | 1 | 2 | 3 | 3 | 1 | 4=no counterweight & light structure, 2=no counterweight & possibly heavy structure, 1=counterweight req. |
| Performance Avg. | 3.0 | 2.0 | 2.0 | 1.7 | 1.7 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Mobility Mech | 0 | 0 | 0 | 2 | 0 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 1 | 2 | 2 | 1 | 1 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 0 | 0 | 0 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.0 | 0.7 | 0.7 | 1.0 | 1.0 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 2 | 1 | 1 | 2 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 2 | 0 | 1 | 0 | 1 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 2 | 0 | 1 | 0 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 2.0 | 0.7 | 1.0 | 0.3 | 1.0 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 6.0 | 3.3 | 3.7 | 3.0 | 3.7 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

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Operation 2: Transport Loads (Nominal)

Option 1: Off-Road Truck (flatbed).
Option 2: On-Road Truck.
Option 3: Load delivered on Wheeled Cradle & pulled.
Option 4: Rail system or overhead trolley.
Option 5: Gantry crane.
Option 6: Forklift.

| Attribute / Option: | 1.Truck | 2.Road | 3.Pull | 4.Rail | 5.Gantry | 6.Fork | |
|---|---|---|---|---|---|---|---|
| Maneuverability | 4 | 1 | 2 | 1 | 1 | 2 | 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Cycle Time (ops) | 2 | 3 | 1 | 4 | 2 | 2 | 4=no traction problems (low cycle time) to 0=a lot of traction prob. & difficult ops |
| System size/mass | 2 | 3 | 1 | 1 | 2 | 1 | 4=fewest number of vehicles required & lightest weight to 0=many vehicles required & heaviest system. |
| Performance Avg. | 2.7 | 2.3 | 1.3 | 2.0 | 1.7 | 1.7 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 0 | 1 | 2 | 1 | 0 | 0 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 1 | 2 | 1 | 2 | 2 | 1 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 0 | 1 | 0 | 0 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.0 | 1.0 | 1.3 | 1.0 | 0.7 | 1.0 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 0 | 1 | 0 | 2 | 2 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 2 | 1 | 2 | 0 | 0 | 1 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 1 | 0 | 1 | 0 | 0 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.7 | 0.3 | 1.3 | 0.0 | 0.7 | 1.0 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 5.3 | 3.7 | 4.0 | 3.0 | 3.0 | 3.7 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

Operation 3: Lift and Position Loads

Option 1: Mobile boom crane.

Option 2: Gantry crane.

Option 3: Erectable, temporary crane structure

Option 4: Forklift.

| Option: | 1.Boom | 2.Gantry | 3.Erect. | 4.Fork | |
|---|---|---|---|---|---|
| Attribute | | | | | |
| Positioning | 4 | 2 | 3 | 2 | 4=Excellent, 3=Good, 2=Fair, 1=Poor. 0=non-applicable. |
| Ops Time | 4 | 2 | 0 | 2 | 4=no setup required & easy ops (low cycle time), 2=some setup or more difficult ops, 0=much setup. |
| Counterweight | 1 | 2 | 3 | 1 | 4=no counterweight & light structure, 2=no counterweight & possibly heavy structure, 1=counterweight req. |
| Performance Avg. | 3.0 | 2.0 | 2.0 | 1.7 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 0 | 0 | 2 | 0 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 1 | 2 | 1 | 1 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 0 | 0 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.0 | 0.7 | 1.0 | 1.0 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 2 | 1 | 2 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 2 | 0 | 0 | 1 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 2 | 0 | 0 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 2.0 | 0.7 | 0.3 | 1.0 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 6.0 | 3.3 | 3.3 | 3.7 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

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Operation 4: Grade/Level Surface

Option 1: Dozer (with angle blade)

Option 2: Dozer/FEL Excavator/Truck

Option 3: Dozer/Rock Drill for Explosives

Option 4: Dozer/Bucket Wheel Excavator/Truck

Option 5: Scraper

| Option: Attribute | 1.Angle | 2.D/FEL | 3.D/Drill | 4.D/BWE | 5.Scrap | |
|---|---|---|---|---|---|---|
| Capability | 1 | 4 | 4 | 3 | 1 | 4=Excellent (can handle large rocks & craters), 3=Good, 2=Fair, 1=Poor, 0=can only handle soil and few craters. |
| Cycle Time (ops) | 4 | 3 | 2 | 4 | 3 | 4=continuous grading (low cycle time) to 0=cyclical operation |
| System size/mass | 4 | 2 | 3 | 2 | 4 | 4=fewest number of vehicles required & lightest weight to 0=many vehicles required & heaviest system. |
| Performance Avg. | 3.0 | 3.0 | 3.0 | 3.0 | 2.7 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 1 | 1 | 1 | 0 | 1 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 2 | 1 | 1 | 1 | 2 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 2 | 1 | 2 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.7 | 1.3 | 1.0 | 1.0 | 1.7 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 2 | 1 | 1 | 0 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 1 | 2 | 1 | 1 | 1 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 2 | 2 | 1 | 1 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.7 | 2.0 | 1.0 | 1.0 | 0.3 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 6.3 | 6.3 | 5.0 | 5.0 | 4.7 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

Operation 5: Excavate & Transport Soil

Option 1: Backhoe and truck
Option 2: Dozer
Option 3: Front Loader and truck
Option 4: Dragline
Option 5: Crane (w/ bucket) & Front Loader
Option 6: Bucketwheel excavator and truck
Option 7: Crane (w/ clamshell) & truck
Option 8: 3-Drum Slusher

| Option: Attribute | 1.Hoe | 2.Dozer | 3.FEL | 4.Drag | 5.Crane | 6.BWE | 7.Clam | 8.3-Drum | |
|---|---|---|---|---|---|---|---|---|---|
| Capability | .4 | 0 | 3 | 2 | 4 | 2 | 4 | 0 | 4=Excellent digging profile (reach/depth) & precisely place soil to 0=poor capability. |
| Cycle Time (ops) | 1 | 4 | 3 | 3 | 3 | 4 | 1 | 3 | 4=continuous grading (low cycle time) to 0=cyclical operation |
| System size/mass | 1 | 4 | 1 | 4 | 2 | 1 | 3 | 3 | 4=fewest number of vehicles required to 0=many vehicles required & heaviest system. |
| Performance Avg. | 2.0 | 2.7 | 2.3 | 3.0 | 3.0 | 2.3 | 2.7 | 2.0 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 1 | 2 | 1 | 2 | 1 | 0 | 1 | 2 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 0 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.3 | 2.0 | 1.3 | 1.7 | 1.3 | 1.0 | 1.3 | 1.0 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 0 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Commonality possiblities of major machine subsystems: 2=High, 1=Medium, 0=Low |
| Redundancy | 0 | 1 | 2 | 0 | 2 | 1 | 0 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.0 | 1.0 | 1.7 | 0.7 | 1.7 | 1.0 | 1.0 | 0.3 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 4.3 | 5.7 | 5.3 | 5.3 | 6.0 | 4.3 | 5.0 | 3.3 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

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Operation 6: Anchor Object

Option 1: Standard: Drill hole and cement/grout in rebar anchor. Equipment: drill & truck carrying hole backfill mix.

Option 2: Deadman: Excavate hole, then bury deadman w/ attached cable. Equipment: Excavator (backhoe) & crane (deadman positioner).

Option 3: Piledriver: Drive anchor pile. Equipment: crane w/ pile driving ram.

Option 4: Natural anchor: Use nearby rocks and crevices. Equipment: None besides anchor cable and tensioning devices.

| Attribute | 1.Stand. | 2.D-man | 3.Pile | 4.Natural | |
|---|---|---|---|---|---|
| Applicability | 4 | 3 | 3 | 0 | 4=Excellent applicability to varying conditions/requirements to 0=very poor capabilities. |
| Cycle Time (ops) | 2 | 2 | 3 | 3 | 4=Easy setup and operation (fast performance) to 0=Difficult and slow operation. |
| System size/mass | 2 | 1 | 2 | 4 | 4=small amount of equipment needed to 0=large number of equipment needed. |
| Performance Avg. | 2.7 | 2.0 | 2.7 | 2.3 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 0 | 0 | 1 | 2 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 0 | 1 | 2 | 0 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 1 | 2 | 1 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 0.3 | 1.0 | 1.3 | 1.3 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 1 | 2 | 2 | 0 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 1 | 1 | 1 | 1 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 1 | 2 | 2 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.0 | 1.7 | 1.7 | 0.3 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 4.0 | 4.7 | 5.7 | 4.0 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

Operation 7: Unload Lander (Contingency)

Option 1: Erectable, temporary crane structure

Option 2: Ramp (ramp tracks), winch/cable to pull cargo onto ramp and control descent.

Option 3: Chute (inflatable), winch/cable to pull cargo onto chute.

Option 4: Erectable structure to lift cargo, then move lander with winch/cable or other system.

| Attribute | 1.Tower | 2.Ramp | 3.Chute | 4.Move | |
|---|---|---|---|---|---|
| Capability | 4 | 2 | 1 | 3 | Reach, adapatability, lift capability: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Cycle Time | 2 | 3 | 3 | 1 | 4=easy setup & ops (low cycle time), to 0=difficult setup and ops. |
| System size/mass | 1 | 3 | 4 | 1 | 4=no counterweight & light structure & few parts to 0=counterweight, many parts, possibly heavy. |
| Performance Avg. | 2.3 | 2.7 | 2.7 | 1.7 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Mechanism Compl. | 1 | 2 | 2 | 1 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 2 | 0 | 0 | 0 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 0 | 2 | 2 | 1 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.0 | 1.3 | 1.3 | 0.7 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 1 | 0 | 0 | 1 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 0 | 0 | 0 | 0 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 0 | 0 | 0 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 0.3 | 0.0 | 0.0 | 0.3 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 3.7 | 4.0 | 4.0 | 2.7 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

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Operation 8: Install or Make Smoothed Surface (Surface Finish for Roads & Pads)

Option 1: Dozer with compactor roll.

Option 2: Gravel surface finish. Equipment: Collect soil/gravel with Excavator/truck, use screens to separate gravel, transport to road site with truck, spread with angle dozer.

Option 3: Melt surface. Equipment: In-situ melter (solar or electric)

| Attribute | Option: 1.Compct | 2.Gravel | 3.Melt | |
|---|---|---|---|---|
| Road finish | 2 | 3 | 4 | 4=Excellent road surface (lowest wear, highest load carrying capability) to 0=very poor finish. |
| Difficulty of op. | 4 | 2 | 2 | 4=Easy surfacing operation (lowest time requirement) to 0=Very difficult surfacing. |
| System size/power | 4 | 2 | 1 | 4=Few equipment needs & low power requirements to 0=large amount of equipment and power needed. |
| Performance Avg. | 3.3 | 2.3 | 2.3 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 2 | 1 | 0 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational | 2 | 0 | 0 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 1 | 0 | 2 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.7 | 0.3 | 0.7 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 2 | 2 | 0 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 1 | 1 | 0 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 2 | 1 | 0 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.7 | 1.3 | 0.0 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 6.7 | 4.0 | 3.0 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |

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Operation 9: Move Lander

Option 1: Lift lander legs (w/ jacks) and lower onto flatbed trucks.

Option 2: Hoist entire lander with crane and lower onto single large truck.

Option 3: Mobile Gantry.

| Option: | 1.Jacks | 2.Crane | 3.Gantry | |
|---|---|---|---|---|
| Attribute | | | | |
| Adaptability | 2 | 4 | 3 | 4=Excellent ability to handle varying conditions to 0=very poor adaptablity. |
| Time to Perform | 3 | 2 | 2 | 4=Easy moving operation (lowest time requirement) to 0=Very difficult. |
| System size | 4 | 1 | 1 | 4=Equipment needs to 0=massive equipment needed. |
| Performance Avg. | 3.0 | 2.3 | 2.0 | Avg. above 3: 4=Excellent, 3=Good, 2=Fair, 1=Poor, 0=non-applicable. |
| Machine Compl. | 2 | 1 | 1 | Machine complexity rating: 2=Low, 1=Medium, 0=High |
| Operational Comp. | 1 | 1 | 2 | Operational complexity: 2=Low, 1=Medium, 0=High |
| Setup Compl. | 2 | 1 | 1 | Setup complexity: 2=Low, 1=Medium, 0=High |
| Complexity Avg. | 1.7 | 1.0 | 1.3 | Avg. above 3: 2=Low, 1=Medium, 0=High |
| Flexibility | 1 | 2 | 2 | Usefulness of machines in other operations/jobs: 2=High, 1=Medium, 0=Low |
| Commonality | 2 | 2 | 0 | Possiblity of major machine subsystems to be common with other systems: 2=High, 1=Medium, 0=Low |
| Redundancy | 0 | 2 | 1 | Ability of machines to be used as backup for other equipment: 2=High, 1=Medium, 0=Low |
| Versatility | 1.0 | 2.0 | 1.0 | Avg. above 3: 2=High, 1=Medium, 0=Low |
| Overall Total | 5.7 | 5.3 | 4.3 | 8=Best, 0=Worst (Sum of Perf.+Complex+Versatile Averages) |



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Comparison Summary

| Operation | Option: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| 1. Unload Lander (Nominal) | 6.0 | 3.3 | 3.7 | 3.0 | 3.7 | | | |
| 2. Transport Loads | 5.3 | 3.7 | 4.0 | 3.0 | 3.0 | 3.7 | | |
| 3. Lift and Position Loads | 6.0 | 3.3 | 3.3 | 3.7 | | | | |
| 4. Grade/Level Surface | 6.3 | 6.3 | 5.0 | 5.0 | 4.7 | | | |
| 5. Excavate & Move Soil | 4.3 | 5.7 | 5.3 | 5.3 | 6.0 | 4.3 | 5.0 | 3.3 |
| 6. Anchor Object | 4.0 | 4.7 | 5.7 | 4.0 | | | | |
| 7. Unload Lander (Conting.) | 3.7 | 4.0 | 4.0 | 2.7 | | | | |
| 8. Surface Roads/Pads | 6.7 | 4.0 | 3.0 | | | | | |
| 9. Move Lander | 5.7 | 5.3 | 4.3 | | | | | |

Major Equipment Requirements

| Operation | Option | Equipment |
|---|---|---|
| 1. Unload Lander (Nominal) | 1 | Mobile boom-crane. |
| 2. Transport Loads | 1 | Truck with off-road capability (i.e. flatbed) |
| 3. Lift and Position Loads | 1 | Mobile boom-crane. |
| 4. Grade/Level Surface | 1 or 2 | Option 1: Angle Dozer alone.<br>Option 2: Dozer, Front-End Loader Excavator or Prime mover dozer w/ front-loader attachment, and Truck. |
| 5. Excavate & Move Soil | 5 | Mobile boom-crane with dumpable bucket attachment and front-end loader. |
| 6. Anchor Object | 3 | Crane with pile-driving ram attachment. |
| 7. Unload Lander (Conting.) | 2 or 3 | Option 2: Ramp and winch/cable system to control cargo descent.<br>Option 3: Inflatable chute and winch/cable system to pull cargo onto chute. |
| 8. Surface Roads/Pads | 1 | Dozer with compactor roll attachment. |
| 9. Move Lander | 1 | Jacks and flatbed cargo transporter trucks. |

Equipment Needs for Tasks 1-9: Mobile boom-crane w/ attachments (cargo hoisting hook, dumpable bucket, and pile-driving ram).
Flatbed truck with cargo holding attachments (cradles, lander leg hold-downs)
Soil transport truck (flatbed truck equipped with dumpable bed).
Prime mover dozer/front-end loader excavator combination or separate.
Prime mover attachments: dozer blade, front-loader bucket, angle blade, compactor roll, backhoe (optional).
Miscellaneous: Ramp or inflatable chute, winch/cable system, jacks.

Operation 1: **Unload Lander (Nominal)**
Option 1: **Mobile boom-crane**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Adaptability | Excellent | The mobile boom-crane has good and variable reach. It is flexible and adapable to varying lifts. It can pick up loads in and over excavations. |
| - Cycle Time | Excellent | No setup is required for mobile boom crane. Operations are relatively easy. |
| - Counterweight | Poor | Counterweight and/or long extendable stabilizing arms are required for stability. Counterweight requirements might be supplied by lunar soil or rocks. |
| Complexity | | |
| - Mobility Mech. | High | Mobility and operating mechanisms complex (rotatable turntable, sliding boom mechanisms to allow varying location of counterweight) |
| - Operational | Medium | Counterweight control (if located on boom) may be tricky (or could place counterweight integral with machine frame to simplify operation). |
| - Setup | Low | No setup required except counterweight bucket must be filled if lunar soil used as counterweight. |
| Versatility | | |
| - Flexibility | High | Mobile boom crane can be used in numerous other tasks provided appropriate attachments are provided (lifting hoist, pile driver ram, dumpable bucket, clamshell bucket, cherry picker for manual access to elevated work areas). |
| - Commonality | High | Possible common subsystems: mobility mechanisms (w/ transporter vehicles, teleoperations, power, control, thermal, etc.). |
| - Redundancy | High | Can serve as backup to excavators. Can grade if equipped with dragline bucket and appropriate winch/boom systems. |

Operation 1: **Unload Lander (Nominal)**
Option 2: **Gantry**

| Comparison Criteria | Rating | Evaluation Comments |
| --- | --- | --- |
| Performance | | |
| - Adaptability | Fair | Low load maneuverability. Good load control. Must drive over or (at best) up to load; reach poor. |
| - Cycle Time | Fair | Huge structure. Likely to be very slow and cumbersome. |
| - Counterweight | Fair | No counterweight but could be heavy structure anyway due to bulk of large, long beams and need to support heavy loads. |
| Complexity | | |
| - Mobility Mech. | High | Mobility requirements for large structure result in complex mechanisms although hoist system relatively simple (ops). |
| - Operational | Low | After setup and if road available, operation easy. |
| - Setup | High | Large gantry for unloading lander will have to be erected. Also, movement/mobility will be greatly improved if wide road is constructed. |
| Versatility | | |
| - Flexibility | High | Machine could be used to both lift <u>and</u> move cargo. Could move lunar lander (if that became necessary). Could be used as mobile hangar (if enclosed with fabric or sheet as protection from solar, thermal, meteoroid environment). Can also use as mobile scaffolding work platform. |
| - Commonality | Low | Not many structural subsystems repeated in other machines. |
| - Redundancy | Low | Will not be capable of providing backup to excavation or other major lunar equipment. |

Operation 1: **Unload Lander (Nominal)**
Option 3: **Bridge assisted boom-crane, hybrid structure**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Adaptability | Poor | No load maneuverability. |
| - Cycle time | Fair | Labor involved for every unloading operation to setup bridge. Bridge must be setup and taken down twice, once at landing pad to unload cargo, and then again at site of final position of cargo. |
| - Counterweight | Good | No counterweight involved. |
| Complexity | | |
| - Mobility Mech. | High | Same as mobile boom-crane. Although counterweight requirement eliminated, this option still has the other disadvantages a boom-crane has (large rotatable bearing surface for boom). |
| - Operational | Low | Simple operation after bridge is setup since counterweight control is eliminated. |
| - Setup | High | Bridge must be erected. |
| Versatility | | |
| - Flexibility | Medium | Smaller mobile boom-crane portion can perform lighter hoisting jobs around base. |
| - Commonality | Medium | Specialized bridge and weight bearing column has very few common attributes with other machines. |
| - Redundancy | Medium | Backup for light excavation/grading duties could be performed by smaller mobile boom-crane. |

Operation 1: **Unload Lander (Nominal)**
Option 4: **Erectable, temporary crane structure** (such as immobile bridge crane)

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Adaptability | Fair | Low load maneuverability. Good load control. |
| - Cycle time | Very poor | Labor intensive to erect and dismantle crane. After erection, operation fairly simple inside reach envelope of crane. |
| - Counterweight | Good | No counterweight required. Support beams for bridge crane may still require massive structure and weight. More study of actual mass requirements needed. |
| Complexity | | |
| - Mechanisms | Low | Since crane is immobile and has low load maneuverability, crane mechanisms are relatively simple. |
| - Operational | Medium | After erection complete, operation fairly simple within cranes reach except: positioning crane to grapple or position payloads will be more difficult due to limited bridge crane mobility. |
| - Setup | High | Erection necessary. |
| Versatility | | |
| - Flexibility | Medium | If deployment could be made simple and quick, crane hoists could be used around base to move material in vertical plane (such as fill soil for habitat radiation protection). |
| - Commonality | Low | No similarity with other equipment. |
| - Redundancy | Low | Not suitable for any other task than hoisting. |

Operation 1: **Unload Lander (Nominal)**
Option 5: **Forklift**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Adaptability | Poor | Cargo must be configured to match forklift capability. Maneuverability of forklift good over distances (maneuverability in proximity to cargo fair to poor). Reach and height of hoist limited. Precise forklift positioning and orientation with cargo is difficult due to poor visibility and maneuverability near cargo. |
| - Cycle time | Good | No setup (unless lunar soil counterweight is used, then only needs to be added once). Operations quick given good road surface and cargo correctly configured. |
| - Counterweight | Poor | Counterweight required. Could use lunar soil/rocks. |
| Complexity | | |
| - Mechanisms | High | Mobilility and lift mechanisms complex. |
| - Operational | Medium | Operation simple except for final orientation. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | Can both unload and transport cargo. |
| - Commonality | Medium | Some common subsystems with other vehicles (mobility, etc.) |
| - Redundancy | Low | Forklift limited to lifting and moving cargo. |

Operation 2: **Transport Loads**
Option 1: **Off-Road Truck (flatbed)**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Maneuverability | Excellent | Must design for unprepared surface so maneuvering capability high. Can go and operate anywhere. |
| - Cycle time | Fair | Travel time will be slower on unprepared surface. |
| - Efficiency | Fair | Loss of efficiency due to regolith slip and bulldozing effect. No need (or equipment) to prepare surface. |
| Complexity | | |
| - Mechanisms | High | Tough, rugged mechanisms required. Articulated frame may be required to traverse lunar terrain. |
| - Operational | Medium | Cross-country travel not easy, however, well-traveled path probable. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | Can go anywhere. Different cradle or wall enclosures could be added to contain different cargo sizes. Bin could be added to carry soil (lifting cylinders & actuators could raise bin for rear-dumping). |
| - Commonality | High | Share mobility subsystems with crane. |
| - Redundancy | Medium | Derivative could be used to transport soil & lander. |

Operation 2: **Transport Loads**
Option 2: **On-Road Truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Maneuverability | Poor | Confined to roads. Road making equipment required. |
| - Cycle time | Good | Speed much faster on roads. |
| - Efficiency | Good | Hauler should be structurally much simplier and perhaps lighter than off-road truck. Rolling on surfaced road reasonably efficient. |
| Complexity | | |
| - Mechanisms | Medium | Self-propelled vehicle. Relative complexity lower than off-road vehicle but higher than pulled vehicle. |
| - Operational | Low | After road is constructed, operations easy. |
| - Setup | High | Road building is required. |
| Versatility | | |
| - Flexibility | Low | Can only go where roads are. |
| - Commonality | Medium | Some commonality possible, but structure should be lighter and less rugged, so fundamentally dissimilar to other construction equipment. |
| - Redundancy | Low | Only applied to transport tasks on roadways. |

Operation 2: **Transport Loads**
Option 3: **Pull Load on Wheels (cargo delivered on wheeled cradle)**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Maneuverability | Fair | Traction on regolith of pulling vehicle may be a problem. Wheeled cradle could be optimized for individual cargo. |
| - Cycle time | Poor | Pulling likely to be slower than self-propelled vehicle. Trailer must be hitched and unhitched. Labor intensive to install & remove wheels (if cargo not delivered on individual cradle). |
| - Efficiency | Poor | Large tractor vehicle needed to pull cargo. Individual wheeled cargo cradles delivered with every cargo. |
| Complexity | | |
| - Mechanisms | Low | Non-powered, pulled trailer simpliest mechanism. |
| - Operational | Medium | Pulling trailer will probably not be easy due to lunar gravity, obstacles and regolith conditions. May need prepared road. |
| - Setup | Medium | If road needed, setup difficult. If not needed, setup easy. |
| Versatility | | |
| - Flexibility | Medium | Use on all cargo types. |
| - Commonality | High | Simple design. Few parts. Some wheel specialization likely for major cargo elements. |
| - Redundancy | Medium | Same technique (pulled) could be used to transport soil, but some power needed for soil dump mechanism. |

Operation 2: **Transport Loads**
Option 4: **Rail system or overhead trolley**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Maneuverability | Poor | Can only go where tracks or trolley go. |
| - Cycle time | Excellent | Very fast transport after tracks/trolley-way emplaced. |
| - Efficiency | Poor | No regolith traction problems (high rolling efficiency) and could get power from base, but labor & equipment intensive to install, hangups (especially for trolley) are possible. |
| Complexity | | |
| - Mechanisms | Medium | Trolley systems and rail drive systems could be complex. |
| - Operational | Low | Operation simple. |
| - Setup | High | Difficult to install rails or overhead trolley systems. |
| Versatility | | |
| - Flexibility | Low | Suitable only for hauling. Probably need very high traffic to justify. |
| - Commonality | Low | Few common systems with other equipment. |
| - Redundancy | Low | Cannot perform other tasks. |

Operation 2: **Transport Loads**
Option 5: **Gantry**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| **Performance** | | |
| - Maneuverability | Poor | Large structure and difficult to maneuver. Prepared surface roadway probably would be required. |
| - Cycle time | Fair | Slow moving. Hoist operation easy if aligned properly. |
| - Efficiency | Fair | No counterweight needed, but large massive structure may be heavy to be stiff and strong enough to support load. |
| **Complexity** | | |
| - Mechanisms | High | Mobility and control systems for large structure likely to be complex. |
| - Operational | Low | Relatively easy to operate if roadway available. |
| - Setup | High | Large structure must be erected. |
| **Versatility** | | |
| - Flexibility | High | Can both transport and unload cargo. |
| - Commonality | Low | Few similarities with other machines. |
| - Redundancy | Low | Cannot perform any other tasks to backup other equipment. |

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Operation 2: **Transport Loads**
Option 6: **Forklift**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| **Performance** | | |
| - Maneuverability | Fair | Reach and maximum lift limited. Mobility good. |
| - Cycle time | Fair | Can quickly pick up and transport cargo having grapple point compatible with forklift (& within reach envelope of forklift). May need prepared surface roadway. Maximum speed low unless extremely stable. |
| - Efficiency | Poor | Needs counterweight. |
| **Complexity** | | |
| - Mechanisms | High | Relatively complex lift and mobility. |
| - Operational | Medium | Easy except cargo unloading and final positioning. |
| - Setup | Low | No setup required. |
| **Versatility** | | |
| - Flexibility | High | Can both unload and transport cargo. |
| - Commonality | Medium | Mobility and hoisting mechanisms similar. |
| - Redundancy | Low | Cannot perform other tasks. |

Operation 3: **Lift and Position Loads**
Option 1: **Mobile boom-crane**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Lift/Pos. Capability | Excellent | Good reach and can lift over excavations. Excellent load maneuverability. Can precisely position loads given good visual clues from on-site observer. |
| - Cycle time | Excellent | Operations easy. |
| - Efficiency | Poor | Counterweight required for stability. If counterweight cannot be derived from lunar materials, Earth launch weight could be high. |
| Complexity | | |
| - Mechanisms | High | Rotating boom turntable, counterweight boom and cable/drum system, and extendible boom add complexity to mechanisms. |
| - Operational | Medium | Counterweight control may add operational complexity. |
| - Setup | Low | No setup required (except to add lunar soil/rock counter-weight if needed). |
| Versatility | | |
| - Flexibility | High | Can perform many additional tasks given appropriate attachments. |
| - Commonality | High | Similar systems used in other equipment. |
| - Redundancy | High | Can backup other types of equipment (excavation, anchoring systems). |

Operation 3: **Lift and Position Loads**
Option 2: **Gantry**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Lift/Pos. Capability | Fair | Must drive up to basic proper position (no reach), so interference with other previously positioned elements may be a problem. Cannot operate well over excavations. |
| - Cycle time | Fair | Slow mobility of large structure likely. |
| - Efficiency | Fair | No counterweight needed. Weight of large frame structure needs further definition. |
| Complexity | | |
| - Mechanisms | High | Control and mobility of large structure complex. |
| - Operational | Low | Easy. Can make vernier adjustments after coarse positioning. |
| - Setup | High | Must erect large structure. |
| Versatility | | |
| - Flexibility | High | Can transport and unload cargo. |
| - Commonality | Low | No other similar systems. |
| - Redundancy | Low | Cannot do other tasks. |

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Operation 3: **Lift and Position Loads**
Option 3: **Erectable crane structure** (immobile tower crane)

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Lift/Pos. Capability | Good | Fixed base. Good positioning within its reach. |
| - Cycle time | Poor | Labor intensive setup required. After setup ops easy. |
| - Efficiency | Good | Counterweight required for tower crane, bridge crane would not need counterweight but load mobility suffers. |
| Complexity | | |
| - Mechanisms | Low | Lack of mobility simplifies mechanisms. |
| - Operational | Medium | Simple operation if crane does not have to be moved. |
| - Setup | High | Erection required. |
| Versatility | | |
| - Flexibility | Medium | Lifts and positions all cargo in envelope. |
| - Commonality | Low | Nothing similar. |
| - Redundancy | Low | Cannot perform any other tasks. |

Operation 3: **Lift and Position Loads**
Option 4: **Forklift**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Lift/Pos. Capability | Fair | Limited reach. Fine tuning load position difficult. |
| - Cycle time | Fair | Slow fine tuning of load position due to poor precision in close quarters positioning. |
| - Efficiency | Poor | Counterweight required. |
| Complexity | | |
| - Mechanisms | High | Relatively complex lift and mobility mechanisms. |
| - Operational | Medium | Final positioning difficult. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | Capable of unloading and transport. Can handle all cargo properly configured for forklifts. |
| - Commonality | Medium | Few common subsystems. |
| - Redundancy | Low | Cannot perform other tasks. |

Operation 4: **Grade/Level Surface**
Option 1: **Angle Dozer**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Poor | Can only move thin surface cuts of material. Cannot load regolith or precisely dig or place soil. Filling deep craters/cavities is possible altho might take some time. However, removing large boulders limited by drawbar or rim pull which depends on traction. Traction in low lunar gravity more difficult. Ballast probably needed. |
| - Cycle time | Excellent | Speed slow but steady, no loss on swing time, therefore cycle time (time it takes per pass) low. |
| - Efficiency | Excellent | Fewest number of vehicles (1) required. But capability much less. Probably will require ballast for better traction (possibly use lunar materials for ballast). |
| Complexity | | |
| - Mechanisms | Medium | Tracked vehicle for better traction highly complex. Simplier wheeled vehicle will require ballast. |
| - Operational | Low | Simple operation. |
| - Setup | Low | No setup. |
| Versatility | | |
| - Flexibility | High | A common prime-mover tractor that can use a bulldozer blade for grading, front-end loader for excavating soil, and a backhoe for digging is possible. |
| - Commonality | Medium | Mobility (wheels etc.) systems will not be common with transporter or crane vehicles. Other subsystems do share common features. |
| - Redundancy | High | A prime mover dozer can backup an excavator, & even assist in contingency lander unloading and cargo transport duties. |

Operation 4: **Grade/Level Surface**
Option 2: **Dozer, Front-End Loader (FEL), with Truck for Soil Transport.**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Excellent | Dozer is excellent grader and can move lots of material while FEL can dig out larger boulders and precisely place soil in deeper craters (but FEL cannot dig well below own grade). Discarding rocks and transporting soil can be speeded up by using a truck. |
| - Cycle time | Good | FEL produces cyclically because must swing from bank to dump. |
| - Efficiency | Fair | 3 vehicles required. A lot of capability but also a lot of mass. |
| Complexity | | |
| - Mechanisms | Medium | Wheeled vehicles less complex than tracked. However, many powered functions increase complexity. |
| - Operational | Medium | Operations between FEL and truck must be synchronized. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | Most soil moving and excavation tasks can be accomplished with this equipment set with these constraints: digging deep holes or trenchs is difficult and the maximum height soil can be lifted is limited. |
| - Commonality | High | Possible to combine front-loader and dozer in one vehicle that uses a multifunctional front bucket/blade. |
| - Redundancy | High | Can support multitude of tasks. |

Operation 4: **Grade/Level Surface**
Option 3: **Dozer with Rock Drill (& explosives or expanding material) for breaking rock**

| Comparison <br> Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Excellent | Combination can handle both boulders and craters. Expanding material might not fragment boulders enough to move by dozer so explosives might be required. However, explosives will constrain operations (evacuate area, greater ejecta distance thrown in low lunar gravity, etc.). |
| - Cycle time | Fair | Drilling and blasting will be time consuming. |
| - Efficiency | Good | Drill will have to be mobile (mounted on dozer, manually carried, or self propelled), drill bits will wear, drill fluid may be needed for rock. |
| Complexity | | |
| - Mechanisms | Medium | Dozer simple, drill adds complexity. |
| - Operational | Medium | Drill operations manual and tough. |
| - Setup | Medium | Drill setup required. |
| Versatility | | |
| - Flexibility | Medium | Drill prehaps double for scientific coring tool. Dozer prime mover useful in multiple base tasks. |
| - Commonality | Medium | Some dozer subsystems common with other vehicles. |
| - Redundancy | Medium | Dozer could serve as soil collecting excavator if necessary. |

Operation 4: **Grade/Level Surface**
Option 4: **Dozer, Bucket Wheel Excavator (BWE), and Truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Good | Neither dozer or bucket wheel can excavate very far below own grade. Both will be limited on maximum boulder size capability (dozer by traction, BWE by bucket size). BWE may be useful for collecting soil to fill craters (soil carried by truck) thus reducing soil moving requirements of dozer. |
| - Cycle time | Excellent | BWE and dozer lose no time in swing to discharge. |
| - Efficiency | Fair | The system requires a large amount of material. |
| Complexity | | |
| - Mechanisms | High | A BWE is a complex machine. |
| - Operational | Medium | Coordination between the 3 machines is necessary. |
| - Setup | Low | No setup is required. |
| Versatility | | |
| - Flexibility | Medium | The dozer and truck are reasonably versatile machines. The BWE is much less so (basically good at collecting soil only). |
| - Commonality | Medium | The truck shares common systems with the crane. The BWE cutting tool share few common features with other equipment, however, the BWE locomotion systems could be similar to the truck's and crane's. |
| - Redundancy | Medium | The dozer and truck provide some redundant capabilities with other base construction equipment (crane, hoisting, etc.). The BWE cannot do other tasks. |

Operation 4: **Grade/Level Surface**
Option 5: **Scraper (Self-Propelled)**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Poor | The scraper can provide some grading capability but it is not as capable as a dozer. It can carry soil (a featured not shared by most of the other excavators) which can be used to fill craters or remove rises. Maximum rock size handled by scraper systems is limited by the scraper gap size. |
| - Cycle time | Good | The scraper can quickly collect and discharge soil. |
| - Efficiency | Excellent | This system consists only of a self-propelled scraper thus reducing equipment requirements. |
| Complexity | | |
| - Mechanisms | Medium | A scraper has several powered functions. |
| - Operational | Low | Operation is simple. |
| - Setup | Low | No setup is required. |
| Versatility | | |
| - Flexibility | Low | No other tasks can be performed by a scraper unless elaborate scaffolding is constructed to allow the scraper to carry its load to a higher elevation where it can dump its load. |
| - Commonality | Medium | Since the scraper combines dozer and truck functions, locomotion subsystems would probably be a compromise between these two |
| - Redundancy | Low | Scraper cannot back up other equipment. |

Operation 5: **Excavate and Transport Soil**
Option 1: **Backhoe and truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Excellent | Can dig below grade. Can move material far from dig site. Not appropriate for leveling tasks. |
| - Cycle time | Poor | Must dig, swing, dump, swing. Backhoe production rate typically low for given bucket size. |
| - Efficiency | Poor | Two vehicles needed. |
| Complexity | | |
| - Mechanisms | Medium | Several powered functions. |
| - Operational | Medium | Coordination between two vehicles required. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | Backhoe can be paired with front-loader for very flexible machine. |
| - Commonality | Medium | Many common truck and cargo transporter subsystems. |
| - Redundancy | Low | Hoe cannot backup many other types of vehicles. |

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Operation 5: **Excavate and Transport Soil**
Option 2: **Dozer**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Very Poor | Cannot excavate deeply or efficiently carry soil great distances. |
| - Cycle time | Excellent | No loss of swing time. |
| - Efficiency | Excellent | Only one type vehicle required. |
| Complexity | | |
| - Mechanisms | Low | Dozer simple in comparison. |
| - Operational | Low | Simple operation. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | Medium | Dozer can be outfitted with attachments to perform a variety of jobs. |
| - Commonality | Medium | Some commonality of subsystems possible. |
| - Redundancy | Medium | Backup transporters and other systems to some extent |

Operation 5: **Excavate and Transport Soil**
Option 3: **Front-end loader (FEL) and truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Good | Front-loader needs to dig from bank for high production rates. FEL can use bulldozer blade (if multipurpose FEL blade is provided) to start bank for higher production. |
| - Cycle time | Good | FEL more efficient than backhoe at collecting soil. |
| - Efficiency | Poor | Two types of vehicles required. |
| Complexity | | |
| - Mechanisms | Medium | FEL more complex than simple dozer. |
| - Operational | Medium | Two vehicles must be coordinated. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | High | FEL and trucks useful in other operations. |
| - Commonality | Medium | Trucks offer common systems with cargo transporters. |
| - Redundancy | High | FEL w/ backhoe could provide redundant capabilities. |

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Operation 5: **Excavate and Transport Soil**
Option 4: **Dragline**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Fair | Excellent ability to dig below own grade. Some leveling capability as well. Reach limited to boom length. |
| - Cycle time | Good | Fairly quick cycle time. |
| - Efficiency | Excellent | Only one vehicle type required. |
| Complexity | | |
| - Mechanisms | Low | Draglines structurally and mechanically simple. |
| - Operational | Medium | Operations sometimes require 2-3 people. |
| - Setup | Low | Some setup of long boom frames may be required. |
| Versatility | | |
| - Flexibility | Medium | Dragline could be converted to boom crane. |
| - Commonality | Medium | Many common systems with boom crane. |
| - Redundancy | Low | Could perhaps be used as boom crane but dragline mobility frequently limited terrestrially. |

Operation 5: **Excavate and Transport Soil**
Option 5: **Mobile boom crane with bucket and front-end loader (possibly truck)**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Excellent | Crane can be used to move soil vertically and within lateral reach of boom while FEL excavates soil. |
| - Cycle time | Good | Cycle time could be speeded up considerably if trucks are used to fill the crane bucket over using just a FEL to fill the soil bucket of the crane. |
| - Efficiency | Fair | Two types of vehicles at least are required, however boom crane might be used to unload lander anyway. |
| Complexity | | |
| - Mechanisms | Medium | Neither boomcrane or truck (or FEL) are extremely complicated. |
| - Operational | Medium | Coordination between different vehicles is required. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | Medium | Mobile boom crane can be used to unload and position cargo. |
| - Commonality | Medium | Common systems between truck and crane possible. |
| - Redundancy | Medium | Boom crane could be used as lander unloader. |

Operation 5: **Excavate and Transport Soil**
Option 6: **Bucket Wheel Excavator (BWE) and Truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Fair | BWE optimized to fill waiting line of trucks. High production rate but cannot dig deep. |
| - Cycle time | Excellent | No dig, swing, dump, swing cycle. |
| - Efficiency | Poor | Requires two types of machines and possibly several trucks to achieve high production rate with no lost time waiting for trucks. |
| Complexity | | |
| - Mechanisms | High | BWE are complex machines. |
| - Operational | Medium | Coordination between vehicles needed. |
| - Setup | Low | No setup required. |
| Versatility | | |
| - Flexibility | Medium | BWE is very specialized and difficult to apply it on other tasks. Trucks are versatile however. |
| - Commonality | Medium | Common truck systems. |
| - Redundancy | Medium | BWE cannot be converted to backup other equipment. |

Operation 5: **Excavate and Transport Soil**
Option 7: **Mobile boom-crane with clamshell bucket and truck**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Excellent | Good ability to dig below grade (except into hard rock), capable of elevating soil, of placing soil in precise location, and good reach over/into excavations. Trucks can carry soil great distance. |
| - Cycle time | Poor | Slow cycle time unless several haulers provided. |
| - Efficiency | Good | Two vehicles types. However, boom crane might be needed for cargo unloading duties as well. |
| Complexity | | |
| - Mechanisms | Medium | Fairly simple mechanisms. |
| - Operational | Medium | Coordination needed between vehicles. |
| - Setup | Low | Little setup required. Counterweight bucket needs to be filled. |
| Versatility | | |
| - Flexibility | High | Clamshell can be used as mobile boom-crane for hoisting given correct attachments provided. |
| - Commonality | Medium | Common locomotive subsystems possible for trucks and crane. |
| - Redundancy | Low | Clamshell could cover for lander unloading vehicle given correct attachment. |

Operation 5: **Excavate and Transport Soil**
Option 8: **3-Drum Slusher**

| Comparison Criteria | Rating | Evaluation Comments |
|---|---|---|
| Performance | | |
| - Capability | Poor | Cannot dig deeply below own grade. Reach limited by location of outlying pulleys. Soil transport vehicles or conveyor required to move soil to where its needed. |
| - Cycle time | Good | Cycle can be fairly quick given that adequate trucks are available to take soil away. |
| - Efficiency | Good | 3-drum scraper simple and only other vehicles needed are trucks. |
| Complexity | | |
| - Mechanisms | Low | 3-drum mechanisms simple. Actual teleoperation (digging) may be more difficult. |
| - Operational | High | Coordination is required between trucks and 3-drum. |
| - Setup | Medium | Pulleys and winch/cable station must be anchored prior to starting up operation. |
| Versatility | | |
| - Flexibility | Low | 3-drum very specialized. Another one would be needed to remove tailings if 3-drum used to provide feedstock for lunar oxygen plant. |
| - Commonality | Medium | Winch/cable system share some commonality with boom-crane, dragline, or other winch/cable systems. |
| - Redundancy | Low | 3-drum cannot provide much backup for other equipment. |

## Appendix B - Construction Equipment Manufacturers

## Appendix B - Construction Equipment Manufacturers

The following list of manufacturers is divided by major types of construction equipment offered. Only a few of the many manufacturers are included in most cases, except for bag-filling machine manufacturers which is as comprehensive as possible because of the interest expressed.

Cranes

- American Hoist & Derrick Co., 63 S. Robert St., St. Paul, Minnesota 55107.
- Coastal Hydraulic Cranes, Inc., PO Box 924855, Houston, TX 77292-4855, 713-462-0063.
- Clark Equipment Co., Crane Division, 1046 S. Main St., Lima, OH 45802.
- Dresser Industries, Inc., 755 S. Milwaukee Ave., Libertyville, IL 60048.
- FMC, Cable Crane & Excavator Division, 1201 6th St. S.W., Cedar Rapids, Iowa 52406.
- The Manitowoc Co. Inc., Manitowoc Engineering Co. Division, 500 S. 16th St., Manitowoc, WI 54220, 414-684-6621.

Dozers and Loaders

- J.I. Case Co., Construction Equipment Division, 700 State St., Racine, WI 53404.
- Caterpillar Tractor Co., 100 NE Adams St., Peoria, IL 61629. Houston dealer: Mustang Tractor & Equipment Co., 12800 Northwest Freeway, Houston, TX 77040, 713-460-2000.
- Clark Equipment Co., Construction Machinery Division, Pipestone Rd., P.O. Box 547, Benton Harbor, MI 49022.
- Dart Truck Co., 1301 Chouteau Trafficway, P.O. Box 321, Kansas City, MO 64141.
- Deere & Company, John Deere Rd., Moline, IL 61265.
- Dresser Industries, Inc., 755 S. Milwaukee Ave., Libertyville, IL 60048.
- Fiat-Allis Construction Machinery, Inc., Box F, 106 Wilmot Rd., Deerfield, IL 60015.
- International Harvester, Construction Equipment Group, 600 Woodfield Ave., Schaumburg, IL 60196.
- Kawasaki Heavy Industries Ltd., 375 Park Av., Seagram Building, Room 3309, 33rd Floor, New York, NY 10022.
- Komatsu Limited, Komatsu Building, 2-3-6 Akasaka Minato-Ku, Tokyo, Japan 107.
- Marathon LeTourneau Co., Longview Division, P.O. Box 2307, Longview, TX 75606.
- Melroe Multi-Wheel, P.O. Box 1059, Longmont, CO 80501.
- Terex, Corp., IBH Group, Hudson, OH 44236.
- Trojan Industries, Inc., Trojan Circle, Batavia, NY 14020.
- VME Americas Inc., 23001 Euclid Avenue, Cleveland, OH 44117, 216-383-3000.

Hydraulic Excavators

- American Hoist & Derrick Co., American Construction Machinery Division, 63 S. Robert St., St. Paul, Minnesota 55107.
- Bucyrus-Erie Co., 1100 Milwaukee Ave., South Milwaukee, WI 53172.
- J.I. Case, Drott & Poclain, P.O. Box 1087, Wausau, WI 54401.

- Caterpillar Tractor Co., 100 NE Adams St., Peoria, IL 61629. Houston dealer: Mustang Tractor & Equipment Co., 12800 Northwest Freeway, Houston, TX 77040, 713-460-2000.
- Demag Corp., 1100 Jorie Blvd., Oakbrook, IL 60521.
- Dresser Industries, Inc., 755 S. Milwaukee Ave., Libertyville, IL 60048.
- FMC, Cable Crane & Excavator Division, 1201 6th St., S.W., Cedar Rapids, Iowa 52406.
- Harnischfeger Corp., P.O. Box 554, Milwaukee, WI 53201.
- Hein-Werner Corp., Construction Equipment Division, Waukesha, WI 53186.
- Insley Manufacturing, AMCA International Corp., 2118 N. Gale, P.O. Box 11308, Indianapolis, IN 46201.
- Koehring, Crane & Excavator Group, P.O. Box 2060, Milwaukee, WI 53202.
- Liebherr-America, Inc., 4100 Chestnut Ave., Newport News, VA 23605.
- Northwest Engineering, Co., 201 W. Walnut St., Green Bay, WI 54305.
- O & K, Orenstein & Koppel, Inc., Box 479, Clifton, NJ 07015.
- Warner & Swasey Company, Construction Equipment, Solon, OH 44139.

Draglines

- American Hoist & Derrick Co., 63 S. Robert St., St. Paul, Minnesota 55107.
- Bucyrus-Erie Co., 1100 Milwaukee Av., South Milwaukee, WI 53172.
- Clark Equipment Co., Crane Division, 1046 S. Main St., Lima, OH 45802.
- Dresser Industries, Inc., Marion Power Shovel Division, 617 W. Center St., P.O. Box 505, Marion, OH 43302.
- Harnischfeger Corp., P.O. Box 554, Milwaukee, WI 53201.
- The Manitowoc Co. Inc., Manitowoc Engineering Co. Division, 500 S. 16th St., Manitowoc, WI 54220, 414-684-6621.
- Northwest Engineering Co., 201 W. Walnut St., Green Bay, WI 54305.
- Page Engineering Co., Clearing Post Office, Chicago, IL 60638.
- Ransomes & Rapier Ltd., Box No. 1, Waterside Works, Ipswich 1P2 8HL, England.
- Weserhutte Aktiengesellschaft, P.O. Box 100940, Bad Oeynhausen, D. 4970, West Germany.

Bucket Wheel Excavators

- Barber-Greene Co., 400 N. Highland Ave., Aurora, IL 60507.
- Buckau R. Wolf, D4048 Grevenbroica, Post F.69, West Germany.
- Bucyrus-Erie Company, 1100 Milwaukee Ave., South Milwaukee, WI 53172.
- CMI Corporation, Box 1985, Oklahoma City, OK 73101.
- Demag Lauchhammer, 4 Dusseldorf-Bernrath, Forststrasse 16, Germany.
- Easi-Miner, Huron Manufacturing Corp., P.O. Box 1398, Huron, SD 57350.
- Eisenwerk Weserhutte AG, 4970 Bad Oeyhausen, West Germany.
- Fried Krupp GMBH, 414 Rhinhausen, Franz-Schubert-Strasse 6, West Germany.
- Mechanical Excavator Inc., 2960 Marsh St., Los Angeles, CA.
- Orenstein & Koppel AG, D-2400 Luebeck 1, Einsiedelstrasse G, West Germany.

Trucks (Off-Road)

- Atlas Hoist & Body, Inc., 7500 Cote de Liesse Rd., Montreal, Quebec, Canada H4T 1E8.
- Caterpillar Tractor Co., 100 NE Adams St., Peoria, IL 61629. Houston dealer: Mustang Tractor & Equipment Co., 12800 Northwest Freeway, Houston, TX 77040, 713-460-2000.
- Dart Truck Co., 1301 Chouteau Tr., P.O. Box 321, Kansas City, Missouri 64141.
- DJB Engineering Ltd., Peterlee, Co. Durham, England, SR8 2HX, DJB Sales Inc. 8280 Patuxent Range Rd., Jessup, Maryland 20794.
- Euclid, Inc., 22221 St. Clair Ave., Cleveland, OH 44117.
- General Motors, Diesel Division, General Motors of Canada, Ltd., P.O. Box 5160, London, Ontario N6A 4N5.
- Goodbary Engineering Co., P.O. Box 100, Cardin, OK 74335.
- International Harvester, Construction Equipment Group, 600 Woodfield Ave. Schaumburg, IL 60196.
- Kenworth Truck Co., P.O. Box 1000, Kirkland, WA 98033.
- Kress Corp., P.O. Box 368, Brimfield, IL 61517.
- Rimpull Corp., Box 748, U.S. 169 South, Olathe, Kansas 66061.
- T & J Industries, Inc., 13850 Wyandotte St., P.O. Box 8620, Kansas City, Missouri 64114.
- Terex Corp., IBH Group, Hudson, OH 44236.
- Unit Rig & Equipment Co., P.O. Box 3107, Tulsa, OK 74101.
- WABCO, Construction & Mining Equipment Division of American Standard, Inc., 2300 N.E. Adams St., Peoria, IL 61639

Bag-Filling Machines

- American-Newlong, Inc., 5310 S. Harding St, Indianapolis, IN 46217, 317-787-9421.
- Amscomatic, Inc., 80-00 Cooper Ave - Bldg 6, Glendale, NY 11377, 718-417-4600.
- Automated Packaging Systems, Inc., 8400 Darrow Rd., Twinsburg, OH 44087, 216-425-4242.
- BAG Corp., 11501 Data Dr., Dallas, TX 75218, 214-340-7060.
- Bemis Packaging Service Machinery Co., 315 27 Ave NE, Minneapolis, MN 55418, 612-782-1200.
- Conveying Industries, Inc., POB 2330, Denver, CO 80201.
- A H Emery Co., 70 Pine St., New Canaan, CT 06840, 203-966-4551.
- Errich International Div., All Packaging Machinery & Supplies Corp., 90 13 Ave, PO Box 1175, Ronkonkoma, NY 11779, 516-588-7310 or 212-895-5870.
- Franklin Miller Inc., Delumper Mixer Div., 50 Okner Parkway, Livingston, NJ 07039, 201-535-9200. **Houston**, TX, 77043: Bruce Wilson, 1462 Brittmoore Rd., 713-468-4383.
- General Packaging Equipment Co., 6101 Westview Dr., **Houston**, TX 77055, 713-686-4331.
- Howe Richardson Division, 680 Van Houten Ave, Clifton, NJ 07015, 201-471-3400.
- S Howes Co., Inc., 138 Howard St., Silver Creek, NY 14136, 716-934-2611.
- Kol-Flo Corp., 320 N Jensen Rd., Vestal, NY 13850, 607-729-9225.
- Midwest International, 105 Stover Rd., Charlevoix, MI 49720, 616-547-4073.

- Mollers North America, Inc., 5305-52 St., SE, Grand Rapids, MI 49508, 616-942-6504.
- National Equipment Corp., 322-326 Bruckner Blvd, Bronx, NY 10454, 212-585-0200.
- National Instrument Co. Inc., 4119 Fordleigh Rd, Baltimore, MD 21215, 301-764-0900, (Sales locations in all principal cities).
- O A Newton & Son Co., Materials Handling Group, US Route #13, PO Box 397, Bridgeville, DE 19933, 302-337-8211.
- Scheme & Equipment, Inc., 1040 Ogden Ave, Downers Grove, IL 60515, 312-963-0630.
- Smico Manufacturing Corp., 500 N MacArthur Blvd, Oklahoma City, OK 73127, 405-946-1461.
- Taylor Products Co., Inc., Route 4, Box 296A, Parsons, KS 67357, 316-421-5550.
- Vibra Screw, Inc., 755 Union Blvd, Totowa, NJ 07511, 201-256-7410, (Sales locations in all principal cities).