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CONCEPTUAL DESIGN OF EQUIPMENT TO EXCAVATE AND TRANSPORT REGOLITH FROM THE LUNAR MARIA
FINAL DESIGN REPORT

73912

P_145

Submitted to:

Mr. James Aliberti
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Kennedy Space Center, Florida

Prepared by:

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Errata Sheet

1. Page vi; delete:
   "Appendix D Traction Analysis .... D1"

2. Page 22; first sentence in last paragraph of 4.2 (Collecting), change to:
   "The operation, advantages, and disadvantages are discussed."

3. Page 28; second to last sentence on page, change to:
   "In addition to transporting regolith, the conveyor belt can be used to transport the maintenance crew and life support supplies to and from the excavation site."

4. Page 39; second to last sentence on page, change to:
   "Depth is varied by rotating a helical pinion on an input shaft to move the rack gear shown in Figure 24 up or down."

5. Page 48; second to last sentence on page, change to:
   "At the processing plant, a hydraulic jack will tilt the transportation bin to unload the regolith."

6. Page 55; second sentence on page, change to:
   "...(see Appendix D in the Supplemental Report, which discusses traction)."

6. Page 62; first two sentences of 6.2 (Power Requirements), change to:
   "The power required for the scarifier/conveyor equipment to operate is about 22 kW. The power required for the transportation equipment to operate when fully loaded is about 35 kW."

7. Page 63; third sentence of 6.5 (Operation), change to:
   "If necessary, the second MDU can push the scarifier/conveyor MDU to provide extra traction."

8. Page C29; first sentence of last paragraph, change to:
   "Since the target regolith excavation rate is constant at 62.5 m^3/hr, varying the belt speed of the conveyor varies the Q value."

9. Page C30; second sentence of last paragraph, delete sentence.

10. Page C30; second to last sentence of last sentence, change to:
    "The dimensions were chosen to..."

11. Page C37; last sentence of C.3 (Transporter), delete second period.

12. Page C38; last line, change to:
    "The total force required to propel the MDU-Bin, F, is"

13. Page C42; last word, change to:
    "operate"

14. Page C51; delete all text between Tables C7 and C8.

MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM
THE UNIVERSITY OF TEXAS AT AUSTIN

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November 6, 1990

Mr. James Aliberti
NASA-Mail Stop PT-PMO
Kennedy Space Center, Florida 32899

Dear Mr. Aliberti:

Attached is the final report for the design project entitled "Conceptual Design of Equipment to Excavate and Transport Regolith from the Lunar Maria" completed by a University of Texas at Austin USRA design team. The excavation equipment uses a scarifier to loosen the regolith and a bucket conveyor to collect the regolith. The regolith is transported to the processing plant by a haul-dump system. The equipment is powered by fuel cells.

The report contains a description of the design alternatives considered, the decision matrices, and the final design solution. Included in the design solution is a description of the configuration, mass and power requirements, and operating features of the equipment.

The team has enjoyed working on this exciting project and is looking forward to seeing you at the final design presentation. The presentation will take place on Tuesday, November 27th, 1990, at 4:00 p.m. in the Engineering Teaching Center II, Room 4.110, at The University of Texas at Austin. A catered luncheon will be served at noon on the day of the presentation.

Sincerely,

Mark Detwiler

Mark Detwiler, Team Leader

Chee Seng Foong

Catherine Stocklin

Catherine Stocklin

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Acknowledgements

The design team thanks the National Aeronautics and Space Administration (NASA) and the Universities Space Research Association (USRA) for the opportunity to work on this project. The design team especially thanks Mr. James Aliberti for his support of the Mechanical Engineering Advanced Design Projects Program.

The design team thanks Mr. John Connolly at NASA for his help throughout the semester. Mr. Connolly aided the team by providing information that would have otherwise been unavailable to the team.

Special thanks go to the team's faculty adviser, Dr. Richard Crawford at the University of Texas at Austin. Dr. Crawford provided invaluable aid in focusing the team on the critical issues involved in the project. Dr. Crawford also helped point out advantages and disadvantages of the team's ideas throughout the semester.

The design team would also like to thank Mr. Hank Kleespies at the University of Texas at Austin for his morale boosts throughout the semester and for acting as a sounding board for the team's ideas.

The design team would like to thank Dr. Leonhard Bernold at the University of Maryland for providing valuable information and expertise on lunar excavation.

In addition, special thanks go to Mr. Wendell Deen for critiquing the design drawings and Mr. Bert Herigstad for providing administrative aid, materials, and advice.

Finally, the team would like to thank Dr. Steven P. Nichols for overseeing the Mechanical Engineering Advanced Design Projects Program, and for providing an opportunity to take part in this rewarding program.

Abstract

Conceptual Design of Equipment to Excavate and Transport Regolith from the Lunar Maria

NASA hopes to have a manned lunar outpost completed by 2005. In order to establish the base, regolith must be excavated from the lunar surface. Regolith will be used as a source for life-supporting elements and as radiation shielding for the lunar outpost. The design team from the University of Texas at Austin designed excavation and transportation equipment for initial operations of the lunar base. The design team also characterized the elements to be found in the regolith and determined the power required to excavate regolith.

The characterization of the soil was based on a literature review of lunar geography. Power requirements for excavation were developed by adapting terrestrial equations for excavation power requirements and adapting them to lunar soil conditions.

The design of the excavation and transportation equipment was broken into three functions: loosening, collecting, and transporting. A scarifier was selected to loosen, a bucket conveyor was selected to collect, and a load-haul system was selected to transport. The functions are powered by a modular fuel cell powered vehicle that provides power for motion of the equipment.

KEY WORDS: LUNAR BASE, LUNAR EQUIPMENT, REGOLITH, EXCAVATION

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Introduction

In 1958, the United States Government commissioned the National Aeronautics and Space Administration (NASA) to research topics related to the exploration of space. Since that time NASA has, among other accomplishments, sent six manned missions to the moon, launched numerous satellites into orbit, and landed a spacecraft on Mars. Currently NASA is working to develop a manned lunar outpost. This outpost is needed to help correct the irreversible depletion of terrestrial resources. The outpost will also be an ideal site for conducting scientific research and developing new technologies.

NASA hopes to have the manned outpost completed by 2005.[1] The cost of the outpost must be minimized since NASA has limited financial resources. Because the cost of transporting payload to the moon is about $33 million/metric ton, the cost of the outpost can be reduced by fabricating products from material available on the lunar surface.[2] However, the material on the moon must be excavated, transported to a processing plant, and processed in order to produce lunar-made products. The excavation and transportation of the lunar materials will require highly specialized equipment. The task presented to the design team from the University of Texas at Austin by NASA and the Universities Space Research Association (USRA) is to develop innovative designs for equipment to excavate and transport lunar regolith.

1.1 Background

Lunar regolith, which is the material covering the outer surface of the moon, will be excavated initially for radiation shielding of the lunar habitat and as raw material for building structures. For these uses, the regolith can be used as-excavated. Once the habitat is constructed, however, regolith must be processed to obtain oxygen, hydrogen, and metals. Oxygen and hydrogen will be needed for life support and fuel while metals will be needed for structural and machine components.[3]

1.2 Project Requirements

There are four requirements for the project as defined by NASA/USRA. They are as follows:

1) Characterize the elements to be found in the lunar regolith.
2) Conceptually design the equipment needed for mining operations.
3) Determine the power required to excavate regolith.
4) Construct a demonstration model of the equipment that illustrates the configuration and operation of the design.

1.3 Design Criteria

The following is a list of criteria that the equipment design must meet. The list was based on research into the lunar environment and previous lunar equipment designs.

1. The equipment must be multipurpose. Multipurpose equipment performs the functions of several single purpose machines, which decreases the amount of equipment needed.

2. The equipment must be modular. Modular components can be used on more than one machine and can be easily replaced.

3. The equipment must have minimum mass and volume. Mass and volume must be minimized to reduce the cost of transporting the equipment to the moon.

4. The equipment must have minimum power consumption. There is little power available on the moon, so its use must be minimized. Most of the available power is necessary for life support.

5. The equipment must have simple components. Simple components are easier to produce, assemble, maintain, and repair than complicated components.

6. The equipment must require minimum manpower. Manpower for excavation must be minimized to reduce human exposure to the lunar environment and to free the lunar base crew for other tasks, such as exploration and scientific experimentation.

7. The equipment must be safe to operate. The safety of the lunar base crew is a primary concern.

8. The equipment must perform successfully in the lunar environment. The equipment must function well in an abrasive environment, at extreme temperatures, in a vacuum, and under constant radiation.

9. The equipment must be economical. Production and maintenance costs for the equipment must not be excessive.

10. The equipment must be reliable. Replacement parts must be transferred from Earth, making the repair of broken equipment difficult.

1.4 Methodology

The design team researched the lunar environment, the structure of the lunar surface, and previous lunar vehicle designs. The characterization of the lunar soil was based on this research. The characterization consists of a discussion of the primary elements present in the lunar surface and in what quantities they are available.

The excavation and transport equipment was broken into the following functions: loosening, collecting, and transporting. Several design alternatives were formulated for each function. These design alternatives were then evaluated in decision matrices and the best alternatives for each function were combined into a final design solution.

The approach outlined above was chosen since the design was basically conceptual. The design team emphasized the conceptual nature of the design because NASA is currently more interested in collecting ideas for solutions than actual detailed solutions.[4]

To determine the power required to excavate the regolith, the design team reviewed literature on the physical properties of the lunar surface. The team used these properties to determine the cutting force required by the loosener.[5] This force was multiplied by the velocity of the equipment to determine the power needed. The power for the collector was determined by adapting an equation for terrestrial equipment power requirements to apply for lunar equipment.[6] The power for the transporter was determined by multiplying the friction force on the wheels by the velocity of the transporter.

The design team is now constructing a demonstration model that illustrates the working principles and overall configuration of the final design. The design team will contract a machinist to complete what the team cannot do itself.

Regolith Characterization

The characterization of the regolith is divided into two sections. The first section discusses the mechanical properties of the regolith. Properties directly affecting the excavating process are emphasized. The second section discusses the composition of the lunar regolith by denoting the elements to be found in regolith and discussing the target elements for excavation.

2.1 Mechanical Properties

Regolith is a highly compact layer of material that covers the lunar bedrock. A core sample of regolith from the Apollo 15 mission varied in density from 1.38 g/cm^3 at the surface to 2.15 g/cm^3 at 242 cm.[7] The porosity of the lunar regolith ranges from forty-one to seventy percent. The range for porosity is high due to the abundance of irregularly shaped glass particles found in the regolith. The density of the regolith can be approximated by the expression

$$p = p_o + k \ln(z+1) \qquad (1)^8$$

where p_o is the surface density, k is the regolith density gradient with respect to depth, z is the depth, and p is the density at a depth z. A plot of the bulk density at two Apollo 15 sites is shown on the next page in Figure 1.

The depth of regolith in a particular area on the moon can be estimated by examining the concentration of craters in the area. A more densely cratered area will have a greater depth of regolith. The flat regions of the moon, called maria, have an average

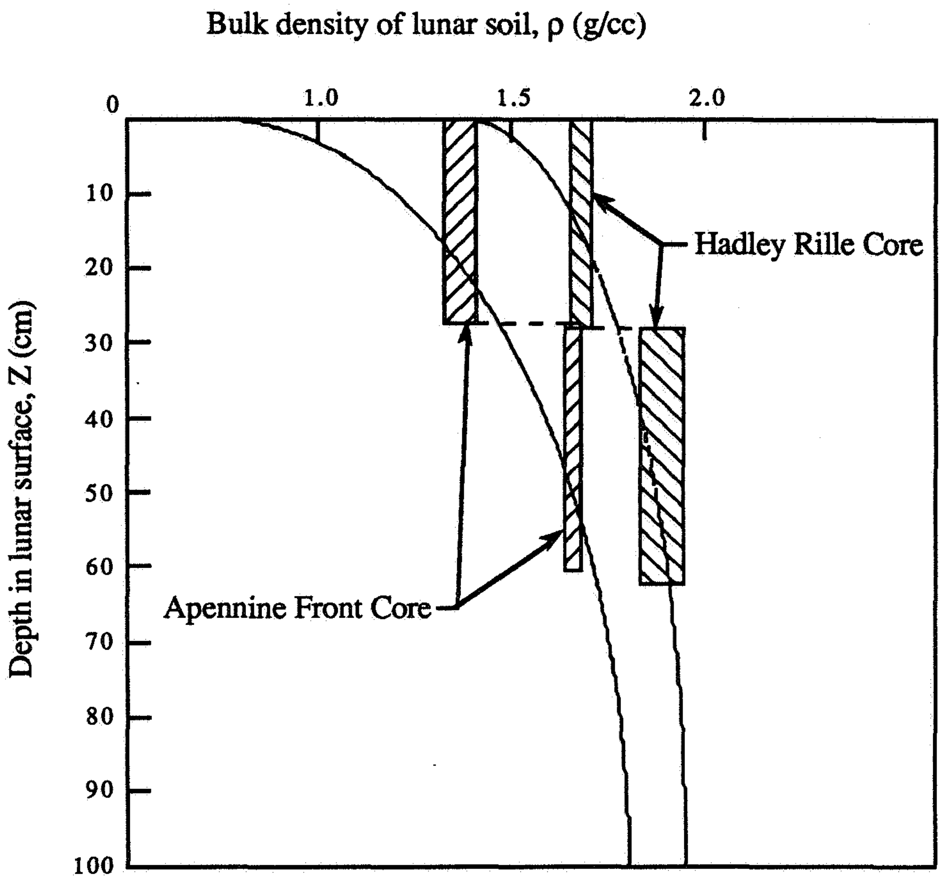

Figure 1. VARIATION OF LUNAR REGOLITH BULK DENSITY WITH DEPTH. The sectioned areas show the actual density variations and the smooth lines show the curve-fit given by Equation 1.[9]

depth of five meters. The average depth in heavily cratered areas, called highlands, is ten meters.[10]

Cohesion of the lunar regolith is low. Cohesion ranges from 0.5 to 3.6 kN/m^3 and is typically 1.6 kN/m^3. The internal angle of friction of the regolith ranges from 30° to 60°.[11] Cohesion is low because there is no moisture on the moon. The cohesion that is present is caused by mechanical interlocking of the irregularly shaped regolith particles. Since there is no weathering on the moon, particles do not become smoothed as they do on Earth. The distribution of particle size of the regolith is shown in Figure 2.

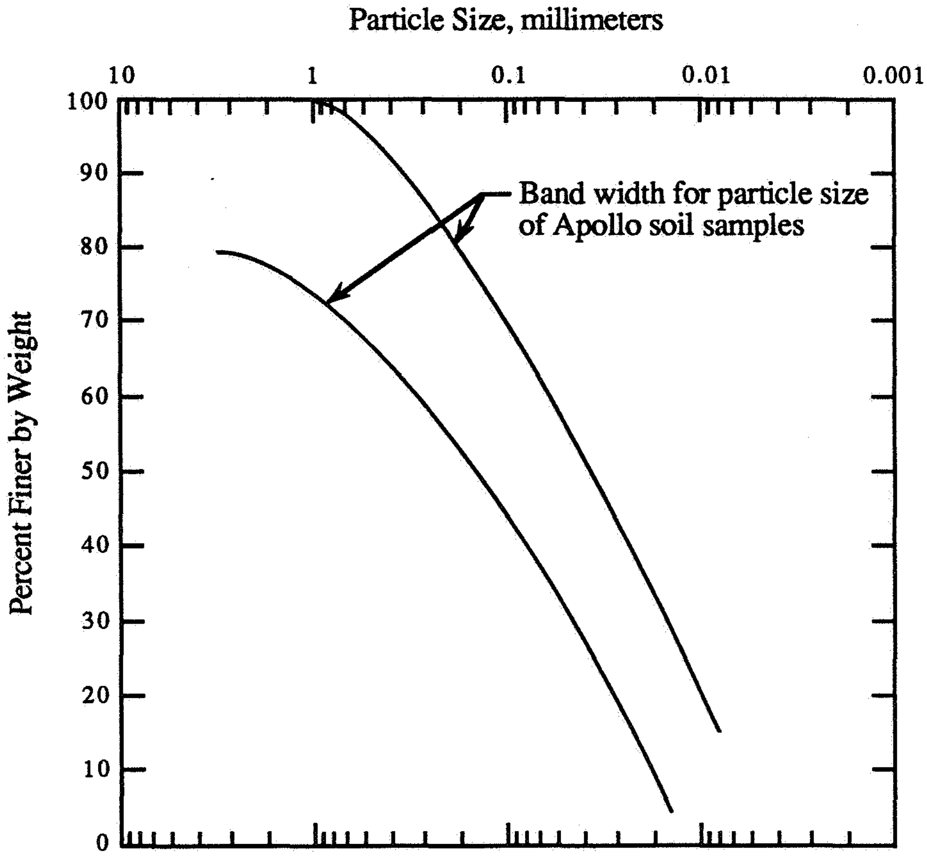

Figure 2. DISTRIBUTION OF PARTICLE SIZE IN REGOLITH[12]

2.2 Composition

Table 1 lists the most common lunar elements and gives their abundances. Helium-3 may be the only true economic ore on the moon. Helium-3 is economically significant since it is a possible fuel for nuclear fusion.[13]

Solar-wind implanted hydrogen and helium are present in the lunar regolith in relatively small quantities. Ilmenite, a mineral available on the moon, acts as a sponge to absorb these elements. Therefore, ilmenite content is the best indicator of hydrogen and helium content. Ilmenite also contains the most easily recoverable oxygen. The ilmenite with the highest concentrations of oxygen, hydrogen, and helium occurs in the maria.

Since these elements will likely be the most valuable elements to be mined on the moon, ilmenite will be the most important mineral on the lunar surface.[14]

Detailed discussions of the element and mineral content of the lunar regolith are available in the literature.[15,16]

Table 1

Element Abundances on the Moon[17]

	Percent of Atoms			Weight Percent of Oxides		
Element	Mare	Highland	Average Surface	Mare	Highland	Average Surface
O	60.3	61.1	60.9			
Na	0.4	0.4	0.4	0.6	0.6	0.6
Mg	5.1	4.0	4.2	9.2	7.5	7.8
Al	6.5	10.1	9.4	14.9	24.0	22.2
Si	16.9	16.3	16.4	45.4	45.5	45.5
Ca	4.7	6.1	5.8	11.8	15.9	15.0
Ti	1.1	0.15	0.3	3.9	0.6	1.3
Fe	4.4	1.8	2.3	14.1	5.9	7.5

Preliminary Considerations

Before the design alternatives were formulated, the design team had to consider three issues. These issues were the lunar environment, the material to excavate, and the type of equipment motion.

3.1 Lunar Environment

The major characteristics of the lunar environment affecting equipment operation are the following:

1) Surface Temperatures
2) Vacuum
3) Radiation
4) Gravity
5) Dust Particles
6) Surface Coefficient of Friction
7) Diurnal Cycle

These environment characteristics and the problems they cause for lunar equipment are discussed below.

3.1.1 Surface Temperatures

The temperature of the lunar surface varies from 127 °C at lunar noon to -173 °C just before lunar sunrise.[18] Because of the wide temperature range, the equipment must be made of materials that have low thermal expansion to reduce thermal stresses.

The low temperatures during the lunar night greatly increase the likelihood of brittle fracture in metals. Therefore, the excavation and transportation equipment will operate during the lunar day only. The high temperatures during the lunar day necessitate the use of a cooling system on the equipment.

3.1.2 Vacuum

The negligible atmospheric pressure on the moon causes fluids to vaporize if they leak from the equipment. However, a benefit of the vacuum is that the lack of air drag will make equipment more power efficient.

The lack of oxygen in the atmosphere retards corrosive wear of equipment parts that are not in contact with the lunar surface. Regolith is sixty percent oxygen by weight, however, so equipment parts that contact the regolith must be made of materials that are insensitive to oxidation.

Another effect of the lunar vacuum is that meteorites continually bombard the lunar surface since there is no atmosphere to burn up the meteorites. Most of the meteors have masses between 10^{-7} to 10^{-2} grams and are called micrometeorites. Particles in the 10^{-4} to 10^{-2} gram range do the most damage to the lunar surface because of their relatively high velocity (20 km/sec).[19] In addition to the smaller particles, between 70 and 150 impacts from meteorites in the 0.1 to 1000 kilogram range are recorded on the lunar surface each year.[20] Lunar equipment must be protected from these meteorite impacts.

3.1.3 Radiation

The lunar surface is subject to intense radiation since there is no magnetic field on the moon to deflect incoming charged particles. The radiation comes from two main sources: solar flares and galactic cosmic rays (GCRs). Solar flares are periodic bursts of energy from the sun that can yield radiation doses up to 960 rem.[21] Since a dose of just

450 rem is lethal to fifty percent of the population within thirty days of exposure, the lunar base crew must be protected from radiation.[22] GCRs are rays from interstellar sources that provide a continuous radiation flux to the lunar surface. GCRs produce a much lower dose than solar flares, but have higher energy. GCRs will cause unprotected materials to embrittle.

3.1.4 Gravity

The gravitational acceleration on the lunar surface is 1.625 m/sec^2, or about one-sixth of Earth's gravity.[23] Low gravity adversely affects vehicle traction on the moon. For the same surface conditions, a vehicle must be six times more massive on the moon than on Earth.

3.1.5 Dust Particles

The top few centimeters of the lunar surface is composed of electrostatically charged dust particles that are abrasive. Because of their charge, the dust particles cling to all surfaces.

3.1.6 Surface Coefficient of Friction

External surfaces on the moon have a higher coefficient of friction than on Earth. The higher coefficient of friction occurs because there is no layer of water vapor to lubricate mating surfaces on the moon. Mating surfaces mechanically interlock to increase the force necessary to cause relative movement.

3.1.7 Diurnal Cycle

The lunar diurnal cycle has fourteen earth days of sunlight and fourteen earth days of darkness.[24] Since the equipment must work continuously during the lunar day, a fourteen earth day power supply must be available for lunar equipment.

3.2 Material to Excavate

The selection of the material to excavate includes considering what type of material should be excavated, how much material should be excavated, and in what type of terrain the excavating should take place.

3.2.1 Type of Material

There are two main types of material to excavate on the moon: regolith and bedrock. Both the regolith and bedrock contain minerals that will be valuable to the lunar base. Bedrock has a higher concentration of ilmenite. However, regolith is easier to excavate. Regolith will also be needed for radiation shielding of the lunar habitat and as raw material for building structures.

The design team concentrated on excavating regolith because there will be a need for regolith excavation throughout the existence of the lunar base. In addition, the regolith excavating equipment can be used to remove the regolith above bedrock and to move loosened bedrock. The transport equipment can be used for both bedrock and regolith excavation.

The quantity of regolith that will need to be excavated from the maria is 62.5 m^3/hr. This volume is derived and discussed in Appendix A.

3.2.2 Type of Terrain

Regolith is found both in the highland and marial regions. While the highlands contain a higher percentage of useful minerals, the terrain of the highlands makes it difficult to establish a base and to excavate regolith. For these reasons, it is likely that the lunar outpost will be located in a marial region.[25]

The excavation site will be near the lunar outpost to reduce the amount of energy required for transportation of the regolith. Therefore, the design team chose to concentrate on the excavation of regolith in the marial regions.

3.3 Equipment Motion Type

Two types of equipment motion were considered. The first type is whether the equipment motion would be continuous or discrete and the second type is whether the motion would be random or organized into rows.

3.3.1 Continuous vs. Discrete Motion

The motion of the equipment could be either discrete or continuous. Discrete motion is accomplished by equipment such as backhoes, draglines, and bulldozers. Discrete volumes of material (in this case regolith) are collected and then loaded into a storage area, such as the back of a dump truck. During the loading process, no collection of material can take place. This system is inefficient since only one process can take place at a time. Also, energy is wasted moving the collecting device to the regolith storage area, which is often on a separate piece of equipment.

With continuous equipment, the excavated material is moved continuously to a storage area that moves with the collecting equipment so that no stopping and starting of the collecting equipment is necessary. A minimum amount of energy is used transporting the material from the collecting device to the storage area. The design team concentrated on continuous motion since it is more efficient. The load-haul-dump system, which has discrete motion, is also discussed because of its prevalence in terrestrial excavation.

3.3.2 Random vs. Organized Motion

The motion of the equipment could be either organized or random. The most common organization of motion is into rows. Motion in rows is used in farming for plowing fields and collecting crops. Since only one pass over the field needs to be performed, this method ensures that the entire field is covered in a minimum amount of time. However, in a mining procedure where an area is covered many times, the equipment no longer needs to be constrained to move in rows and may move randomly. The main advantage of random motion is that it is easier to automate. The equipment can move randomly over the surface using either discrete or continuous motion. When an obstacle is encountered, the equipment can turn and move in another direction. Equipment moving in rows, on the other hand, is constrained to move in one direction. When an obstacle is encountered, outside intervention is necessary for the system to continue motion.

Random motion has several disadvantages. First of all, variations in the height of the surface can occur that may develop into ruts. These ruts may cause the equipment to get trapped and travel only in the ruts. Another disadvantage is that the lunar crew will not know exactly where the excavation equipment is at all times. Finally, random motion is not a proven method of excavation. NASA wants to use proven methods of excavation at the lunar outpost to avoid unforeseen problems.[26]

Due to the reasons listed above, the design team decided to concentrate on motion in rows that is continuous.

3.4 Power Module

The team has designed a modular Main Drive Unit (MDU) to provide mobility for the loosening, collecting, and transporting function modules. The alternative designs presented are modular attachments to the MDU that can be attached or detached as needed. Section 5.5 discusses the MDU in detail.

Design Alternatives

The two main functions that terrestrial excavation systems must accomplish are collection and transportation. However, overall power consumption of the lunar excavation process can be reduced by having a separate regolith loosening step. Therefore, the three excavation steps required on the moon are

1) Loosening
2) Collecting
3) Transporting

Loosening breaks up the regolith to make collecting easier. Collecting is the picking up of regolith from the surface. Transporting is the moving of collected regolith from the excavation site to the processing plant.

4.1 Loosening

Four options for loosening were considered. These options are

1) Bladed Roller
2) Explosives
3) Auger
4) Scarifier

Each loosening alternative is discussed in this section. Included is a short description of how each alternative functions and its advantages and disadvantages.

4.1.1 Bladed Roller

The first alternative for loosening is the bladed roller shown in Figure 3. The roller itself is an adaptation of a compacting drum suggested for use in lunar road construction.[27] The adaptations are shown in Figure 4. By putting channels in the compacting drum, the drum can be used with bladed attachments to loosen regolith or with flat attachments to compact roads. The blades on the roller can be curved or straight. Straight blades require less power, but curved blades disrupt the surface more. The roller must have enough weight to keep the blades in the lunar surface. A bin full of lunar rocks is placed above the roller to achieve the required weight. The bladed roller turns freely and does not require

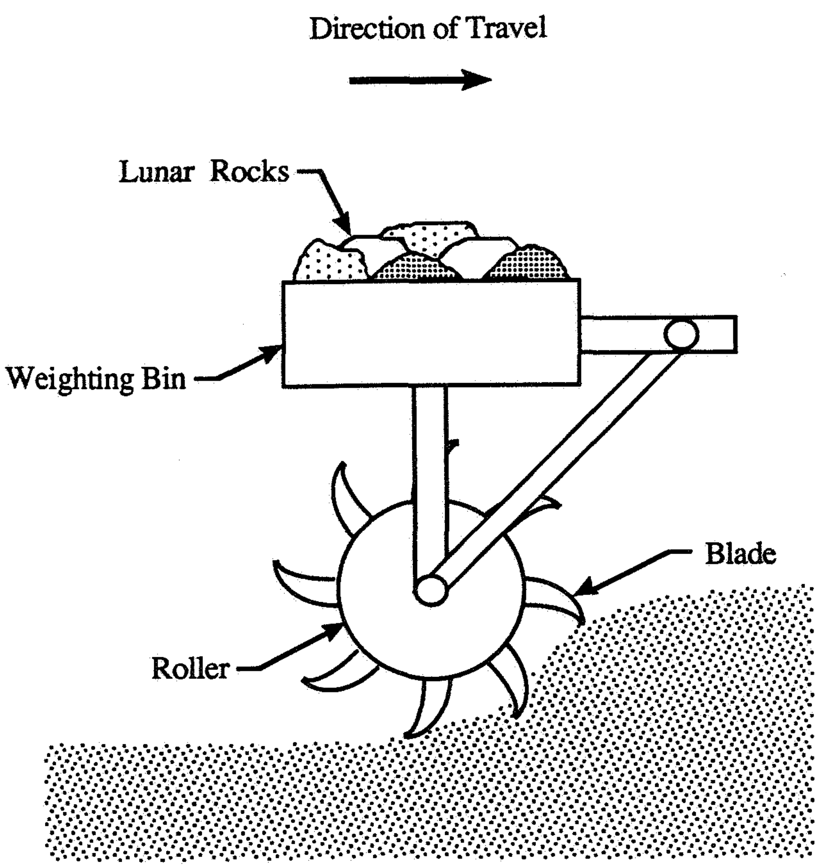

Figure 3. BLADED ROLLER

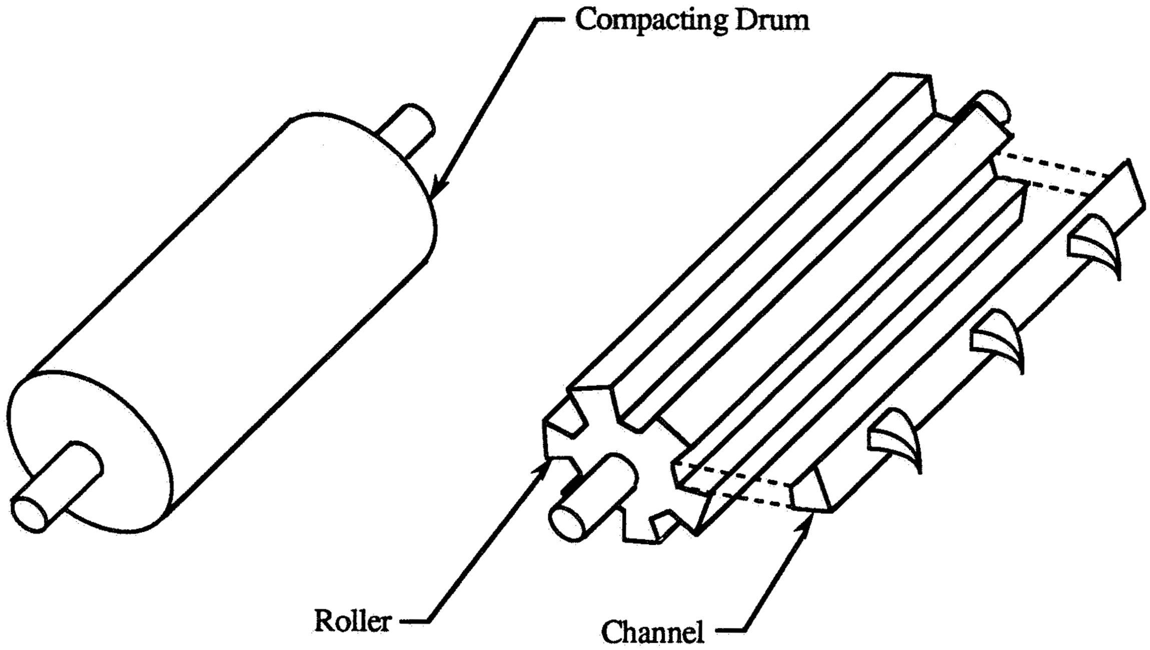

Figure 4. ADAPTATION OF ROAD COMPACTING DRUM FOR BLADED ROLLER

separate power transmission from the power module. Friction between the blades and the lunar surface causes the roller to turn.

The most important advantage of the bladed roller is that it is multipurpose. The bladed roller can be used in road construction with minimal modifications. Because no gear arrangement is required to power the roller, there are few moving parts. The bladed roller also uses simple components, has low power consumption, and is reliable.

The main disadvantage of the bladed roller is that it may not loosen effectively. The roller must be heavily weighted to maintain a constant depth of cut, which will increase the force resisting forward motion of the power vehicle. This will cause the power vehicle to lose traction.

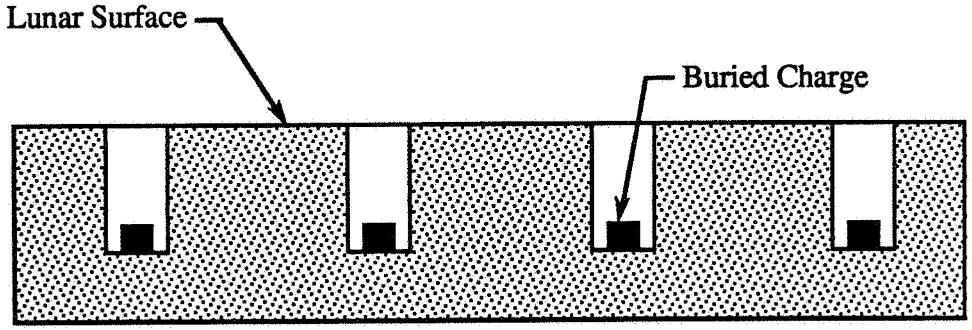

Figure 5a. EXPLOSIVE LOOSENING ON LUNAR SURFACE

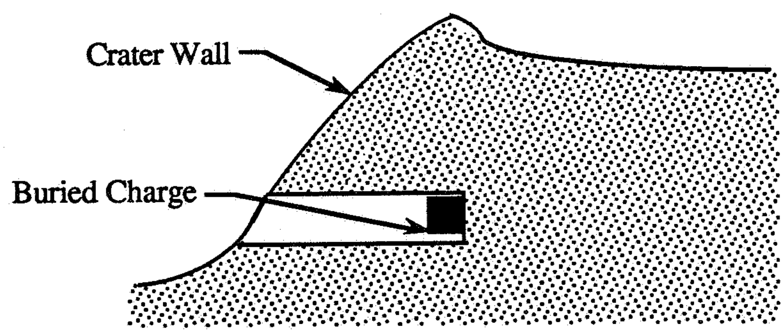

Figure 5b. EXPLOSIVE LOOSENING ON CRATER WALL

4.1.2 Explosives

The second alternative for loosening is explosives. The explosives are detonated by an electrically-triggered chemical reaction. Explosive loosening for surface mining can be accomplished by burying the explosives in a grid pattern to make shallow craters on the surface (see Figure 5a). Explosive loosening in the heavily cratered highlands can be accomplished by explosively shearing the sides of large craters and collecting the fallen regolith (see Figure 5b).

The main advantage of using explosives to loosen is that they are multipurpose. Explosives can be used to make craters for the lunar habitat and the planned lunar nuclear reactor. In addition, explosives can be used to excavate bedrock.

The first disadvantage of explosives is that an explosives specialist is needed to plan the layout for the explosives grid and to determine the optimum depth-of-burial for the charges. Another disadvantage is that explosives are potentially dangerous. The explosives eject material at high velocities, which can harm both people and equipment. A final disadvantage is that explosives are untested on the moon. Lunar conditions may produce unexpected results for explosive loosening.

4.1.3 Auger

The auger, shown in Figure 6, is the third alternative for loosening. The auger can be either stationary or rotating. The blades are oriented so that regolith is churned into a central aisle. If the regolith were moved to an aisle on the side, the loosener would need to maintain a balancing torque to compensate for the torque applied by the regolith. Organizing the regolith into an aisle allows for easier collection. The rotating auger is powered through a transmission link from the power vehicle.

One advantage of the auger is its ability to loosen regolith effectively when rotating. The stationary auger does not loosen as effectively, but is more reliable due to fewer moving parts. A disadvantage of the auger is that it is not multipurpose since it is only useful for loosening regolith. Also, the power requirement for the rotating auger is high.

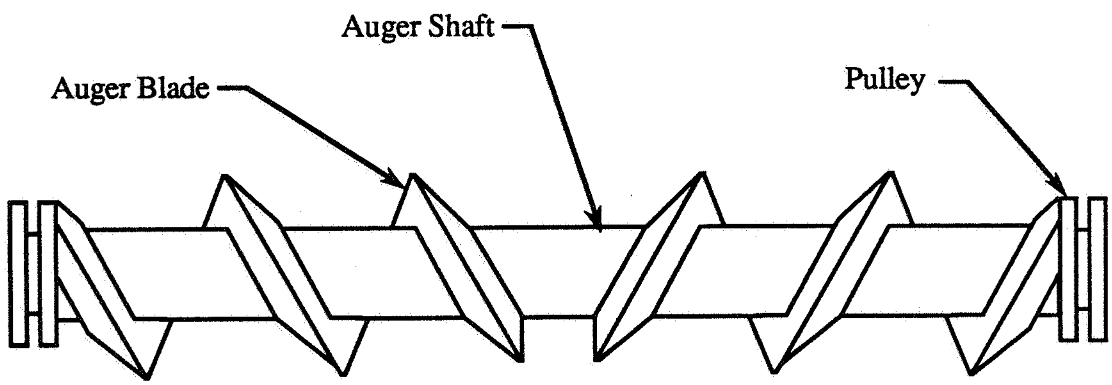

Figure 6. AUGER

4.1.4 Scarifier

The scarifier is a platform of blades that is dragged along the ground as a rake (see Figure 7). The blades are pushed into the ground by its own weight and by the force of the

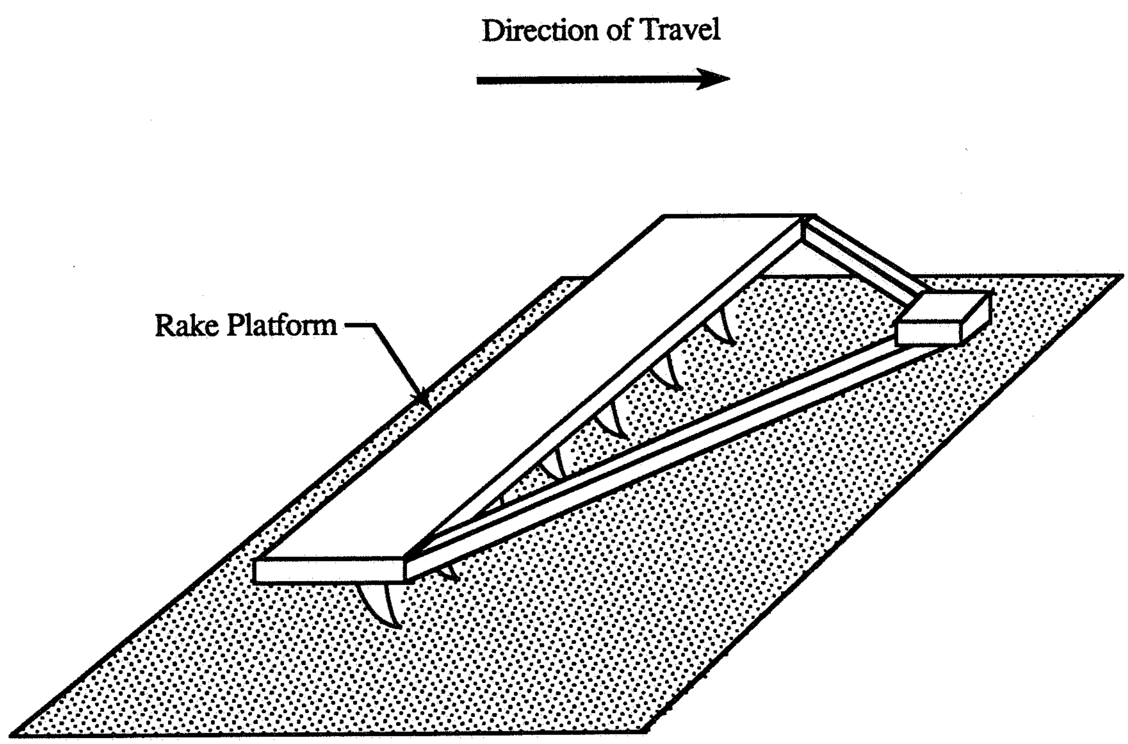

Figure 7. SCARIFIER

soil on the blades. A bin that holds regolith can be added above the platform to increase the weight of the scarifier and thus help loosening.

An advantage of the scarifier is simplicity. The scarifier also has no moving parts, low mass, and low power use. A disadvantage of the scarifier is that it is not multipurpose since it has no uses other than loosening of the surface regolith.

4.2 Collecting

Once the regolith has been loosened, it must be collected from the lunar surface. The collector gathers the regolith and loads it into a storage area, such as a bin or bag. Four alternatives for collectors were considered. These alternatives are

1) Conveyor Belt
2) Inclined Plane
3) Bucketwheel
4) Front End Loader

The operation, advantages, and disadvantages of each collector is discussed. The front end loader will not be discussed in this section, but will be discussed in transporting as part of the load-haul-dump transportation system.

4.2.1 Conveyor Belt

The conveyor belt alternative consists of a conveyor belt attached to the front of a collecting bin as shown in Figure 8. Placing the conveyor close to the storage area allows for a conveyor of minimum length, which reduces the number of moving parts and mass of the conveyor. The forward movement of the system forces regolith onto the conveyor belt.

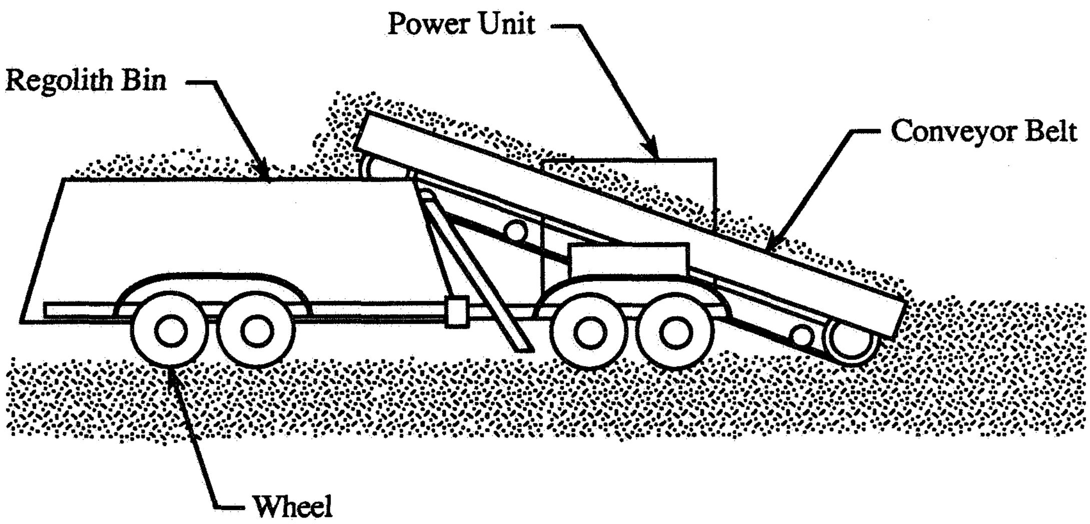

Figure 8. CONVEYOR BELT COLLECTOR

An advantage of conveyor belts is that they are well tested on Earth and so should be reliable. However, the conveyor belt collector has several disadvantages. The conveyor has a number of moving parts and does not use simple components. A major drawback of this design is the complexity of transmitting power from the modular power source to the conveyor.

4.2.2 Inclined Plane

Three variations of the inclined plane were considered for collecting. The advantages and disadvantages common to the three variations will be discussed collectively at the end of this section.

The first variation is shown in Figure 9. An inclined plane is attached to the front of a collector bin. When the collector moves forward, the pre-loosened regolith moves up the inclined plane until it falls into the bin.

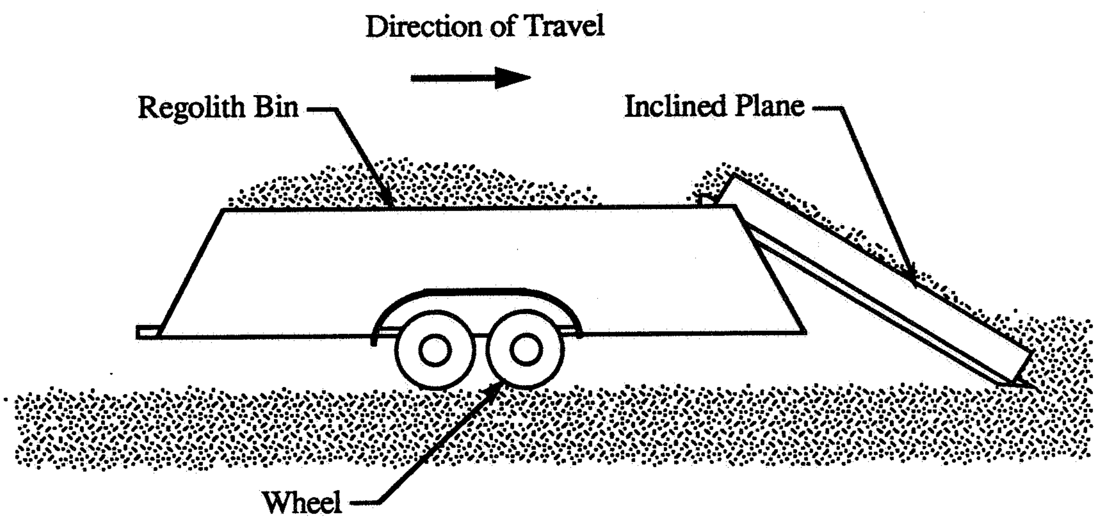

Figure 9. INCLINED PLANE WITH COLLECTOR BIN

Figure 10 shows the second variation. This option combines the inclined plane and conveyor belt collecting alternatives. The forward motion of the collector pushes the regolith up the inclined plane to the conveyor belt. This arrangement minimizes wear on the belt from pushing directly into the regolith. Also, there is no torque on the end of the belt since the cutting force acts on the inclined plane.

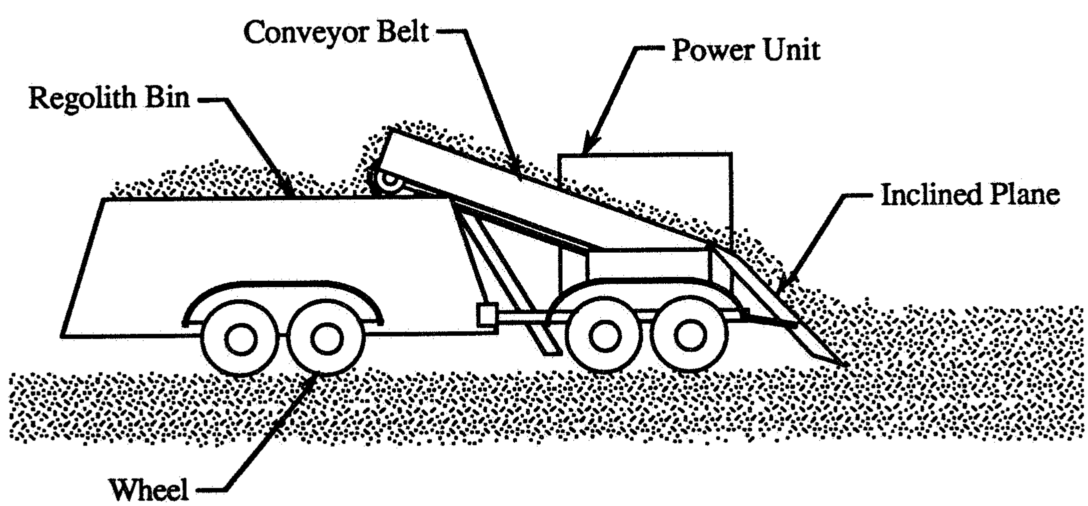

Figure 10. INCLINED PLANE WITH CONVEYOR BELT

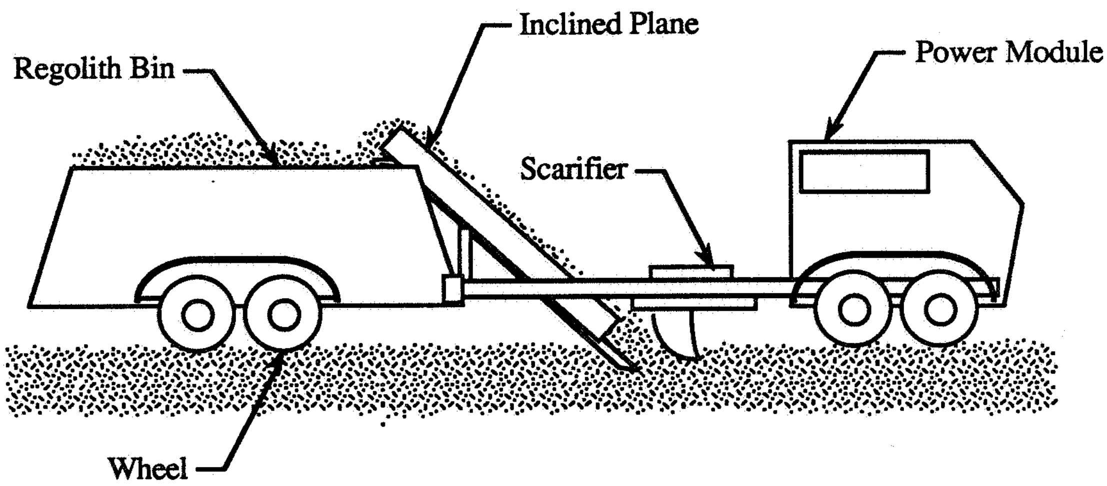

Figure 11. INCLINED PLANE WITH SCARIFIER

The third inclined plane variation is shown in Figures 11 and 12. This inclined plane is directly behind a loosening device. Figure 11 shows the loosening device to be a scarifier and Figure 12 shows the loosening device to be an auger. The auger moves the regolith to a central narrow area, which reduces the width of the inclined plane.

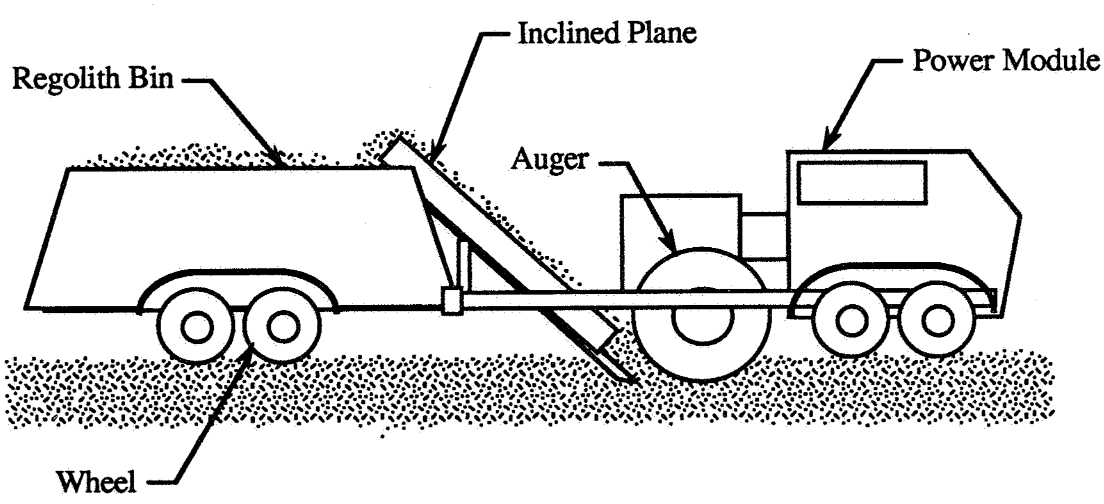

Figure 12. INCLINED PLANE WITH AUGER

The inclined plane uses extremely simple components, has no moving parts, and is reliable. The only disadvantage of this system is that it needs high traction from the power vehicle to function effectively. Much of the regolith is pushed in front of the plane instead of being forced up the incline. This increases the force resisting motion which may make the vehicle may slip.

4.2.3 Bucketwheel

A bucketwheel collector is shown in Figure 13. The arm from the MDU to the bucketwheel is used to support the bucketwheel. Since the bucketwheel cuts deep into the regolith, the loosening stage is unnecessary. The bucketwheel can also be placed behind or beside the MDU.

An advantage of the bucketwheel is that it is used widely on Earth. Its well developed technology makes the bucketwheel collector reliable. However, the bucketwheel collector has a large mass and volume and is not composed of simple components.

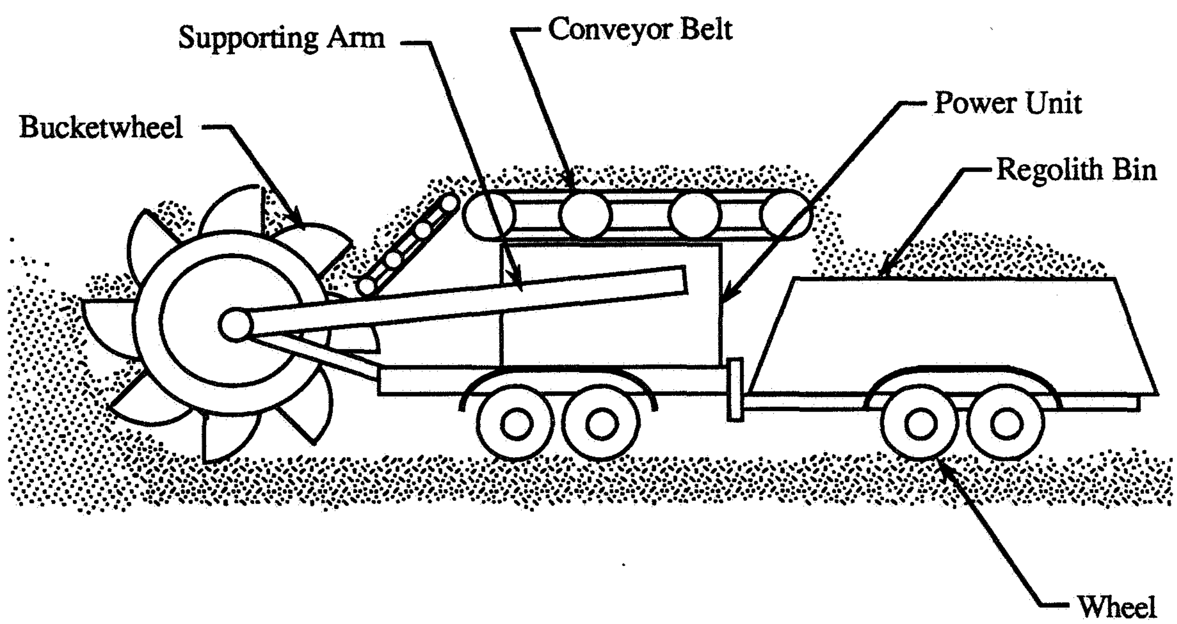

Figure 13. BUCKETWHEEL

4.3 Transporting

Transporting equipment is needed to move the collected regolith from the excavation site to the processing site. The alternatives considered for transportation equipment were

1) Lunar Lander
2) Conveyor Belt
3) Cable Tram
4) Load-Haul-Dump

Each transportation alternative will be described and its advantages and disadvantages discussed.

4.3.1 Lunar Lander

A lunar lander, shown in Figure 14, will be used at the lunar base to provide transportation between the lunar base and lower lunar orbit. It can also be used to transport regolith from the excavation site to the processing plant. The regolith bins can be placed on top of the lander or be attached to the sides of the lander.

One advantage of the lunar lander is its high speed, which is especially useful for transporting over long distances. Another advantage is that the problem of traveling over difficult terrain is bypassed. Also, the lunar lander is multipurpose since it will also be used for transporting supplies and crew members to and from lower lunar orbit. The major disadvantage of the lander is that it has very high power consumption. The lander also has a small cargo area relative to trucks and therefore needs to make many trips to and from the processing site.

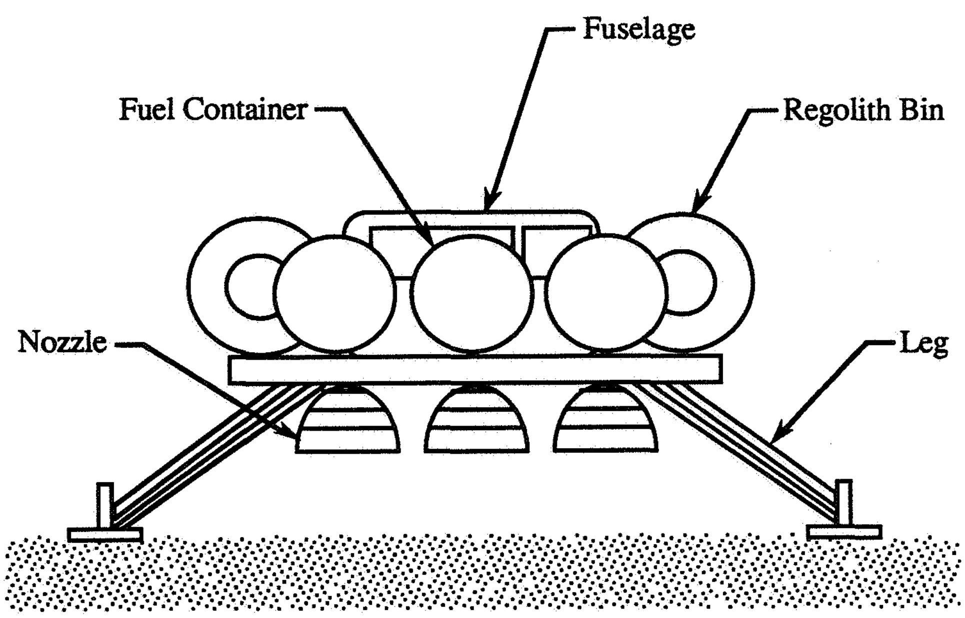

Figure 14. LUNAR LANDER

4.3.2 Conveyor Belt

A conveyor belt transporter consists of a long belt running on several rollers driven by a motor. Collected regolith is dumped onto the receiving end of the conveyor belt and moved to the other end of the belt, where the regolith either falls onto a second conveyor belt or into the processing site storage area (see Figure 15). Compared to a single conveyor belt that runs several kilometers, several shorter conveyors joined end-to-end are easier to relocate.

The major advantage of the conveyor belt system is that it transports a high volume of regolith continuously. Also, once the conveyor system is set up, it works well in all types of terrain. In addition to transporting regolith, the conveyor belt can be used to transport he maintenance crew and life support supplies to and from the excavation site. Finally, the conveyor supports can suspend electrical cables that supply power to the excavation equipment.

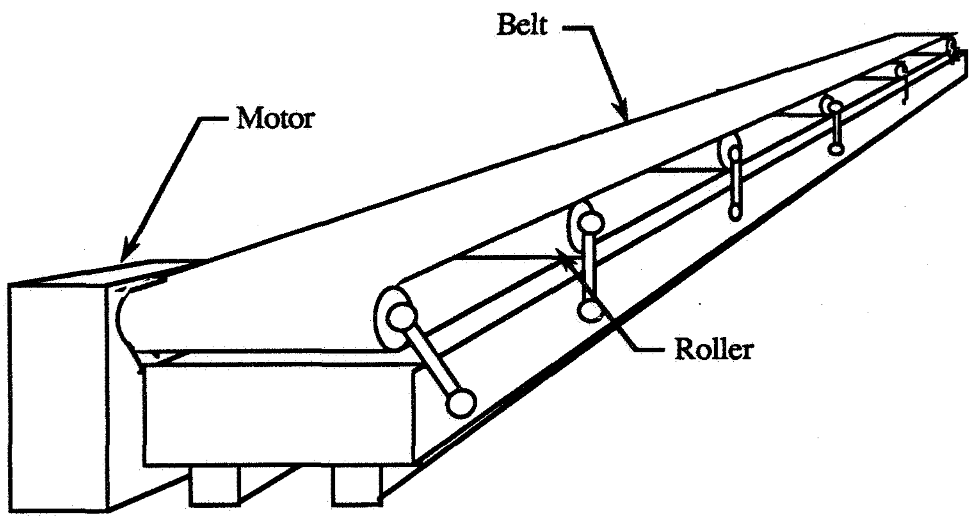

Figure 15. CONVEYOR BELT TRANSPORTER

There are, however, a number of disadvantages. First of all, initial installation for the conveyor belt requires much time and work. Also, once the system has been installed, it is not easy to move. Because of the extent of the initial installation work, the conveyor belt system is not suitable for transporting over long distances. Finally, the conveyor belt system is not modular and has many moving parts that must be shielded from radiation and the abrasive lunar dust.

4.3.3 Cable Tram

Another continuous transporting machine is the cable tram system shown in Figure 16. The system has a series of posts supporting several long cables on which trams travel. The tram lines are driven by a large motor. The cable slows down and speeds up cyclically to load and unload regolith from the trams.

Cable trams have essentially the same advantages and disadvantages as the conveyor belt system. However, cable trams are simpler than a conveyor system. A drawback of the cable trams is that they are not as continuous as conveyors since there is a discrete interval of time between trams.

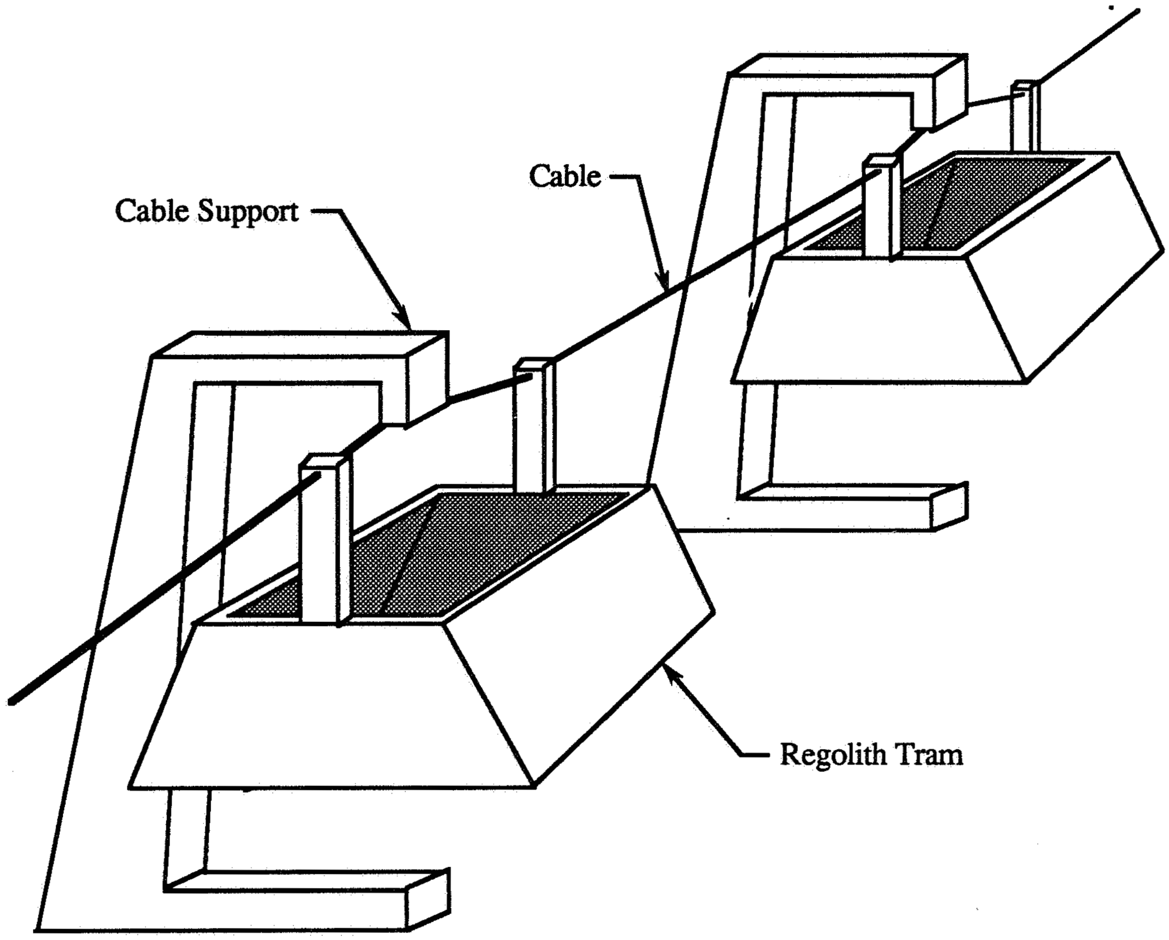

Figure 16. CABLE TRAM

4.3.4 Load-Haul-Dump

A load-haul-dump (LHD) is a machine capable of loading, hauling, and dumping regolith. The loader is a hydraulic shovel on the front end of the LHD. The shovel collects the loosened regolith and dumps it into a walled bed on the back of the LHD. Once the bed is full, the LHD hauls the regolith back to the processing site and dumps the regolith.

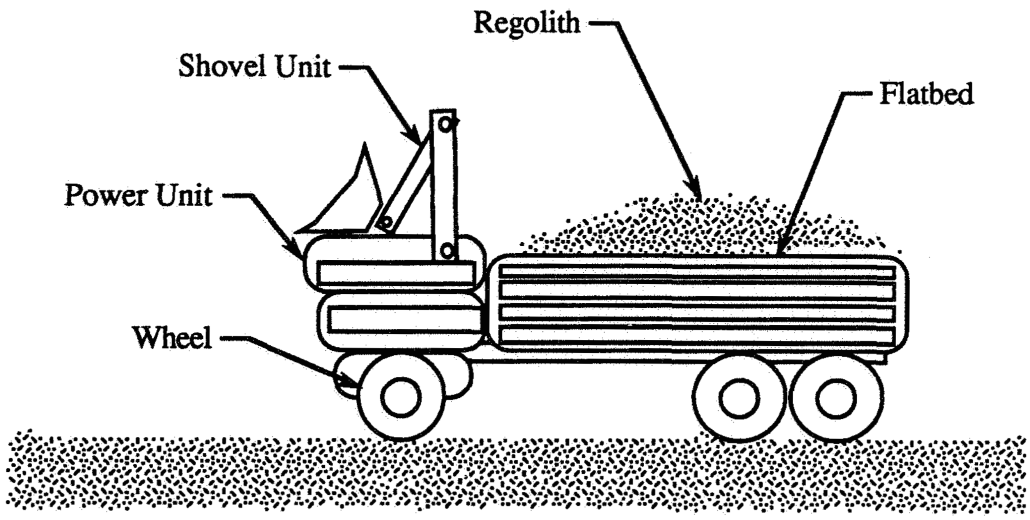

Figure 17. LOAD-HAUL-DUMP

Two variations of the LHD were considered. The first variation is shown in Figure 17. The shovel is permanently connected to the front of the equipment. The main disadvantage of this arrangement is that when the LHD is transporting the regolith to the processing plant, the shovel must be transported as well. This not only wastes energy by needlessly transporting the shovel to and from the processing site, but ensures that no collecting can take place during transporting.

The second variation of the LHD, shown in Figure 18, has a front loading shovel that can separate from the rest of the machine. When only transporting is required, the shovel unit can be detached. Another MDU can then be attached to the shovel unit to perform collecting or loading tasks. Therefore, several haul-dump (HD) units can share a common shoveling unit.

The most important advantage of the LHD is that it is multipurpose. The LHD can be used in other construction tasks, such as road and habitat construction. The LHD can also adapt well to different mining conditions. It can easily move from one excavation site to another and is useful in both highland and marial regions.

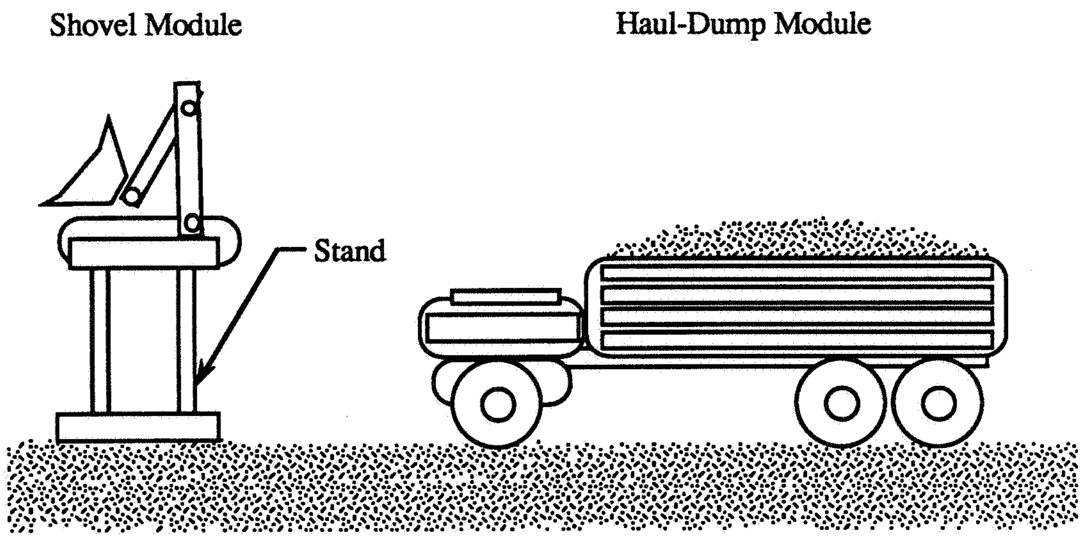

Figure 18. MODULAR LOAD-HAUL-DUMP

The major disadvantage of the LHD is that more than one haul-dump unit is required to make the excavating and transporting process continuous. Otherwise, collecting must stop while the collected regolith is transported to the processing site. Having more than one HD unit increases the mass and volume of this alternative.

Design Solution

The design team selected the scarifier to loosen regolith, the bucket conveyor to collect regolith, and the haul-dump unit to transport regolith. The decision matrices used to make these choices are shown in Appendix B. The calculation of all dimensions and power requirements is shown in Appendix C.

The complete design is shown in Figure 19. The scarifier and bucket conveyor are connected to one MDU and the regolith bin used for transportation is attached to another MDU. The scarifier has a variable depth of cut and organizes the regolith into a row to make collection easier. The depth of cut is varied by a rack and pinion gear system. The bucket conveyor is powered by a motor that receives electrical energy from the MDU.

The MDU is powered by fuel cells. Functioning modules can mechanically attach to the MDU. The MDU provides electrical power to the functioning modules through electrical cables.

The design uses hemispherical wheels as the drive mechanism. Cooling is achieved through heat radiation to deep space. The materials selected for the equipment are the titanium alloy Ti-6Al-4V and the aluminum alloy Ceralumin ASM. High stress applications will use Ti-6Al-4V while low stress applications will use Ceralumin ASM. The equipment is controlled through tele-operation from the lunar base.

5.1 Operation

The complete excavation and transport system is shown in Figure 19. The MDU consists of four wheels, a frame, and fuel cells. Functioning modules of the MDU, such as the regolith bin and the scarifier/bucket conveyor assembly, are permanently attached to frames that can mechanically attach to an MDU.

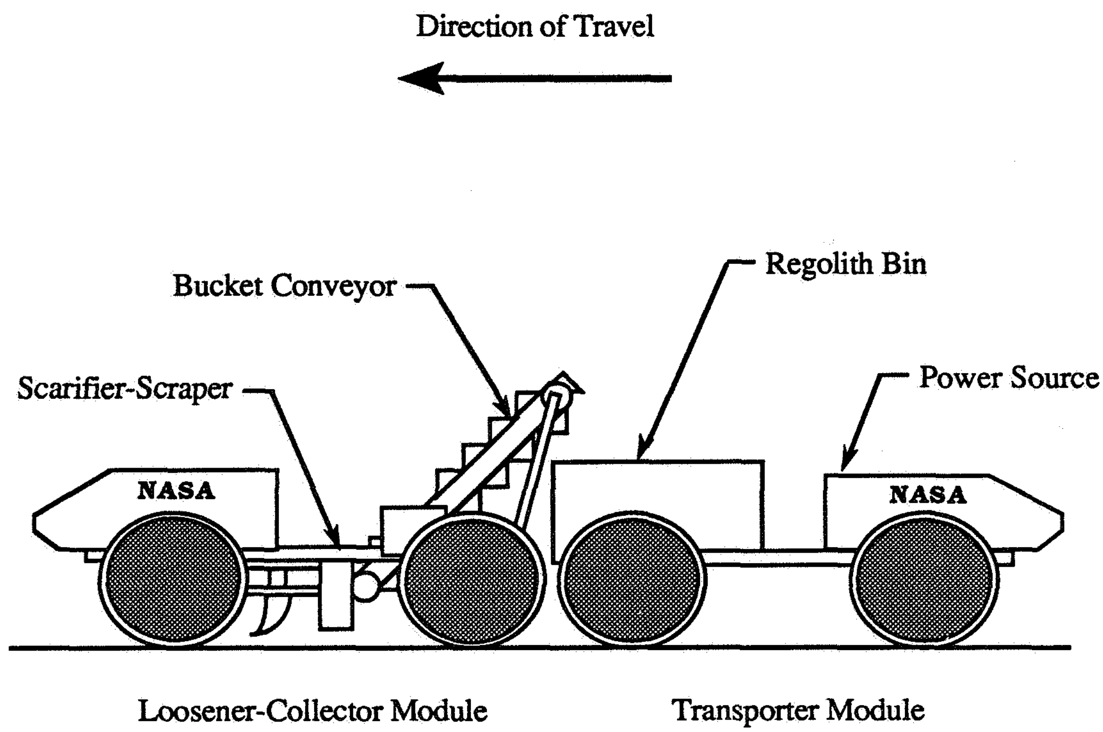

Figure 19. COMPLETE DESIGN

The scarifier loosens by disrupting the regolith. The scarifier is followed by scrapers that push the loosened regolith into an aisle. Next, an inclined plane attached to the bottom of the bucket conveyor funnels the regolith upward and into an even narrower aisle. The bucket conveyor moves the regolith from the top of the inclined plane to the regolith bin.

The overall power of the excavation and transportation system can be minimized by using five HD units (see Appendix C). At any time, one HD unit is following the scarifier/conveyor belt assembly while four HD units are moving regolith to and from the processing plant. The HD unit behind the scarifier/conveyor assembly is powered independently. If necessary, the HD unit can be used to provide extra traction.

5.2 Loosener

A scarifier was selected to loosen the regolith. Scrapers are attached to the scarifier to push the regolith into a central aisle. The regolith is put into an aisle for two reasons. First, the collector can be narrower and smaller than would otherwise be possible, which decreases the equipment mass. Secondly, the buckets of the bucket conveyor fill easier when the regolith is organized into a row.

5.2.1 Selection

The alternatives considered for loosening the lunar regolith were a bladed roller, explosives, an auger, and a scarifier.

Explosives were eliminated because they are untested on the moon and are potentially dangerous. The auger was eliminated for two reasons. First, the stationary auger will not loosen effectively. The regolith will pile up in front of the auger rather than move through the threads of the auger blade. Secondly, the power requirement of the rotating auger will be very high. The bladed roller was eliminated because it will not loosen effectively. The blades will not cut deep enough into the surface since the resistance force from the regolith will push the blades out of the lunar surface. If more mass is added to the bladed roller, there will not be enough power available for the roller to move forward. The scarifier was selected since it is reliable, simple, and effective. Also, the scarifier does not have the disadvantages of the other alternatives.

5.2.2 Configuration

The scarifier is a platform of blades that is dragged between the power module and bucket conveyor. The scrapers are attached behind the scarifier blades (see Figure 20).

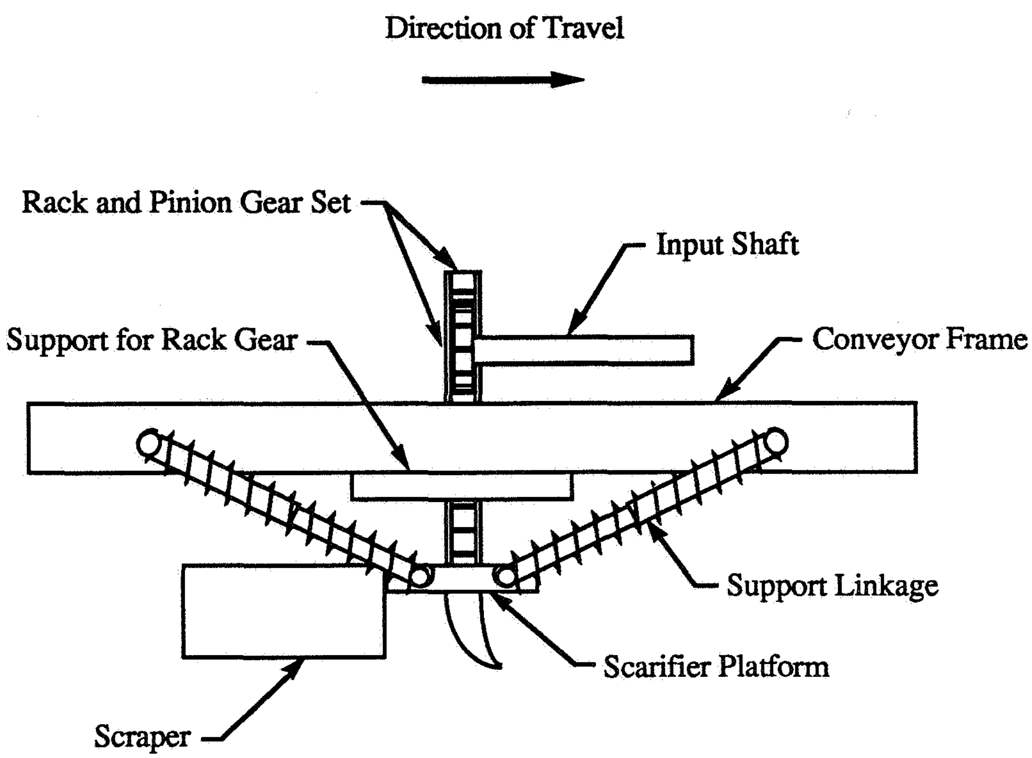

Figure 20. SCARIFIER LOOSENER

The support linkage shown in Figure 20 are coil springs. During operation of the scarifier, the linkages offer lateral support to the scarifier while allowing the scarifier to move up and down. The scrapers shown in Figure 21 are located just behind the blade platform and organize the loosened regolith into a central aisle. The scarifier blades are detailed in Figure 22.

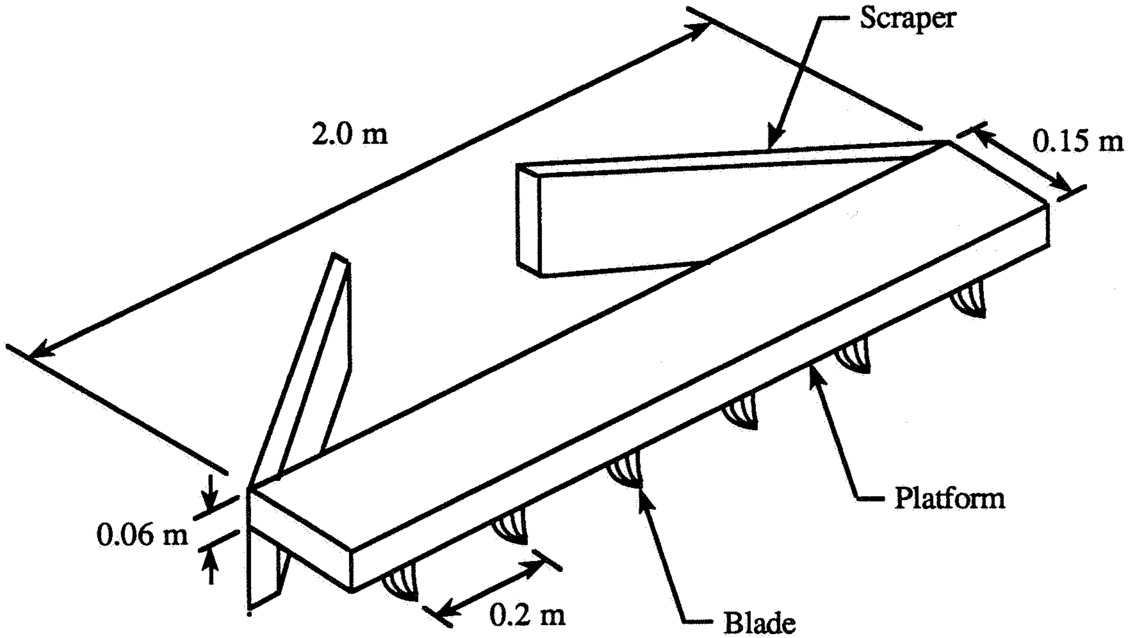

FIGURE 21. SCARIFIER PLATFORM DIMENSIONS.

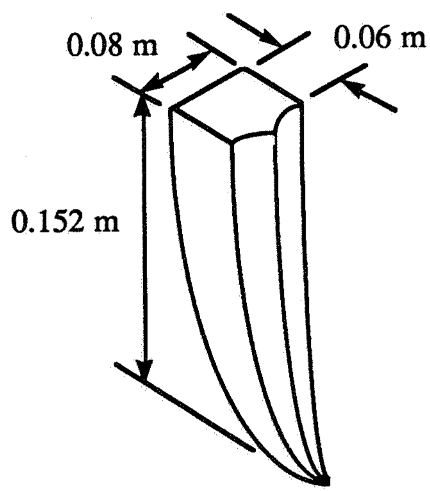

FIGURE 22. SCARIFIER BLADE DIMENSIONS.

5.2.3 Mass

The total mass of the scarifier is 184.8 kg. The mass of the separate scarifier components is shown in Table 2.

Table 2

Breakdown of Mass of Scarifier Components

Parts	Mass (kg)
Blades	6.5
Platform	53.2
Scrapers	35.1
Miscellaneous *	90.0
Total	184.8

* estimation of mass for support linkages, gears, nuts, bolts, etc.

5.2.4 Attachment

The support linkages attach the scarifier to the frame of the bucket conveyor. Hooks at the ends of the coil springs attach to pins on the conveyor frame. Telescoping supports are placed within the coil springs to prevent buckling when the platform is raised. The telescoping support rotates about the pin when the platform depth is varied.

5.2.5 Operation

The scarifier is dragged through the regolith like a rake. The regolith is disrupted by the blades and is forced into an aisle by the scrapers.

The scarifier has a variable depth of cut. The advantage of having a variable depth of cut is that if vehicle traction is lost, the platform can be raised to decrease the force resisting motion. In addition, the platform can be raised to avoid large rocks in the regolith. Depth is varied by rotating a gear on the input shaft as shown in Figure 24. The input shaft must be held stationary while the scarifier is loosening.

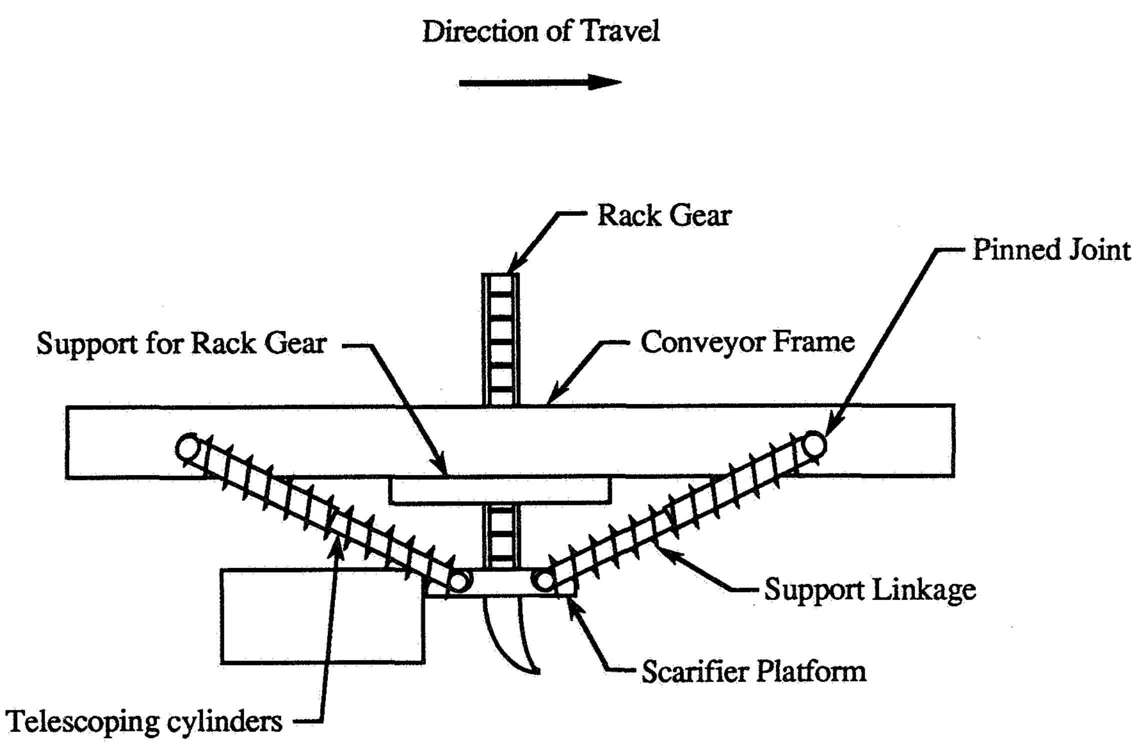

Figure 24. CONNECTION OF SCARIFIER TO FRAME

5.3 Collector

The collector selected is a bucket conveyor. The bucket conveyor is powered by a motor that receives electrical energy from the MDU. The bucket conveyor connects mechanically to the MDU. An inclined plane is attached to the bottom of the conveyor to force the loosened regolith onto the conveyor and into the buckets. The combined action of the scarifier scrapers and inclined plane of the bucket conveyor allows for a bucket conveyor of minimal width.

5.3.1 Selection

The four alternatives for collectors were the front-end loader, bucketwheel, inclined plane, and conveyor. The front-end loader was eliminated because it is time inefficient. The front-end loader can either be picking up regolith or moving regolith to the storage area, but not both. Also, the front-end loader requires precise control and so needs constant supervision. The lunar outpost will not have enough people available to have one person constantly controlling the front-end loader.

The inclined plane collector is not feasible because there is insufficient traction available on the moon. The inclined plane moves regolith forward as it is moving regolith up the inclined plane. The force required to move the regolith forward directly opposes traction and will cause the collector to slip.

A bucketwheel requires a conveyor belt to move regolith away from the bucketwheel to the storage area. Since the bucketwheel alternative includes a conveyor, it has the disadvantages of both the conveyor plus the disadvantages of the bucketwheel itself. Therefore, the bucketwheel was eliminated in favor of the conveyor.

The conveyor, however, also has a major drawback. The angle the conveyor makes with the ground may not exceed the angle of repose of the regolith (about 45°) or else the regolith will not move up the conveyor. In order to resolve this problem, the design team chose the conveyor alternative and added buckets to the conveyor. The buckets do not greatly increase the power requirements of the conveyor, yet allow the conveyor to be tilted at angles greater than the angle of repose of the regolith.

A short inclined plane (not shown) is attached at the bottom of the bucket conveyor to move the regolith up to the bucket conveyor. A short inclined plane does not push enough regolith forward to cause traction failure. Also, the inclined plane funnels the regolith into a narrower path to allow the use of a smaller bucket conveyor than could otherwise be used.

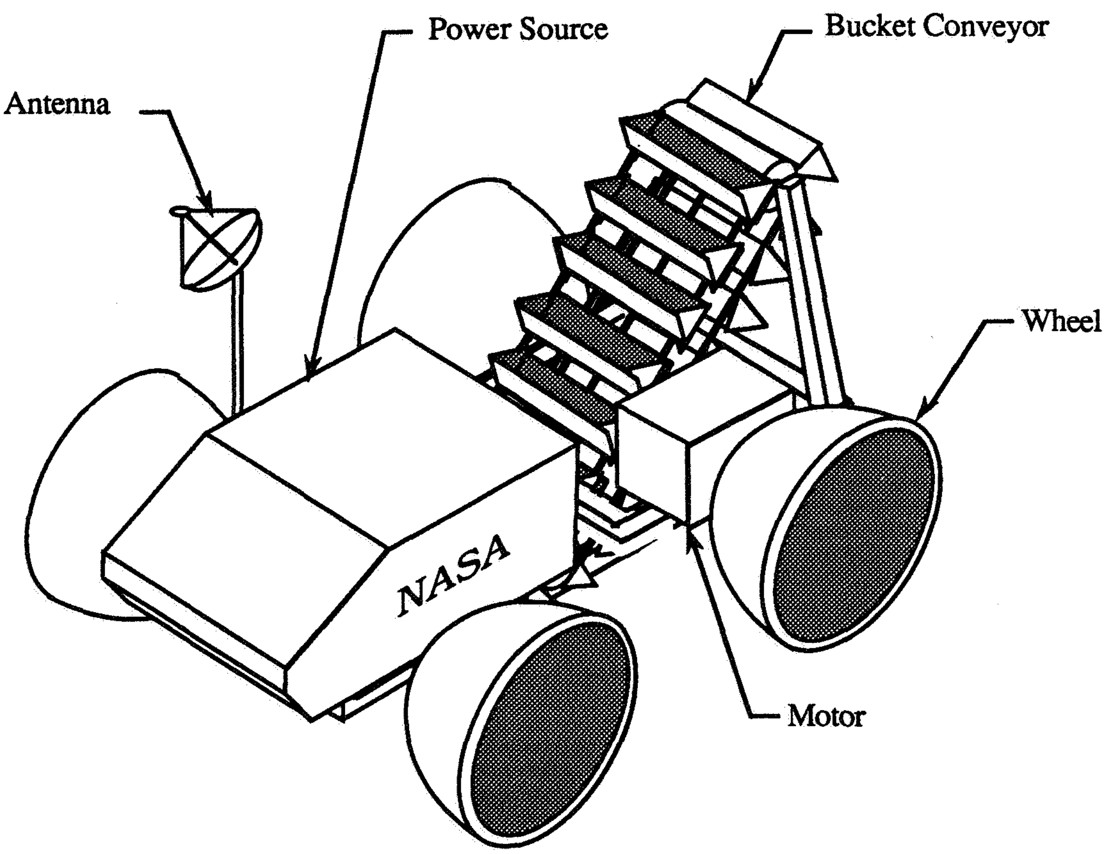

Figure 25. BUCKET CONVEYOR COLLECTOR

5.2.2 Configuration

The bucket conveyor is shown in Figures 26 and 27. The conveyor is powered by an electric motor that gets its energy from the MDU. The motor turns the powered sprocket which drives four chains. Buckets are attacked to the chains. Since the size of the buckets is large relative to the radius of the sprockets, the buckets are hinged so that they can travel around the sprockets. The hinged buckets do not need to bend around the radius of the sprocket, but only stay attached to the hinge as it moves around the sprocket. The entire conveyor belt arrangement is attached to a frame that can attach to an MDU.

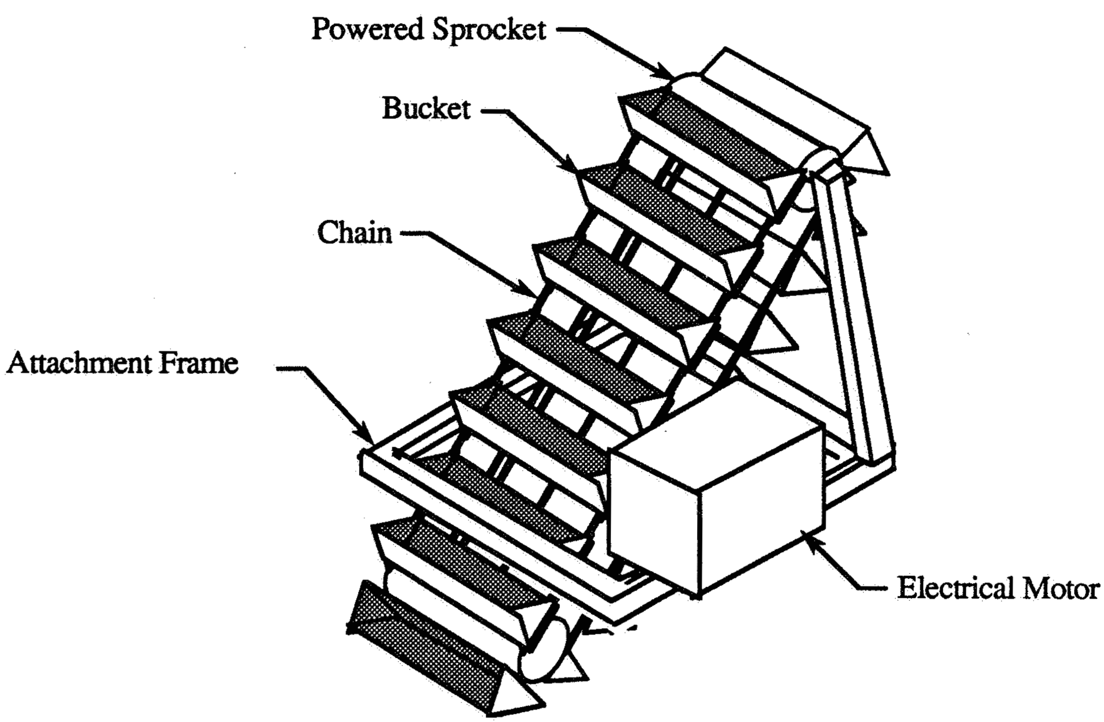

Figure 26. CONFIGURATION OF BUCKETWHEEL CONVEYOR

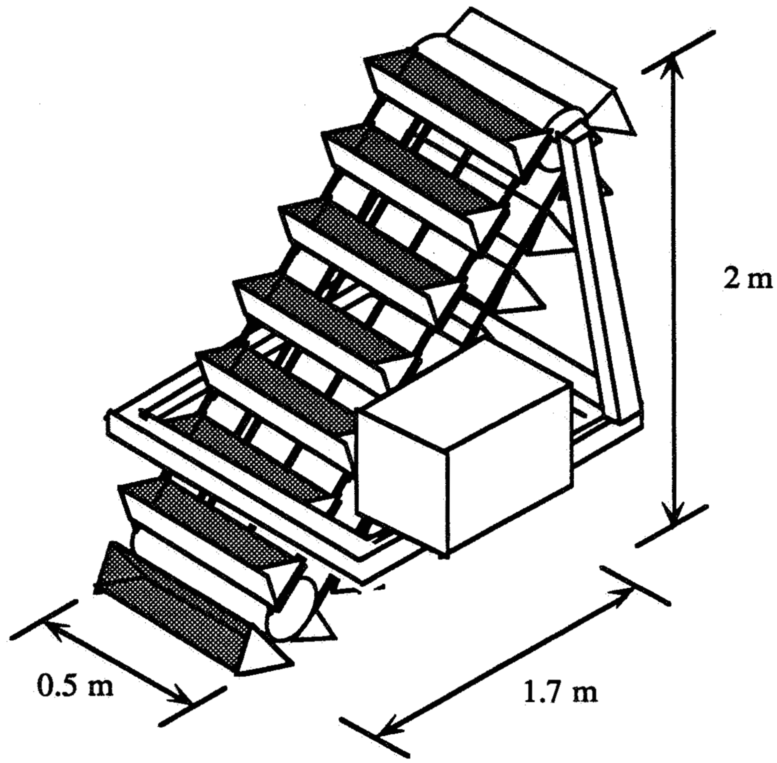

Figure 27. DIMENSIONS OF BUCKET CONVEYOR

5.3.3 Mass

The mass for the different components of the bucket conveyor is shown in Table 3. The miscellaneous parts category accounts for the number of smaller parts that are part of the bucket conveyor.

Table 3

Mass of the Bucket Conveyor

Parts	Mass (kg)
Chains	47
Pulleys	162
Buckets	259
Miscellaneous	70
Total	538

* estimation of mass for support linkages, gears, nuts, bolts, etc.

5.3.4 Power Transmission

Electrical energy from the MDU is used to power the motor for the conveyor. Power must be transmitted from the turning motor shaft to the powered roller of the conveyor. The two main devices used to transmit torque from one location to another are gears and flexible elements. Gears are very rugged and durable. Their power transmission efficiency is as high as 98 percent. However, gears are massive and more expensive than flexible elements.[28]

Flexible elements include belts and chains. Flexible elements permit power to be transmitted between shafts that are separated by a large distance. Flexible elements are a light-weight means to transmit torque from one location to another.[29]

Flexible elements are a better choice than gears for use on the bucket conveyor since gears are relatively mass intensive. Flexible elements are best for transmitting power over a large distance, which is a requirement for the bucket conveyor. Chains are easier to repair than belts. If a link in a chain breaks, only that link needs to be replaced. If a belt breaks the entire belt must be replaced. Belts are usually used for either high-speed machines or for short distances. Therefore, chains were chosen to transmit power from the motor to the powered roller of the conveyor.

5.3.5 Storage Area

The regolith storage area can either be in the form of a rigid bin or a bag. Normally, rigid bins will be used as the storage area since they are easy to connect and disconnect for transportation purposes. Also, bins are mechanically simple and can carry a large volume of regolith. By contrast, bags are difficult to fill and difficult to connect to transportation vehicles. Bags can only contain a limited volume of regolith. However, the advantage of using bags is that they can be used directly for radiation protection of the habitat. By filling the bags directly, a step between excavation and placement of the regolith bags is eliminated. Furthermore, no additional equipment is required to fill the radiation protection bags.

The design team decided to use bins since bins will be needed for most of the time the excavation and transport equipment will be operating.

5.3.6 Operation

The bucket conveyor is located directly behind the scarifier. The inclined plane moves the regolith up to the bucket conveyor. The bucket conveyor turns continuously to move the regolith from the inclined plane to the top of the conveyor. At the top of the conveyor, the regolith falls off of the conveyor into the storage area.

5.4 Transporter

The haul-dump (HD) was selected to transport the collected regolith. The HD is the LHD without the front-end loader. The front-end loader is not necessary since another collector, the bucket conveyor, has been selected.

5.4.1 Selection

The four alternatives for transportation equipment were a lunar lander, conveyor belts, cable trams, and a haul-dump system. The lunar lander was eliminated because of its extremely high power requirement. Up to ninety percent of the lunar lander weight is propellant fuel.

Conveyor belts and cable trams are very similar. The main difference is that the cable trams are simpler while the conveyor belts are more continuous. These two alternatives were compared with the haul-dump system. Cable trams and conveyor belts do not require much manpower once they are set up and can carry a large volume of regolith. However, the cable trams and conveyors were eliminated due to their inflexibility to changing excavation sites and complexity of set up. The haul-dump system was selected because it is multipurpose and adaptable to different terrain.

5.4.2 Configuration

The HD consists of an MDU and a regolith bin. The MDU is discussed in section 5.5. The regolith bin attaches to the frame of the MDU as shown in Figure 28. The regolith bin is shown in Figure 29. The bin is joined to the frame at the two corners of the rear side by pinned joints. The front two corners are connected to the frame with locking pins. When the pins are unlocked, the bin can be tilted by a hydraulic jack to unload the regolith. The walls slant outward to make loading and unloading of the regolith easier.

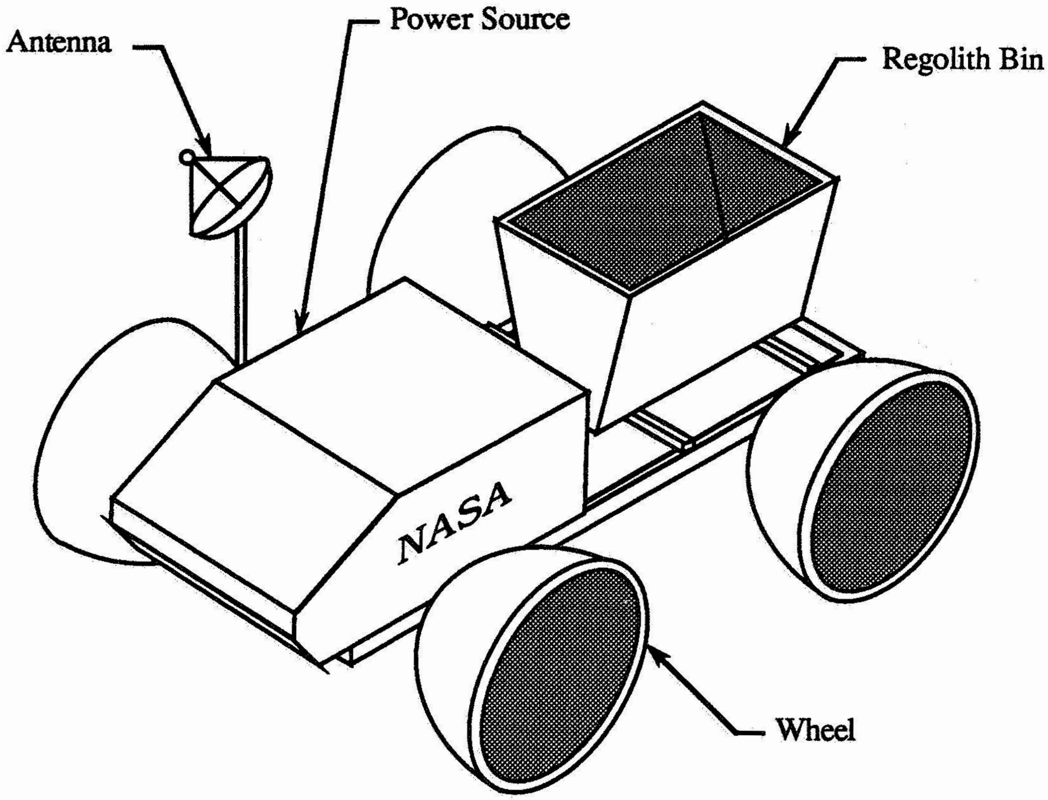

Figure 28. HAUL-DUMP SYSTEM

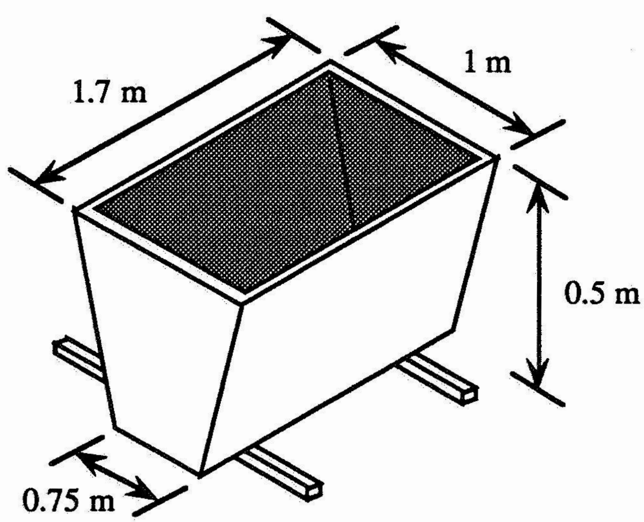

Figure 29. REGOLITH BIN

5.4.3 Mass

The mass for the different components of the transportation equipment is shown in Table 4.

Table 4

Mass of Transportation Components

Component	Mass (kg)
Bin	103
Frame	145
Wheels	538
Control Unit	20
Fuel Cells	740
Total	1546

5.4.4 Operation

Once the regolith bin is full, the HD transporter hauls the regolith to the processing plant. An empty HD transporter takes the place of the full HD transporter. At processing site, a hydraulic jack will tilt the transportation bin to unload the regolith. The empty transportation bin is then returned to the excavation site to follow the collector module.

5.5 Power Requirements

The excavation unit requires about 22 kW while the transportation unit requires about 35 kW. The power requirements were determined assuming a rate of collection of 62.5 m^3/hr, an excavation speed of 0.25 m/s, a depth of cut of 0.15 m, a load of 1960 kg for the transporter, and a speed of 14 m/s for the transporter.

The power required for the excavation unit is the sum of the power required for loosening and collecting. The power required for the transporter is the sum of the power lost due to friction, wheel deformation, and drawbar-pull. Drawbar-pull is power required beyond the power requirement for motion. For example, drawbar-pull will be needed for accelerating and moving up inclines.

5.6 Main Drive Unit

Each function module requires electricity to work. Electricity is needed to power the motor of the conveyor bucket, to move the scarifier up and down, and to move the transportation bins. The MDU consists of the power source, function module attachment, power transmission cables, and frame.

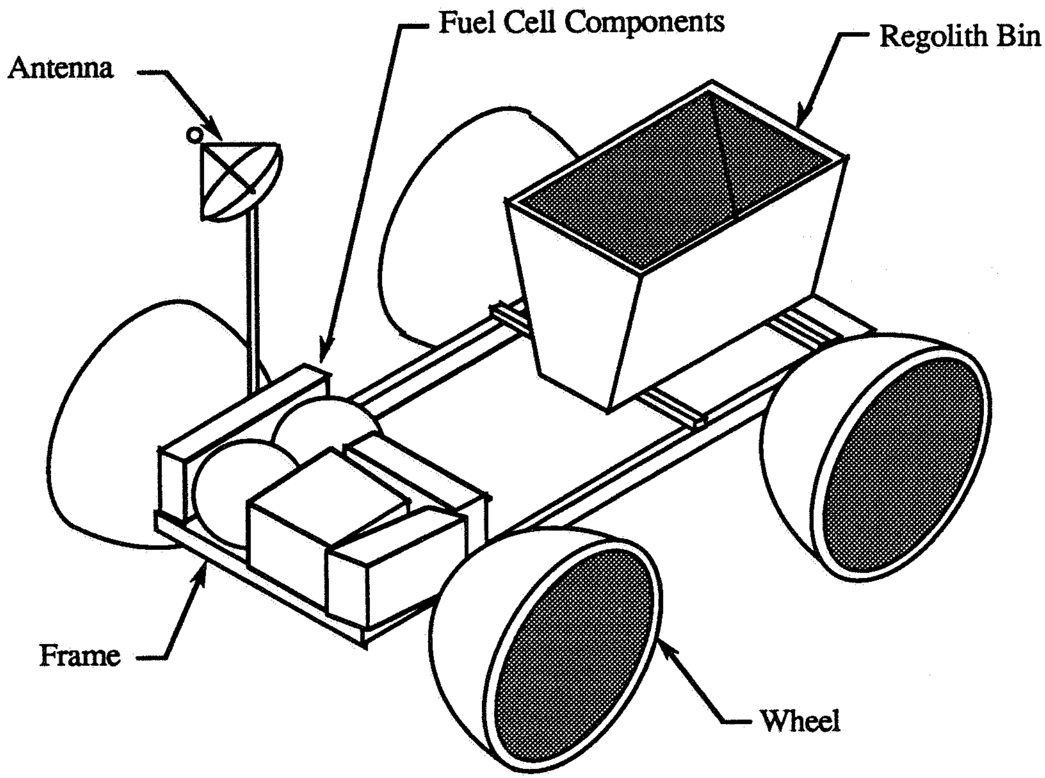

Figure 30. FUEL CELLS OF THE MAIN DRIVE UNIT

5.6.1 Power Source

Power from the moon can be derived from solar panels, a nuclear power generator, batteries, and fuel cells. The power source has to be light and deliver sufficient power.

Solar panels take advantage of the long lunar days. However, solar panels cannot deliver the required power without being excessively large. The Gallium Arsenide solar cell, for example, is only about 18% efficient and provides 200 watts of energy for every square meter of cells. Currently, even the most advanced solar cells are only 31% efficient.[30] Therefore, a very large solar panel would be needed to generate enough power for the excavation equipment. Furthermore, the solar panels would be exposed to damaging cosmic radiation and meteors.

A nuclear power system for the spacecraft, called the Dynamic Isotope Power System or DIPS, is currently being developed jointly by the Department of Energy, the Air Force, and the Strategic Defence Initiative Office. The DIPS can produce up to five kilowatts of electricity and weighs about 400 kilograms.[31] However, nuclear power generators pose safety problems. The nuclear power system will give off gamma radiation and is susceptible to melt-downs. In addition, the nuclear power system is opposed politically.

Batteries are simple and safe. However, batteries are also high in mass. To generate the required 35 kilowatts of power for the mining operation, a zinc-silver battery would weigh 7.5 metric tons.[32]

Fuel cell technology is well developed and has been used in previous space programs. Each fuel cell can deliver about 1000 watts of power and weighs about 20 kg.[33] Fuel cells are regenerated with hydrogen and oxygen, elements which will eventually be produced on the moon. Fuel cells are recommended for the excavation equipment because of their small mass, high power output, and high safety.[34] A supplement will be provided to the sponsor that describes fuel cells.

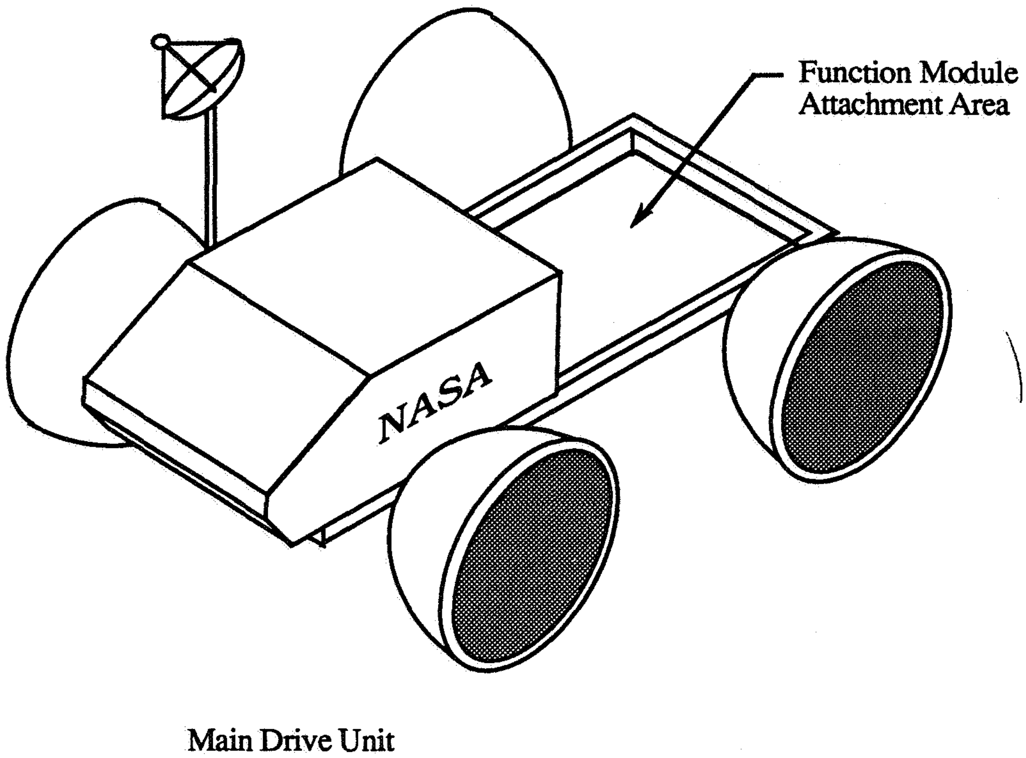

Figure 30. MAIN DRIVE UNIT

5.6.2 Control Unit

The MDU will be tele-controlled from the lunar base. The control unit houses the antenna, signal processor, and transmitter of the MDU. Control signals received from the lunar base will be processed and sent to the function module actuators to perform the desired task.

5.6.3 Power Transmission Cables

Actuators and motors will be located as near the function modules as possible so that power will not need to be transmitted mechanically from the power module. Instead, power can be transmitted electrically through cables to the actuators and motors.

5.6.4 Frame

The power source, function module, and control unit will be situated on the MDU frame as shown in Figure 32. The dimensions of the MDU frame are based on the requirements of the bucket conveyor since the bucket conveyor is the largest function module.

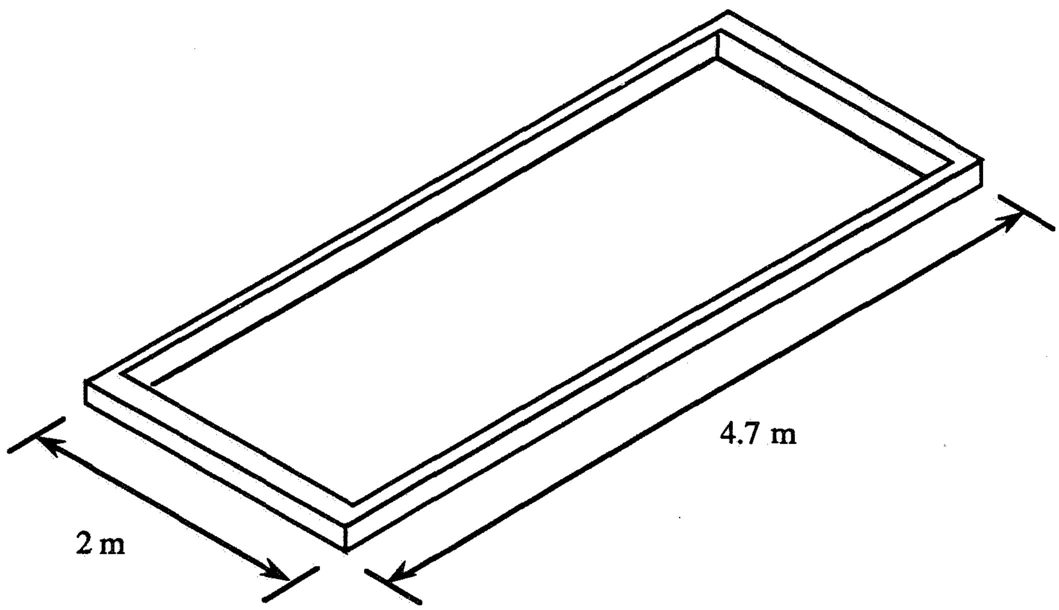

Figure 32: FRAME FOR THE MDU

5.6.5 Mass Calculations for the mass of the MDU were based on on the MDU's dimensions, as shown in Appendix C. The total mass of the MDU, including the power source and wheels, is 3500 kg.

Table 4

Mass of the MDU

Component	Mass (kg)
Regolith Bin	103
Wheels	538
Frame	145
Fuel Cells	725
Control Unit	20
Total	1328

5.7 System Characteristics

There are several characteristics that are common to all units of the excavation equipment. These characteristics are the drive mechanism, cooling, materials, control, and storage of equipment.

5.7.1 Drive Mechanism

In determining the drive mechanism, the design team examined literature that discussed lunar drive mechanisms. The two main types of drive mechanisms for use on the moon are wheels and tracks. For wheels, the literature agrees that hemispherical wheels (see Figure 26) are the best type.[39, 40] Hemispherical wheels are durable and mechanically simple. Also, hemispherical wheels have low stress concentrations at the shaft joint.[35]

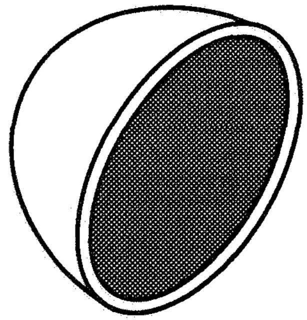

Figure 26. HEMISPHERICAL WHEEL

Tracks have better traction than wheels.[36] Also, tracks are less likely to sink into the soil (see Appendix D, which discusses traction). However, tracks have many moving parts that require sealing from the lunar environment and lubrication. Tracks are also mechanically complex. In addition, tracks disturb the surface more than wheels. If a vehicle with tracks moves over a road very often, the road will need high maintenance.

Hemispherical wheels were selected as the drive mechanism because of the disadvantages of tracks. Hemispherical wheel will provide sufficient traction and are less massive and complicated than tracks.

5.7.2 Materials Selection

The materials used for lunar excavation and transportation equipment must be able to function in the lunar environment. Materials that have been used in the past for lunar applications are alloys of aluminum, beryllium, iron, magnesium, titanium, cobalt, molybdenum, and tungsten. The refractory metals cobalt, molybdenum, and tungsten were not considered because they are very heavy and expensive. In addition, molybdenum and tungsten are very brittle. The materials considered were alloys of aluminum, beryllium, iron, magnesium, and titanium.

Aluminum alloys. Aluminum alloys are lightweight and strong. Aluminum alloys are excellent heat conductors, which reduces thermal stresses at high temperatures Also, aluminum alloys are insensitive to radiation, do not sublimate (lose mass) significantly in the lunar vacuum, and are corrosion resistant.[37]

Beryllium alloys. Since beryllium alloys are brittle, they are highly susceptible to damage from meteorite bombardment. Vibration and impact of brittle materials tend to propagate cracks and cause catastrophic failure.[38]

Iron alloys. Iron alloys (steels) are strong but have a low strength-to-weight ratio. Also, steels corrode when exposed to oxygen, which will cause problems for parts in contact with the oxygen-rich regolith.

Magnesium alloys. Magnesium alloys suffer significant material loss (0.01 cm/year) at high temperatures in a vacuum.[39] This loss of material will drastically reduce strength.

Titanium alloys. Titanium alloys are expensive, but very strong. In addition, they are resistant to corrosion, have a high strength-to-weight ratio, and do not easily propagate cracks. Titanium alloys also are ductile.[40]

Titanium alloys were selected for use in high strength applications. Aluminum alloys were selected for use in non-critical areas of the design.[41] The physical properties of the particular alloys chosen are shown in Table 5 below.

Table 5

Physical Properties of Materials for Lunar Excavation Equipment

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Density (g/cc)
Ceralumin ASM	300	170*	2.56
Ti-6Al-4V	1117	1000	4.42

* Proof Strength Value

√

5.7.3 Cooling and Lubrication

The lunar environment presents problems for the cooling and lubricating of equipment. These problems and possible solutions are discussed in this section.

Cooling of Equipment. The three ways to transfer heat are conduction, convection, and radiation. Because there is no air on the moon, equipment cannot be convectively cooled. Therefore, the two types of external heat transfer possible on the moon are conduction and radiation. The surface temperature of the moon during the lunar day ranges up to 127 °C, but below a depth of one meter the temperature is approximately constant at -50 °C.[42] Therefore, the moon itself is a possible heat sink for conduction. However, since lunar regolith is a strong thermal insulator, an external path is needed to conduct heat from the equipment to beneath the surface. There is no practical way to have a mobile ground to a meter below the surface, so the lunar surface cannot be used as a conductive heat sink.

Radiation is the best way to conduct heat on the moon. An ideal heat sink for radiation is free space. Heat is convected from the hot areas of the equipment in a closed piping system using gas or liquid. The heat is piped to a radiator, where excess heat is radiated into free space. Free space has an unlimited capacity for heat absorption. However, present vacuum heat radiators are less effective than atmospheric heat radiators.[43] More research is needed to develop an efficient cooling mechanism for lunar equipment.

One promising radiation cooling system being developed for space applications is 50% lighter than comparable heat radiators.[44] More information on this radiation cooling system is given in a supplemental report.

Lubrication of Equipment. Dry film lubricants will be used instead of liquid lubricants since liquids will vaporize if accidently exposed to the vacuum environment of the moon. Possible lubricants include graphite, molybdenum disulfide, and polytetraflourothylene (PTFE). These materials can be used in a vacuum environment, under a radiation flux, and over a wide range of temperatures. All of these materials are available as powders and can be applied dry.

Graphite has a low coefficient of friction, but needs to have an adsorbed film of moisture on the surface to work effectively. Without this film, it acts as an abrasive. In addition, the graphite lubricant causes corrosion of aluminum surfaces.[45]

Molybdenum disulfide is best applied as a resin bonded film. It provides a coefficient of friction of 0.0025 to 0.035 at temperatures from -38 °C to 816 °C.[46]

PTFE can be applied as a thin coating to the parts to be lubricated and heated to fuse the lubricant into a coating. It provides a coefficient of friction of 0.004 and can withstand loads up to 345 MPa before breaking down. It can be used at temperatures up to 316 °C.[47]

The design team decided to use resin bonded molybdenum disulfide for lubrication purposes because of its low coefficient of friction and wide temperature range for operation. PTFE has a higher coefficient of friction and a lower operating temperature range than molybdenum disulfide. Graphite is not a feasible solution since it corrodes aluminum and is abrasive in a dry atmosphere.

5.7.4 Control

Lunar equipment can be operated using any of the following methods:

1) On-equipment control
2) Tele-control from earth
3) Tele-control from the lunar base
4) Automation

The merits of each method for controlling lunar excavation and transportation equipment are discussed below.

On-Equipment Control. Terrestrial equipment is predominantly controlled by an on-equipment operator. On-equipment control allows for precise control of equipment, but is labor intensive. On the moon, human time is very valuable, so little labor can be spared. Furthermore, on-equipment control exposes the operator to the harsh lunar environment.

Tele-Control from Earth. The second method of lunar equipment control is tele-control from earth. Video transmitters located on the lunar equipment relay the on-site images via microwaves to a receiver on earth. The control signal for the equipment is then sent from Earth. This method of control has been used effectively in controlling the Voyager series spacecraft and the Mars surface probe.[48]

Tele-control from earth does not work well for equipment that requires precise position control since there is a 2.6 second time lapse between transmission of the video signal and reception of the control signal. The Soviet space team experienced severe problems in using tele-control from earth during the Lunokhod lunar surface explorer mission. The Soviet rover nearly collided with the lunar lander and later was accidently destroyed by driving over a cliff.[49]

Tele-Control for the Lunar Base. The third method of lunar equipment control is tele-control from the lunar base. Tele-control from the lunar base provides more accurate control than tele-control from earth and isolates the controller from the operating environment. Control accuracy is better since the time lapse is much less between the equipment and the lunar base than between the equipment and earth. Tele-control is used on Earth to handle hazardous materials such as toxic waste.

Tele-control from the lunar base, however, is labor intensive. In addition, a tele-operated excavation site either has to be within "sight" of the lunar base or the signal has to be transmitted to the base by a series of "line-of-sight" relay transmitters.[56] Since the moon has no ionosphere, transmitted signals are not bent around the lunar horizon.

Automation. The last method of control for lunar equipment is automation. This method of control requires the equipment to be intelligent enough to make decisions such as how to move around a rock that cannot be loosened or what to do when the collecting bin is full. Automation does not expose an operator to the hazards of the lunar environment, requires no manpower, and does not limit location of the excavation site. However, the technology to fully automate moving equipment is not yet developed.

Presently, the most feasible solution is to operate the lunar excavation and transportation equipment by tele-control from the lunar base. The technology is well-developed and has been used effectively. Therefore, the design will be tele-operated from the lunar base.

5.7.5 Storage of Equipment

The excavation and transport equipment performs during the lunar day. During the lunar night, the machinery must either be protected from the extreme cold or be designed to withstand it Once the base is well-established, there will be a maintenance building that the equipment can be parked in during the night. This building will protect the equipment. However, there will not be a maintenance building available initially. Therefore, the extreme cold was taken into consideration when designing the equipment. Specifically, solar night conditions were taken into consideration when choosing materials and type of lubrication.

Conclusion for Design Solution

The information presented satisfies the project requirements. The elements found in the lunar regolith have been characterized and the power requirements for excavation have been determined. Excavation equipment has been designed. The scarifier was selected to loosen, the bucket conveyor was selected to collect, and the haul-dump was selected to transport. Five of the more important aspects of the excavation and transportation equipment are discussed below.

6.1 System Mass

The total mass for the design is 5725 kg, which is high. The most massive component of the design is the MDU. The fuel cells that are used as the power source are very mass intensive. While mass was a criteria in the decision-making process, the time constraints of the project did not allow enough time to optimize the machinery for minimum mass. A mass optimization and careful materials selection would reduce the mass of the design.

6.2 Power Requirements

The power required for the scarifier/conveyor equipment to operate is about 35 kW. The power required for the transportation equipment to operate when fully loaded is also about 35 kW. This power requirement is very high and should be viewed as an upper limit for the power required. A design that more carefully minimized mass and optimized the scarifier and conveyor designs with respect to efficiency would require significantly less power.

6.3 Material Selection

The materials were selected for the structural components of the design. Since the design is conceptual, there was no attempt to specify materials for each part of the machinery. The materials selected can withstand the harsh lunar environment while providing structural support. However, a more extensive and thorough materials selection for each part of the equipment is required.

6.4 Machine Versatility

The excavation and transport equipment is versatile since it can be used in any construction task to collect and move regolith. The MDU is versatile since modular functioning devices can attach to it. Also, the fuel cells can be detached and used for power in the lunar habitat during the lunar night. The scarifier is only useful for loosening an d the bucket conveyor is only useful for loosening.

6.5 Operation

An MDU pulls the scarifier and bucket conveyor. A second MDU moves behind the bucket conveyor and carries the transportation bin. If necessary, the second MDU can push the loosener/collector assembly to provide extra traction. When the transportation bin is full, the second MDU leaves to go to the processing site and an empty transportation MDU comes to move behind the bucket conveyor.

Recommendations

The design team makes five recommendations:

1) Research lunar soil mechanics
2) Add beneficiation to the excavation process
3) Investigate rock management
4) Research automation of lunar equipment
5) Develolp a bagging system

Each of these recommendations is discussed below.

7.1 Research Lunar Soil Mechanics

The design team could not develop relationships that were entirely reliable due to the lack of detailed information about lunar soil mechanics. Tests need to be performed to determine the variation of properties with depth, not just average values. Information about cohesion and friction would be particularly helpful.

7.2 Add Beneficiation to the Excavation Process

When excavation is performed in order to recover oxygen, only the fine portion of the regolith will be needed. The fine portion, which consists of particles less the one centimeter in diameter, contains loose single crystals of ilmenite that may be collected without crushing hard rocks. Therefore, the regolith will need to be beneficiated in order to remove the larger part of the regolith. One way to beneficiate the regolith is to have a sieving operation on the excavation equipment. Magnetic beneficiation is one possibility since the regolith has a weak electrostatic charge. Mechanical sieving through a screen is another possibility

7.3 Investigate Rock Management

A tacit assumption the design team made is that no rocks get in the way of the equipment. In reality, this is not a good assumption. Rocks cover the outer surface of the moon. A method for handling the rocks needs to be devised. One possible solution is an attachment to the front of the equipment that can crash any rocks that are in front of the equipment. A powered drill or type of jack hammer could also be used to crush rocks. Another method is to add a step to the excavation process. The area to be excavated could be prepared for the excavation process by removing all of the rocks from the area.

7.4 Research Automation of Lunar Equipment

More research needs to be done on the automation of lunar equipment on the moon. A possible solution is to partially automate the equipment. The equipment functions automatically until encountering a problem such as an immovable rock. The equipment then transmits a signal to the lunar base to alert a human operator. The human operator would then solve the problem using tele-control. Partially automatic equipment is less labor intensive than tele-control from the lunar base. Similarly, tele-control from earth is an improvement over tele-control from the lunar base. However, both of these options require the development of new technology. The equipment must either be able to act independently or operate slow enough that the time delay from earth would not cause problems.

7.5 Develop Bagging System

A bagging system should be developed that can attach to the excavation and transportation equipment. A bagging system that attaches directly to the excavation and transportation equipment would eliminate a step between the excavation and placement of the radiation bags that will be used to radiation shield the habitat. Also, there will be no need for special equipment to bag the regolith.

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Appendix A
Volume Rate Calculations

Preliminary Calculations

The amount of oxygen and hydrogen required for the lunar outpost governs the power, size, and number of machines necessary to excavate the lunar surface. According to the literature, about 150 metric tons of oxygen and 15 metric tons of hydrogen will be required to fully support the lunar outpost.[1]

The composition of the regolith and the efficiency of the extraction process are also factors to be considered in the design of the mining equipment. The maximum yield of oxygen from processing is 0.32% and the maximum yield for hydrogen is 50 parts per million.[2]

In computing the excavation rate of regolith, the following assumptions were made:

1) The regolith swells 50% in volume after being excavated.
2) The equipment operates for 24 Earth hours a day for 150 days per year. This number assumes 30 days of down time per year for maintenance and repair of equipment.
3) The excavated regolith has a density of 2000 kg/m^3.

Based on these parameters, the design team determined that 62.5 m^3/hr of regolith must be excavated for the lunar base to be self-sufficient. This quantity of regolith was derived following the method shown on the next page.

For oxygen:

$$\text{Amount of regolith required} = \frac{150 \text{ mt/yr}}{0.32\%}$$

$$= 46875 \text{ mt/yr}$$

For hydrogen:

$$\text{Amount of regolith required} = \frac{15 \text{ mt/yr}}{50\text{E-}6}$$

$$= 300\ 000 \text{ mt/yr}$$

Since hydrogen requires much more regolith, it governs the amount of regolith to be excavated. Therefore,

$$\text{Regolith excavation rate} = \frac{(300\ 000\ 000 \text{ kg})(1.5)}{(2000 \text{ kg/m}^3)(150 \text{ days})(24 \text{ hr/day})}$$

$$= 62.5 \text{ m}^3\text{/hr}$$

The design team used this excavation rate as a basis in designing the speed and capacity of the lunar mining equipment.

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Appendix B
Decision Matrices

The decision matrices used to determine the design solution are shown beginning on page B3. The loosener, collector, and transporter were each evaluated in separate decision matrices.

The design criteria (listed on page 2 of the report) were used in the decision matrices to judge the design alternatives. The design alternatives were judged on a scale of one to four. A one rating implies poor performance against a criterion and a four implies excellent performance against a criterion. Each criterion is discussed below.

Modularity depends on the complexity of connection needed between the design alternative and the Main Drive Unit.

Multipurpose depends on the number of functions that the alternative could perform with little or no modification.

Mass should be minimized.

Safety is the risk caused by operation of the design alternatives.

Power evaluates the relative orders of magnitude of the power consumed by the design alternatives.

Manpower evaluates the need of the design for constant supervision. Alternatives that needed an on-site operator were judged worst.

Reliability evaluates the number of moving parts and whether the equipment has been tested on the moon.

Simplicity is the ease of maintenance as well as the simplicity of the design.

DESIGN CRITERIA	WEIGHTING FACTORS	SCARIFIER		AUGER		EXPLO-SIVES		BLADED ROLLER	
MODULARITY	0.083	3	0.249	2	0.166	1	0.083	3	0.249
MULTI-PURPOSE	0.139	1	0.139	2	0.278	3	0.417	3	0.417
MASS	0.083	2	0.166	2	0.166	2	0.166	2	0.166
SAFETY	0.139	3	0.417	2	0.278	1	0.139	2	0.278
POWER	0.139	3	0.417	3	0.417	2	0.278	2	0.278
MANPOWER	0.222	3	0.666	3	0.666	2	0.444	3	0.666
RELIABILITY	0.167	4	0.668	2	0.334	2	0.334	2	0.334
SIMPLICITY	0.028	4	0.112	2	0.056	4	0.112	2	0.056
TOTAL	1.000	2.834		2.361		1.973		2.444	

Figure B1. DECISION MATRIX FOR LOOSENERS

DESIGN CRITERIA / WEIGHTING FACTORS / ALTERNATE DESIGNS		FRONT END LOADER		BUCKET-WHEEL		INCLINED PLANE		CONVEYOR	
MODULARITY	0.083	4	0.332	3	0.249	4	0.332	4	0.332
MULTI-PURPOSE	0.139	4	0.556	2	0.278	1	0.139	2	0.278
MASS	0.083	3	0.249	1	0.083	3	0.249	2	0.166
SAFETY	0.139	3	0.417	2	0.278	3	0.417	3	0.417
POWER	0.139	3	0.417	3	0.417	4	0.556	2	0.278
MANPOWER	0.222	1	0.222	3.5	0.777	3	0.666	3	0.666
RELIABILITY	0.167	3	0.501	3	0.501	3	0.501	3	0.501
SIMPLICITY	0.028	2.5	0.070	2.5	0.070	4	0.112	2.5	0.070
TOTAL	1.000	2.764		2.653		2.972		2.708	

Figure B2. INITIAL DECISION MATRIX FOR COLLECTORS

DESIGN CRITERIA	WEIGHTING FACTORS	BUCKET-CONVEYOR	AUGER
MODULARITY	0.083	4 / 0.332	4 / 0.332
MULTI-PURPOSE	0.139	2 / 0.278	1 / 0.139
MASS	0.083	2 / 0.166	1.5 / 0.125
SAFETY	0.139	3 / 0.417	3 / 0.417
POWER	0.139	3 / 0.417	2.5 / 0.348
MANPOWER	0.222	4 / 0.888	4 / 0.888
RELIABILITY	0.167	3 / 0.501	3 / 0.501
SIMPLICITY	0.028	2 / 0.056	3 / 0.084
TOTAL	1.000	3.055	2.834

Figure B2. FINAL DECISION MATRIX FOR COLLECTORS

DESIGN CRITERIA	WEIGHTING FACTORS	LUNAR LANDER	CONVEYOR BELT	CABLE TRAM	LOAD HAUL DUMP
MODULARITY	0.083	1 / 0.083	1 / 0.083	1 / 0.083	3 / 0.249
MULTI-PURPOSE	0.139	3 / 0.417	2 / 0.278	2 / 0.278	4 / 0.556
MASS	0.083	3 / 0.249	1 / 0.083	2 / 0.166	4 / 0.332
SAFETY	0.139	1 / 0.139	4 / 0.556	3 / 0.417	3 / 0.417
POWER	0.139	1 / 0.139	3 / 0.417	3 / 0.417	3 / 0.417
MANPOWER	0.222	1 / 0.222	4 / 0.888	3 / 0.666	2 / 0.444
RELIABILITY	0.167	1 / 0.167	2 / 0.334	2 / 0.334	4 / 0.668
SIMPLICITY	0.028	1 / 0.028	2 / 0.056	2 / 0.056	4 / 0.112
TOTAL	1.000	1.444	2.695	2.417	3.195

Figure B3. DECISION MATRIX FOR TRANSPORTERS

Appendix C

Power Calculations for Lunar Excavation and Transportation Equipment

This appendix shows the power calculations for the scarifier, the bucket conveyor, and the haul-dump unit. Each piece of equipment is discussed separately.

C.1 Scarifier

The power requirement of the scarifier was calculated by multiplying the cutting resistance force on the blades by the vehicle velocity. The dimensions, cutting force, and power requirements for the scarifier are derived below.

C.1.1 Assumptions

The major assumptions in deriving the equations for cutting resistance force are shown below.

1) The superposition principle is applicable.
2) The cutting resistance forces due to loosening are much greater than the forces due to the surface friction.
3) Ploughing due to blunt edges of the scarifier blades is negligible.
4) The external pressure acting on the regolith is negligible.
5) The cutting angle of the scarifier blades is 90°.
6) The coefficient of friction for regolith on the titanium blades is about one-half the regolith-to-regolith coefficient of friction[1]

7) The blade shape is approximated by a pyramid.

8) The point of application for the cutting resistance force on the scarifier blades is one-half of the depth-of-cut.

C.1.2 Equation Derivation

The derivation of the equations for the power needed for the scarifier is taken from work done by V. I. Balovnev.[2] The derivation is developed below from the free body diagram of the generalized blade shown in Figure C1.

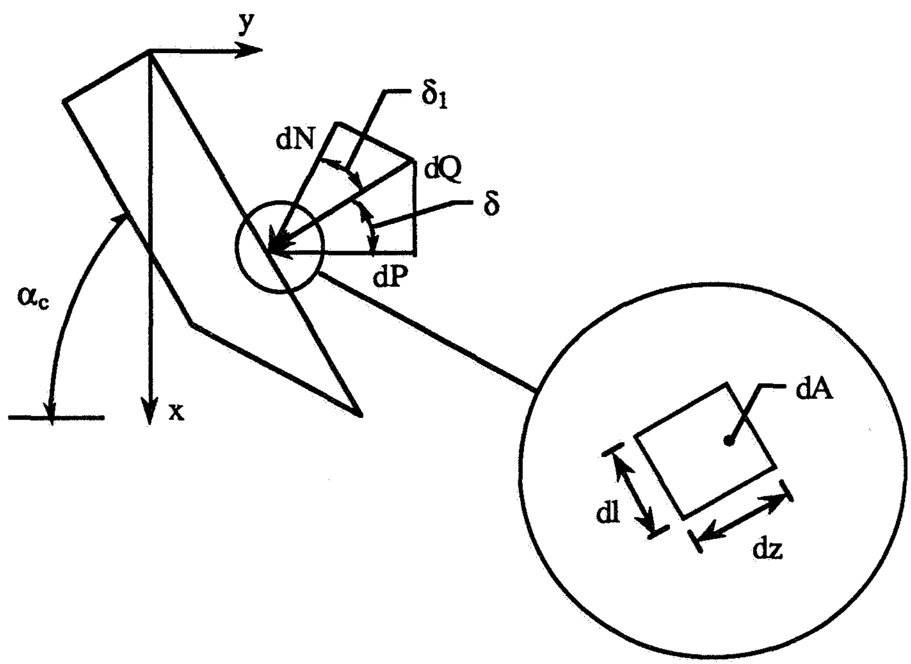


Figure C1. FREE BODY DIAGRAM OF A GENERALIZED CUTTING BLADE[3]

The cutting resistance force on the blade in the figure is found by integrating dP over the entire projected area of the blade shown by

$$P_{blade} = \int_{0}^{h} \int_{0}^{B_1} dP\,(xz) \tag{C1}$$

The differential force dP is found by multiplying the normal stress by dA (Equation C2) and using trigonometry (Equations C3-C8) to get dP as a function of σ_n, dx, and dz as shown in Equation C9.

$$dN = \sigma_n \, dl \, dz \tag{C2}$$

$$dQ = \frac{dN}{\cos \delta_1} \tag{C3}$$

$$dP = dQ \cos \delta \tag{C4}$$

$$dl = \frac{dx}{\sin \alpha_c} \tag{C5}$$

$$\delta = 90^o - (\alpha_c + \delta_1) \tag{C6}$$

$$dQ = \frac{\sigma_n \, dl \, dz}{\cos \delta_1} \tag{C7}$$

$$dP = \frac{\sigma_n \cos \delta}{\cos \delta_1} dl \, dz \tag{C8}$$

$$dP = (1 + \cot \alpha_c \tan \delta_1) \, \sigma_n \, dx \, dz \tag{C9}$$

The expression for σ_n can be found through Coulomb shear stress theory to be a function of regolith cohesion, internal angle of friction of the regolith, angle of friction between regolith and the blade, specific weight of regolith, height of the blade, and blade cutting angle. The relation is given in Equation C10.

$$\sigma_n = c \cot\rho + (\gamma x + c\cot\rho)\frac{\cot\delta\,(\cot\delta + \sqrt{\sin^2\rho - \sin^2\frac{\rho}{2}}\,)}{1-\sin\rho}\exp[2\alpha_c - \pi + \delta + \sin^{-1}(\frac{\sin\delta}{\sin\rho})\tan\rho] \qquad \text{(C10)}$$

Equation C9, with σ_n described by equation C10, is substituted back into Equation C1 and integrated to get the equation for cutting resistance force on a blade. The result is given in Equation C11.

$$P_{blade} = B_1 h\ \{c\cot\rho + (\gamma\frac{h}{2} + c\cot\rho)\frac{\cos\frac{\rho}{2}[\cos\frac{\rho}{2} + \sqrt{\sin^2\rho - \sin^2\frac{\rho}{2}}\,]}{1-\sin\rho} *$$
$$\exp[\frac{\rho}{2} + \sin^{-1}(\frac{\sin\frac{\rho}{2}}{\sin\rho})\tan\rho]\} \qquad \text{(C11)}$$

where

dQ	= resultant of forces on element dA
dP	= horizontal component of dQ
	= differential cutting resistance force acting on horizontal projection of dA element
c	= cohesion of regolith
ρ	= internal angle of friction of regolith
δ	= regolith angle of friction on blade
α_c	= cutting angle of blade
B_1	= effective blade width
	= number of blades on platform times blade width for platform assembly
	= projected width of scraper blade
h	= depth of cut
γ	= specific weight of regolith
P_{blade}	= cutting resistance force of regolith against blade

C.1.3 Results

A computer program was written using Equation C11 to determine the dimensions of the platform assembly. The program generated the cutting resistance force for different values of blade depth, blade width, platform width, and depth of cut for the scarifier. The location of the dimensions are shown in Figure C2. The program also calculated the maximum stress on the blade due to the bending moment from cutting resistance. The maximum stress was calculated to determine if the blade would fail. A listing of the program is given starting on page C8. Data and graphs generated from the program are given starting on page C12.

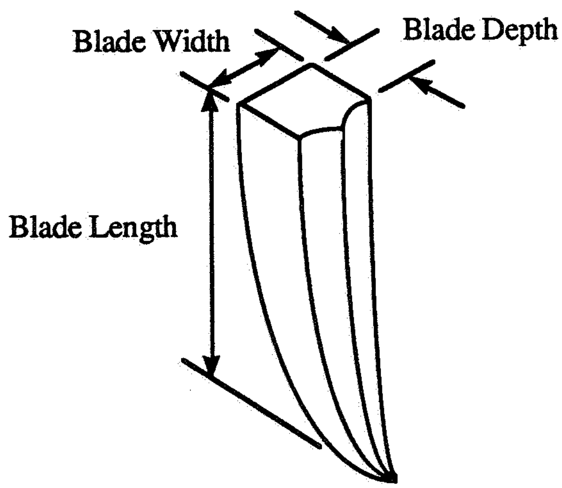


Figure C2. REPRESENTATION OF SCARIFIER BLADE DIMENSIONS

Figures C3 and C4 show that the cutting resistance force remains relatively constant for varying blade depth and width, but the normal stress due to bending decreases when the blade depth and width increase. Figure C5 shows that the cutting resistance increases with depth of cut.

Total cutting resistance force and power consumption for the scarifier and scraper were calculated in another computer program. This program varied blade depth, blade width, platform width, depth of cut, and velocity of the vehicle to obtain the best dimensions and operating characteristics for the scarifier. A listing of the program is shown starting on page C18. Data and graphs are shown starting on page C23. Figures C6 through C8 show plots of the total cutting force on the scarifier and power needed to loosen as a function of the platform width, depth of cut, and velocity. Tables C4 through C6 show the data for these plots.

After examining all the different graphs, the design team chose a loosener with a blade depth of 0.06 meters, a blade width of 0.08 meters, and a platform width of 2.0 meters

The dimensions and operating characteristics for the scarifier are the following:

- Blade depth = 0.06 meters
- Blade width = 0.08 meters
- Blade length = 0.152 meters
- Platform width = 2.0 meters
- Maximum depth of cut for blades = 0.15 meters
- Number of blades on platform = 6
- Scraper length = 0.943 meters
- Cutting resistance force on blades = 3.9 kN
- Total cutting resistance force = 20 kN
- Maximum normal stress on blades due to bending = 9.8 MPa
- Velocity of vehicle = 0.250 m/s
- Power needed to loosen = 5 kW

```
      program scarifier blade
c
c
c     This program generates data for determining the
c     optimum depth-of-cut, blade dimensions, blade
c     platform width, and number of blades per row
c     for the scarifier loosening device for excavation
c     and transportation of lunar regolith
c
c
c     Drafted by Mark Detwiler
c     Date: 10-25-90
c     Copyright 1990
c
c     Drafted for use by members of NASA/USRA Lunar Mining
c     Equipment Design Team
c
c     Team Members:   Mark Detwiler, Team Leader
c                     Chee Seng Foong
c                     Catherine Stocklin
c
      open(unit=6,file='a:output')
      write(6,*) 'All dimensions in meters'
      write(6,*) 'All forces in Newtons'
      write(6,*) 'All stresses in pascals'
      write(6,*)
      write(6,*)
      write(6,100)
      write(6,101)
      write(6,102)
      write(6,*)
c
c     Variables used
c
c     bo  = depth at the top of the scarifier blade
```

```
c    h   = depth of cut into the lunar soil
c    h1  = limiting blade length of stress equation validity
c    wo  = width at the top of the scarifier blade
c    pbl = cutting resistance force of soil on blade
c    p   = internal angle of friction of lunar soil
c    b   = width of scarifier platform
c    tw  = total width of scarifier blades
c             = # of blades (n) times width of one blade (wo)
c    gam = specific weight of lunar soil
c    c   = cohesion of lunar soil
c    n   = number of blades on scarifier
c    x   = distance along length of scarifier blade
c
c
c    Start of program
c
c    Initializing variables
c
     gam = 2779.5
     bo = 0.02
     p = 0.8552
     c = 1600.0
c
c    Beginning of nested loops to determine stresses
c    and loads for all combinations of dimensions
c
  10 if(bo.gt.0.08) go to 19
     wo=0.02
  11 if(wo.gt.0.05) go to 18
     b=2.0
  12 if(b.gt.4.0) go to 17
     n=(b/wo-1.)/3.5
     tw=n*wo
     h=0.05
  13 if(h.gt.0.2) go to 16
```

```
      h1=h/2.+0.0254
      x=0.0
   14 if(x.gt.h1) go to 15
c
c     Calculation of blade loads using equation (13) from
c     Balovnev V.I.,"New Methods for Calculating Resistance
c          to Cutting of Soil", translated from Russian,
c          Amerind Publishing Co. Pvt. Ltd., (New Delhi:1983),
c          p.29.
c     See Power Calculations Appendix for derivation
c
      pbl1 = (cos(p/2.)*(cos(p/2.)+((sin(p))**2.
     * -(sin(p/2.))**2.)**.5))/(1.-sin(p))
      pbl2 = pbl1*exp(((p/2.)+asin(sin(p/2.)/sin(p)))*tan(p))
      pbl = tw*h*(c*cotan(p)+(c*cotan(p)+gam*h/2.))*pbl2
c
c     Calculation of blade normal stresses due to bending
c     See Power Calculations Appendix for derivation
c
      sig=6.0*pbl*(h1-x)/(wo*bo**2.*(1-x/(h1+h/2.))**3.)
c
c     Output to file
c
       write(6,103) bo,wo,b,h,n,x,pbl,sig
c
c     ending for nested loops
c
      x=x+.025
      go to 14
   15 h=h+.05
      go to 13
   16 b=b+.5
      go to 12
   17 wo=wo+.01
      go to 11
```

```
 18 bo=bo+.02
   go to 10
 19 continue
c
c   Formatting for output to file
c
 100 format(1x,'BLADE',T9,'BLADE',T16,'PTFRM',T23,
    * 'DEPTH',T32,'# OF',T40,'DISTANCE',T55,'CUT',T63,'BLADE BND.')
 101 format(1x,'DEPTH',T9,'WIDTH',T16,'WIDTH',T23,
    * 'OF CUT',T31,'BLADES',T39,'ALONG BLADE',T54,'FORCE',
   * T63,'NORM. STR')
 102 format(1x,'-----',T9,'-----',T16,'-----',T23,
    * '------',T31,'------',T39,'-----------',T52,'---------',
   * T63,'----------')
 103 format(1x,F5.3,T9,F5.3,T16,F5.3,T23,F6.4,T32,
   * I3,T41,F6.4,T52,E9.2,T63,E9.2)
   close(unit=6)
   stop
   end
```

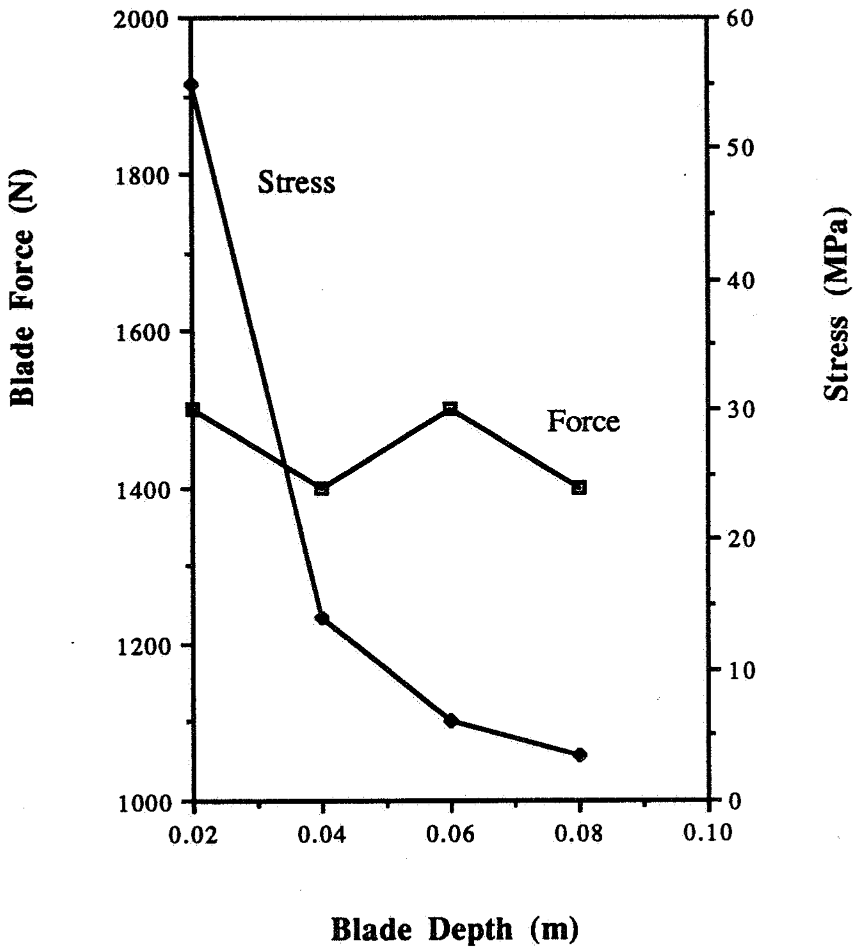


Figure C3. VARIATION OF BLADE CUTTING RESISTANCE FORCE AND NORMAL STRESS DUE TO BENDING WITH BLADE DEPTH

This graph was plotted using the following parameters:

Blade Width = 0.02 m

Platform Width = 2.0 m

Depth of Cut = 0.05 m

Table C1
Data for Plot of Blade Cutting Resistance Force and Normal Stress Due to Bending With Blade Depth

Blade Depth (m)	Blade Cutting Resistance Force (N)	Normal Stress (MPa)
0.02	1500	55.0
0.04	1400	14.0
0.06	1500	6.1
0.08	1400	3.4

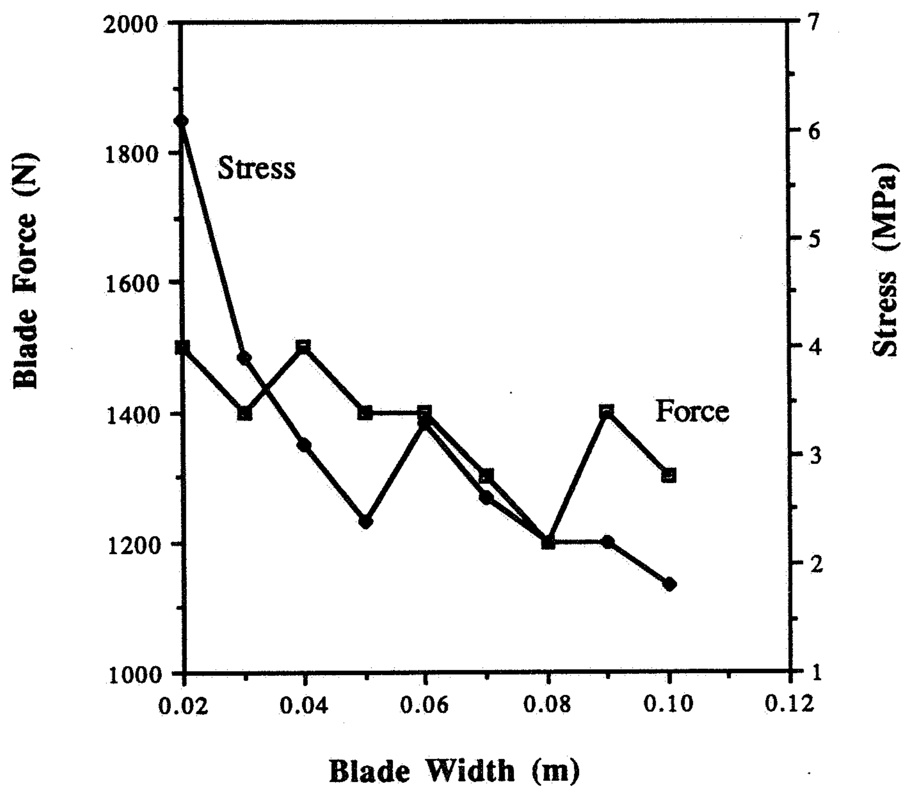


Figure C4. VARIATION OF BLADE CUTTING RESISTANCE FORCE AND NORMAL STRESS DUE TO BENDING WITH BLADE WIDTH

This graph was plotted using the following parameters:

Blade depth = 0.06 m

Platform width = 2.0 m

Depth of cut = 0.05 m

Table C2
Data for Plot of Blade Cutting Resistance Force and Normal Stress Due to Bending With Blade Width

Blade Width (m)	Blade Cutting Resistance Force (N)	Normal Stress (MPa)
0.02	1500	6.1
0.03	1400	3.9
0.04	1500	3.1
0.05	1400	2.4
0.06	1400	3.3
0.07	1300	2.6
0.08	1200	2.2
0.09	1400	2.2
0.10	1300	1.8

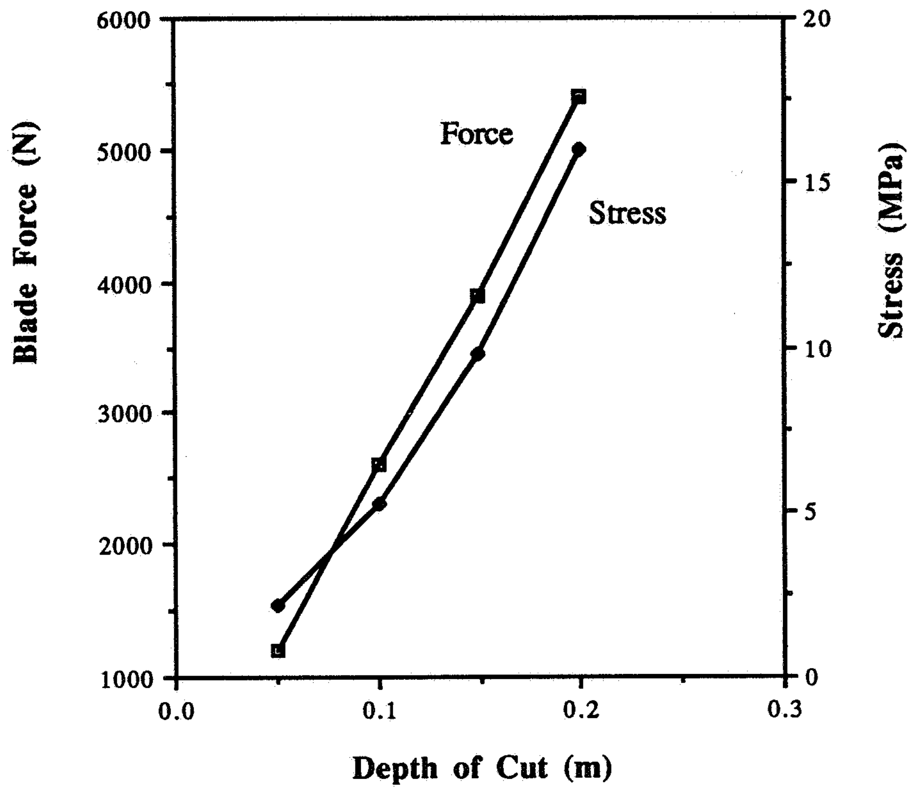


Figure C5. VARIATION OF BLADE CUTTING RESISTANCE FORCE AND NORMAL STRESS DUE TO BENDING WITH DEPTH OF CUT

This graph was plotted using the following parameters

Blade depth = 0.06 m

Blade width = 0.08 m

Platform width = 2.0 m

Table C3
Data for Plot of Blade Cutting Resistance Force and Normal Stress Due to Bending With Depth of Cut

Depth of Cut (m)	Blade Cutting Resistance Force (N)	Normal Stress (MPa)
0.05	1200	2.2
0.10	2600	5.2
0.15	3900	9.8
0.20	5400	16.0

```
      program scarifier power
c
c
c     This program generates data for determining the
c     optimum depth-of-cut, blade dimensions, blade
c     platform width, and number of blades per row
c     for the scarifier loosening device for excavation
c     and transportation of lunar regolith
c
c
c     Drafted by Mark Detwiler
c     Date: 10-25-90
c     Copyright 1990
c
c     Drafted for use by members of NASA/USRA Lunar Mining
c     Equipment Design Team
c
c     Team Members:   Mark Detwiler, Team Leader
c                     Chee Seng Foong
c                     Catherine Stocklin
c
      open(unit=6,file='a:output2')
      open(unit=7,file='a:output3')
      write(6,*) 'All dimensions in Meters'
      write(6,*) 'All forces in Newtons'
      write(6,*) 'All stresses in Pascals'
      write(7,*) 'All dimensions in Meters'
      write(7,*) 'All forces in Newtons'
      write(7,*) 'All powers in Watts'
      write(6,*)
      write(6,*)
      write(7,*)
      write(7,*)
      write(6,100)
      write(6,101)
```

```
      write(6,102)
      write(7,103)
      write(7,104)
      write(7,105)
      write(6,*)
      write(7,*)
c
c     Variables used
c
c     bo  = depth at the top of the scarifier blade
c     h   = depth of cut into the lunar soil
c     h1  = limiting blade length of stress equation validity
c     wo  = width at the top of the scarifier blade
c     pbl = cutting resistance force of soil on blade
c     p   = internal angle of friction of lunar soil
c     b   = width of scarifier platform
c     tw  = total width of scarifier blades
c           = # of blades (n) times width of one blade (wo)
c     gam = specific weight of lunar soil
c     c   = cohesion of lunar soil
c     n   = number of blades on scarifier
c     ptot= total cutting resistance force on loosener
c     vel = velocity of collector/loosener machine
c     pow = power for process
c     sig = surface stress on rake blades due to bending
c           caused by cutting resistance force
c
c
c     Start of program
c
c     Initializing variables
c
      gam = 2779.5
      bo = 0.06
      p = 0.8552
```

```
      c = 1600.0
c
c     Beginning of nested loops to determine stresses
c     and loads for all combinations of dimensions
c
   10 if(bo.gt.0.06) go to 21
      wo=0.08
   11 if(wo.gt.0.08) go to 20
      b=2.0
   12 if(b.gt.2.0) go to 19
      n=(b/wo-1.)/3.5
      tw=n*wo
      h=0.05
   13 if(h.gt.0.2) go to 18
      h1=h/2.+0.0254
      x=0.0
   14 if(x.gt.h1) go to 17
      vel=0.25
c
c     Calculation of blade loads using equation (13) from
c     Balovnev V.I.,"New Methods for Calculating Resistance
c          to Cutting of Soil", translated from Russian,
c          Amerind Publishing Co. Pvt. Ltd., (New Delhi:1983),
c          p.29.
c     See Power Calculations Appendix for derivation
c
      pbl1 = (cos(p/2.)*(cos(p/2.)+((sin(p))**2.
     * -(sin(p/2.))**2.)**.5))/(1.-sin(p))
      pbl2 = pbl1*exp(((p/2.)+asin(sin(p/2.)/sin(p)))*tan(p))
      pbl = tw*h*(c*cotan(p)+(c*cotan(p)+gam*h/2.))*pbl2
      ptot = pbl*(1+(2./3.)*(1.+tan(p/2.))*(b/tw))
c
c     Calculation of blade normal stresses due to bending
c     See Power Calculations Appendix for derivation
c
```

```
      sig=6.0*pbl*(h1-x)/(wo*bo**2.*(1-x/(h1+h/2.))**3.)
c
c     Output to file
c
      if(x.eq.0.0) then
 15      if(vel.gt.2.25) go to 16
c
c        Calculation of power to move loosener/collector--does not
c        include inertia of loosener/collector
c        See Power Calculations Appendix for derivation
c
         pow = ptot*vel+(53.8+(0.36/b))
         write(7,107) bo,wo,b,h,vel,ptot,pow
         vel=vel+0.25
         go to 15
      endif
      write(6,106) bo,wo,b,h,n,x,pbl,sig
c
c     ending for nested loops
c
 16   x=x+.025
      go to 14
 17   h=h+.05
      go to 13
 18   b=b+.5
      go to 12
 19   wo=wo+.01
      go to 11
 20   bo=bo+.01
      go to 10
 21   continue
c
c     Formatting for output to file
c
 100  format(1x,'BLADE',T9,'BLADE',T16,'PTFRM',T23,
```

```
     * 'DEPTH',T32,'# OF',T40,'DISTANCE',T55,'CUT',T63,'BLADE BND.')
101 format(1x,'DEPTH',T9,'WIDTH',T16,'WIDTH',T23,
     * 'OF CUT',T31,'BLADES',T39,'ALONG BLADE',T54,'FORCE',
     * T63,'NORM. STR')
102 format(1x,'-----',T9,'-----',T16,'-----',T23,
     * '------',T31,'------',T39,'-----------',T52,'---------',
     * T63,'----------')
103 format(1x,'BLADE',T9,'BLADE',T16,'PTFRM',T23,
     * 'DEPTH',T43,'SCAR.')
104 format(1x,'DEPTH',T9,'WIDTH',T16,'WIDTH',T23,
     * 'OF CUT',T31,'VELOCITY',T43,'FORCE',T54,'POWER')
105 format(1x,'-----',T9,'-----',T16,'-----',T23,
     * '------',T31,'--------',T43,'------',T54,'-----')
106 format(1x,F5.3,T9,F5.3,T16,F5.3,T23,F6.4,T32,
     * I3,T41,F6.4,T52,E9.2,T63,E9.2)
107 format(1x,F5.3,T9,F5.3,T16,F5.3,T23,F6.4,T32,
     * F6.3,T41,E9.2,T52,E9.2)
      close(unit=6)
      close(unit=7)
      stop
      end
```

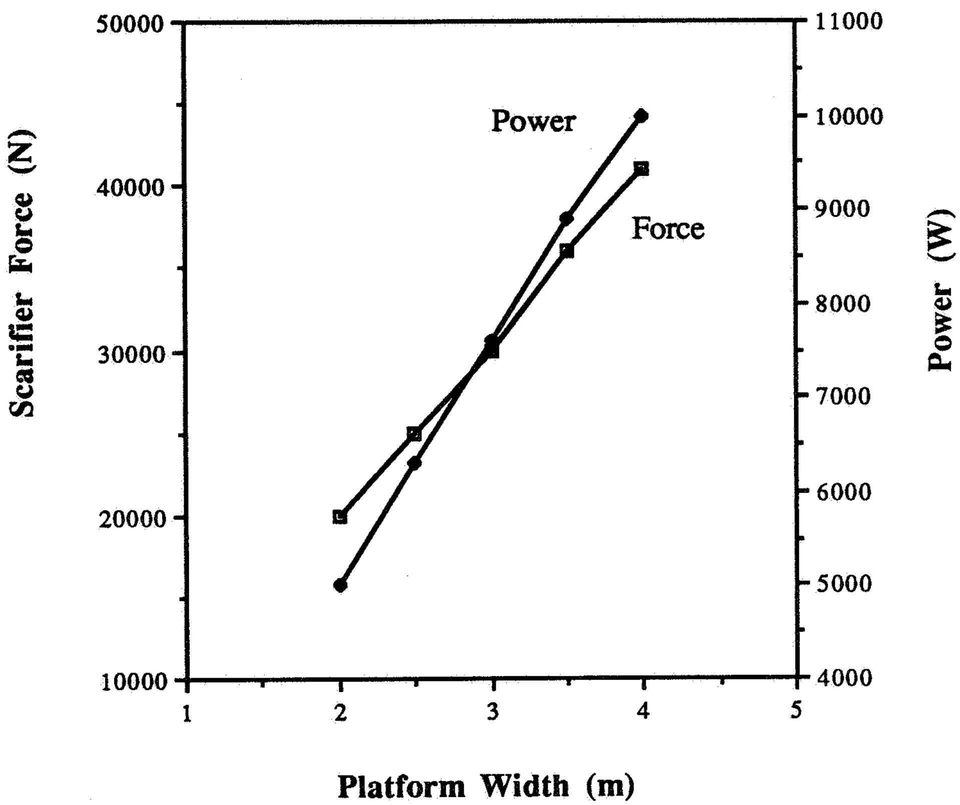


Figure C6. VARIATION OF TOTAL CUTTING RESISTANCE FORCE AND POWER NEEDED TO LOOSEN WITH PLATFORM WIDTH

This graph was plotted using the following data:

Blade depth = 0.06 m

Blade width = 0.08 m

Depth of cut = 0.15 m

Table C4
Data for Plot of Total Cutting Resistance Force and Power Needed to Loosen With Platform Width

Platform Width (m)	Total Cutting Resistance Force (N)	Power to Loosen (W)
2.00	20000	5000
2.50	25000	6300
3.00	30000	7600
3.50	36000	8900
4.00	41000	10000

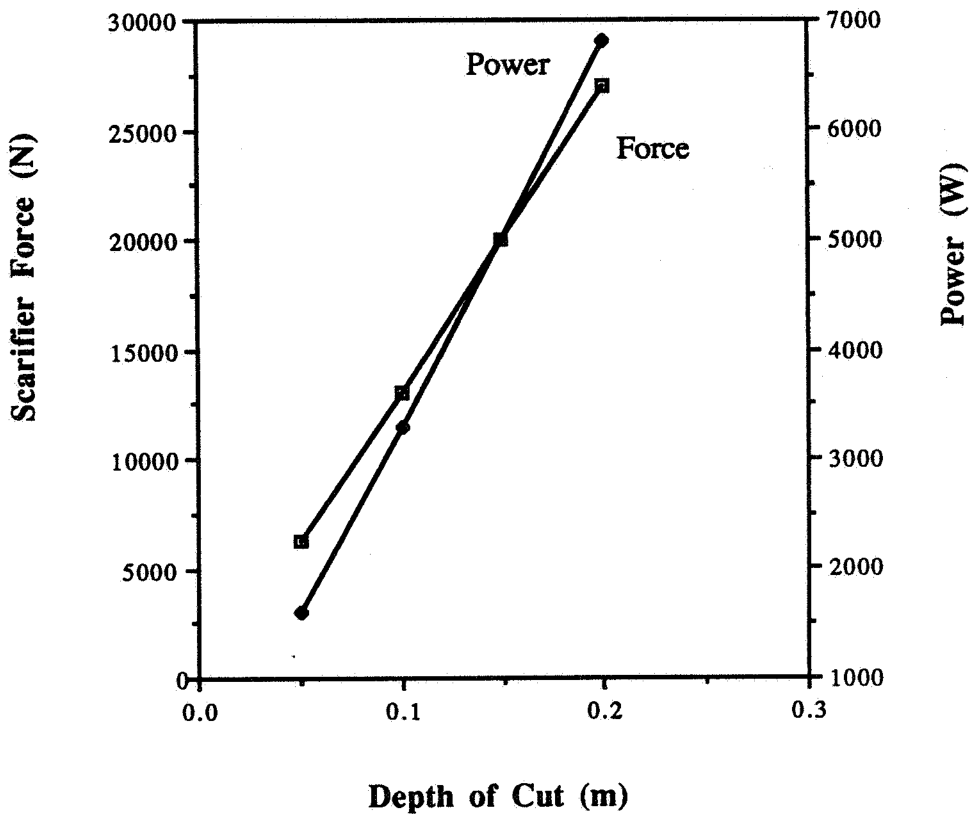


Figure C7. VARIATION OF TOTAL CUTTING RESISTANCE FORCE AND POWER NEEDED TO LOOSEN WITH DEPTH OF CUT

This graph was plotted using the following data:

Blade depth = 0.06 m

Blade width = 0.08 m

Platform width = 2.0 m

Table C5
Data for Plot of Total Cutting Resistance Force and Power Needed to Loosen With Depth of Cut

Depth of Cut (m)	Total Cutting Resistance Force (N)	Power to Loosen (W)
0.05	6300	1600
0.10	13000	3300
0.15	20000	5000
0.20	27000	6800

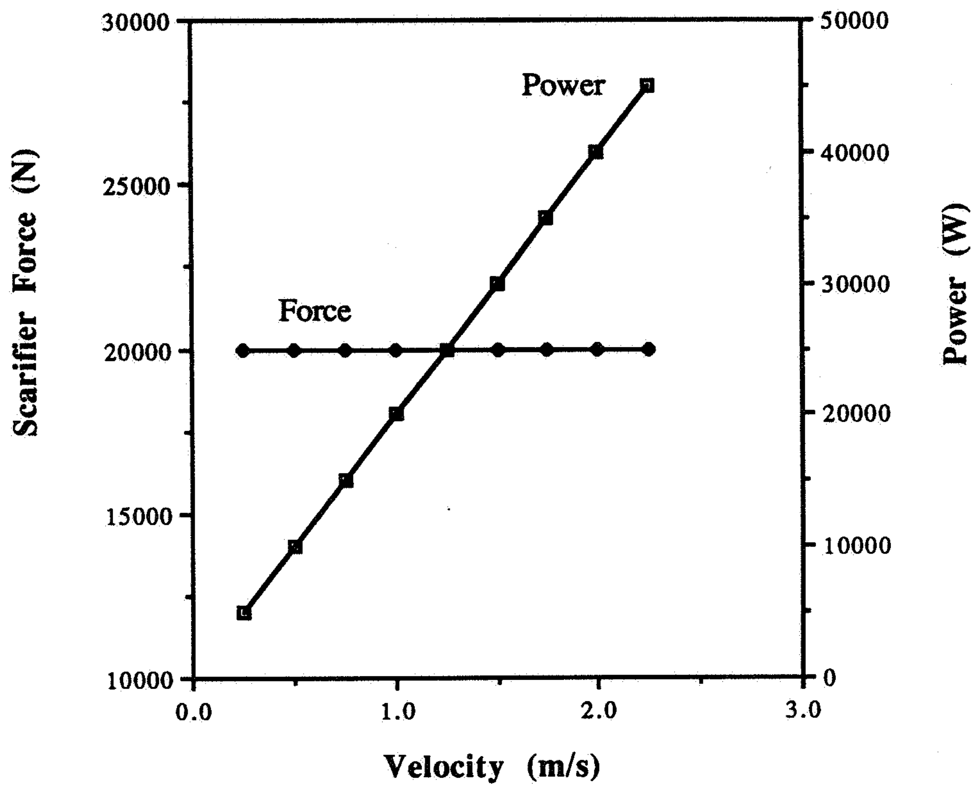


Figure C8. VARIATION OF TOTAL CUTTING RESISTANCE FORCE AND POWER NEEDED TO LOOSEN WITH VELOCITY

This graph was plotted using the following data:

Blade depth = 0.06 m

Blade width = 0.08 m

Platform width = 2.0 m

Table C6
Data for Plot of Total Cutting Resistance Force and Power Needed to Loosen With Velocity

Velocity (m/s)	Total Cutting Resistance Force (N)	Power to Loosen (W)
0.25	20000	5000
0.50	20000	10000
0.75	20000	15000
1.00	20000	20000
1.25	20000	25000
1.50	20000	30000
1.75	20000	35000
2.00	20000	40000
2.25	20000	45000

C.2 Bucket Conveyor

The power requirement for the bucket conveyor was determined by adding the power required for the conveyor and the power required for the inclined plane. The inclined plane power calculations were done similarly to the scarifier calculations.

C.2.1 Assumptions

The assumptions made in making power calculations for the bucket conveyor are

1) Friction factor of idler is 0.03
2) Drive and friction losses are 15% of the power required
3) Density of materials is 2700 kg/m^3 (density of aluminum)
4) Quantity to excavate is 62.5 m^3/hr
5) Terrestrial equations can be adapted for lunar conditions
6) All assumptions made for the scarifier power calculations

C.2.2 Equation Derivation

The equation used to determine conveyor power for terrestrial equipment is

$$\text{Horsepower} = \frac{LSCQ}{33000} + \frac{LCT}{990} + \frac{TH}{990} + \text{miscellaneous} \qquad \text{(C12)}[4]$$

where

L = length in ft of conveyor

S = speed in fpm of belt

C = friction factor of idler

Q = weight of moving parts per ft of conveyor

T = capacity in tons per hr

H = change in elevation in ft

This equation was modified to work for metric units. The modified equation is

$$P = LSCQ + LCT + TH + \text{miscellaneous} \qquad \text{(C13)}$$

The miscellaneous addition is due to friction and drive losses, so the final equation becomes

$$P = 1.15\,LSCQ + 1.15\,LCT + 1.15\,TH \qquad \text{(C14)}$$

where

P	= power in Watts
L	= length in m of conveyor
S	= speed in m/s of belt
C	= friction factor of idler
Q	= weight of moving parts per length in N/m
T	= capactiy in N/s
H	= change in elevation in m

C.2.3 Results

A program was written that varied the belt speed, height, angle of the conveyor. The angle of the conveyor is the angle that the conveyor makes with the surface. The program listing is given starting on page C33 and the graphs and data from the program are given starting on page C35.

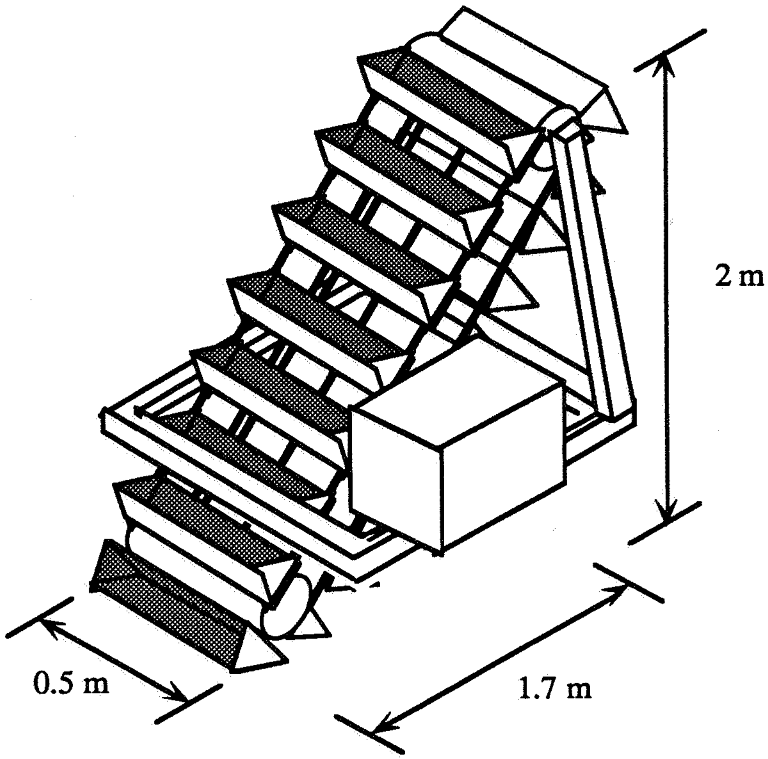
Since the target regolith excavation rate is constant at 62.5 m^3/hr, the belt speed of the conveyor varies the Q value. The faster the belts move, the smaller the buckets can be.

As expected, the power increased with increasing height. This was expected since the volume of regolith must be lifted higher, and work against gravity is proportional to height.

Increasing the belt speed increased the overall power requirement of the conveyor. The plot is very nearly linear, which implies that the savings in mass associated with moving the belt faster is very low. The power increases since the regolith must be accelerated from a zero velocity to the speed of the belt. The higher the speed of the belt, the more is the energy that is required.

The power requirement remained relatively constant with varying angle of the conveyor. This makes sense since the height and speed of the conveyor, which dominate the power equation, are not affected by the angle. The length of the conveyor decreased with increasing angle, while the weight per a unit length increased. For the designed conveyor, the actual power increased slightly with increasing angle.

The width of the conveyor is constant at 0.5 m. Since the power with the different design parameters is very nearly linear, the selection of exact dimensions is not critical to the power consumption of the equipment. However, the dimensions were chosen to minimize the mass of the design, to handle the fixed volume of 62.5 m^3/hr, and of a width of 0.50 m. The exact dimensions selected are given in Figures C9.



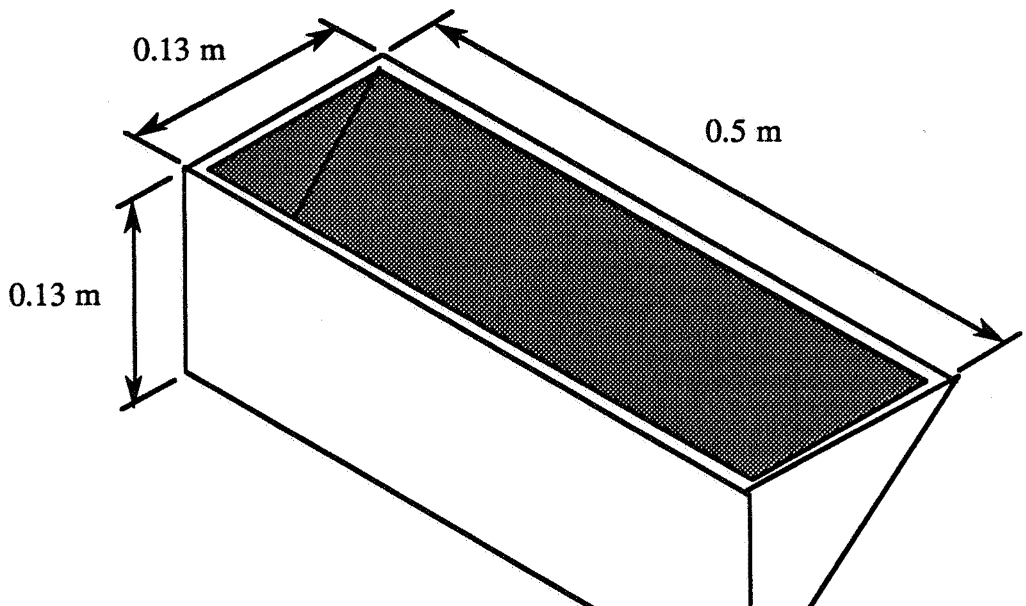


Figure C9. BUCKET CONVEYOR AND BUCKET DIMENSIONS

Program to Determine Bucket Conveyor Power Requirements

```
      PROGRAM CONVEYOR
]C
C  PROGRAMMED BY ME466K DESIGN TEAM
C  THE UNIVERSITY OF TEXAS AT AUSTIN
C  FALL, 1990
C  TEAM MEMBERS:   MARK DETWILER, TEAM LEADER
C                  CHEE SENG FOONG
C                  CATHERINE STOCKLIN
C
C  DECLARE VARIABLES
C
      REAL L, S, Q, T, H, WID, THETA
      REAL DTHET, POWER, VOL, VRATE
C
C  THIS PROGRAM SHOWS HOW THE POWER REQUIREMENT
C  OF THE BUCKET CONVEYOR VARIES WITH DIFFERENT
C  HEIGHT, BELT SPEED, AND CONVEYOR ANGLE.
C
C
      OPEN(UNIT=6, FILE='OUTPUT4')
      WRITE(6,*)  'ALL DIMENSIONS IN METERS'
      WRITE(6,*)  'ALL ANGLES IN DEGREES'
      WRITE(6,*)  'ALL POWER IN WATTS'
      WRITE(6,*)
      WRITE(6,*)
C
C  THE EQUATION WE ARE USING IS FROM A BOOK
C  BY STUART WOOD, JR ENTITLED "HEAVY CONSTRUCTION:
C  EQUIPMENT AND METHODS"(PRENTICE-HALL, 1977), P. 182
C
C  L     = LENGTH OF THE CONVEYOR  (M)
C  S     = SPEED OF BELT     (M/S)
C  Q     = WEIGHT/LENGTH CONVEYOR (N/M)
C  T     = CAPACITY                 (N/HR)
C  H     = CHANGE IN ELEVATION    (M)
C  WID   = WIDTH OF CONVEYOR            (M)
C  DTHET = CONVEYOR ANGLE     (DEG)
C  THETA = CONVEYOR ANGLE     (RAD)
C  BUC   = # OF BUCKETS/METER          (1/M)
C  BCH   = CHORD LENGTH OF BUCKET  (M)
C  VOL   = VOLUME IN BUCKET    (M^3)
C  VRATE = VOLUMETRIC CAPACITY   (M^3/HR)
C
C  THE EQUATION HAS BEEN MODIFIED FROM THE ONE IN THE
C  TEXT SO THAT THE EQUATION WORKS FOR METRIC UNITS.
C
C  LETS INITIALIZE SOME VARIABLES
C
      DTHET = 40
```

```
      THETA = DTHET*3.141592654/180.
      VRATE = 62.5
      T    = 42.3
      H    = 2.
      WID  = 0.5
      BUC  = 6.
      BCH  = 0.15
      VOL  = ((COS(45)*BCH)**2)*0.75*WID
      S    = VRATE/(BUC*VOL)
      WRITE(6,100)
100   FORMAT(///,9X,'ANGLE',7X,'POWER',/)
C
C  LETS VARY THE CONVEYOR ANGLE
C
      DO 10 DTHET = 40, 70, 2
         THETA = DTHET*3.141592654/180.
         L=H*SIN(THETA)
         Q=(340.+(4385.*2.*L*BUC*(0.0282843*WID*BCH+0.015*BCH**2.)))/L
         POWER=(1.149540371*T*H)+(0.034486389*(L*S*Q+L*T))
         WRITE(6,*) DTHET, POWER, L, Q, T, S, BUC, BCH
10    CONTINUE
110    FORMAT(6X,F7.1,F15.2)
       DTHET = 50
      THETA = DTHET*3.141592654/180.
      L = H*SIN(THETA)
      WRITE(6,120)
120    FORMAT(//,5X,'CHORD LENGTH',5X,'POWER',/)
      S = 0.3
C
C  LET VARY THE SPEED OF THE CONVEYOR.  NOTE THAT THIS ALSO
C  VARIES THE MASS SINCE THE CAPACITY IS FIXED.  THE FASTER
C  THE BELT MOVES, THE SMALLER THE SIZE OF THE CONVEYOR
C  NEEDS TO BE.
C
       DO 20 S = 0.3, 0.8, 0.05
         BCH=0.215165742*((1/(S*BUC*WID))**0.5)
         Q=(340.+(4385.*2.*L*BUC*(0.0282843*WID*BCH+0.015*BCH**2)))/L
         POWER=(1.149540371*T*H)+(0.034486389*(L*S*Q+L*T))
         WRITE(6,*)        DTHET, POWER,L,Q,T,S,BUC,BCH
20    CONTINUE
130    FORMAT(6X,F7.3,F15.2)
C
C  TA DA!!
C
      STOP
      END
```

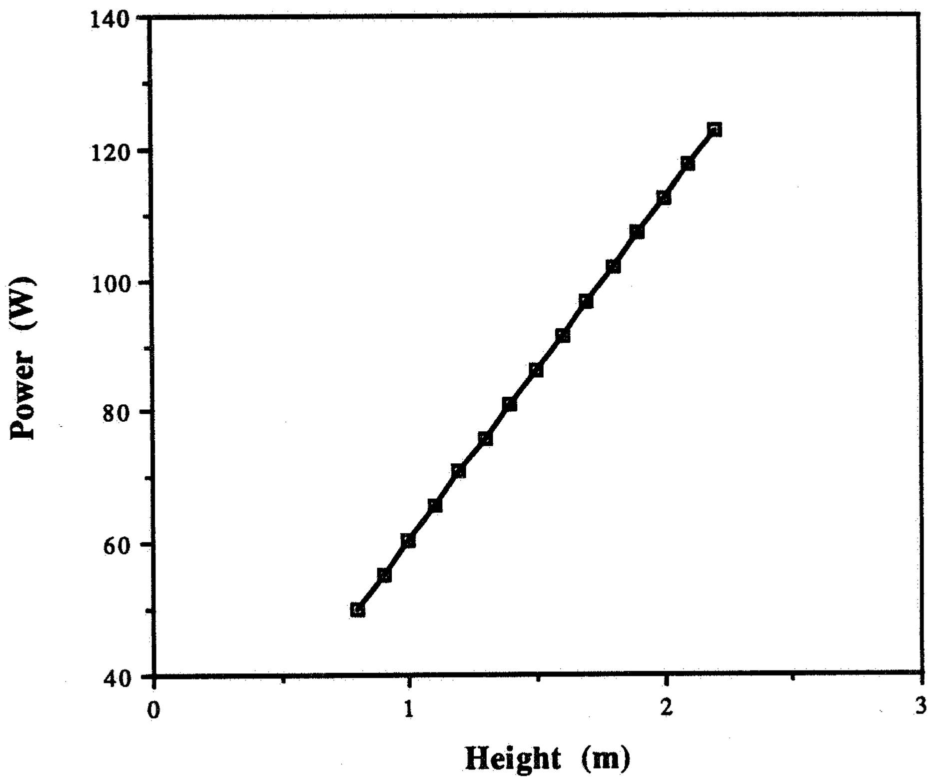


Figure C10. VARIATION OF POWER WITH HEIGHT OF BUCKET CONVEYOR

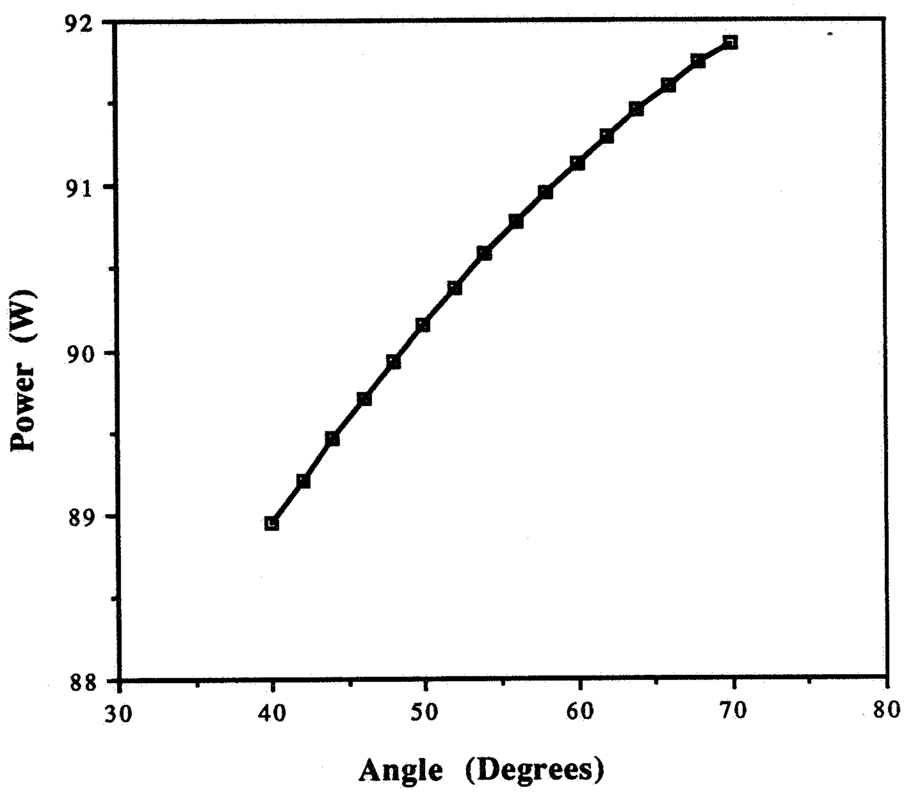


Figure C11. VARIATION OF POWER WITH ANGLE OF BUCKET CONVEYOR

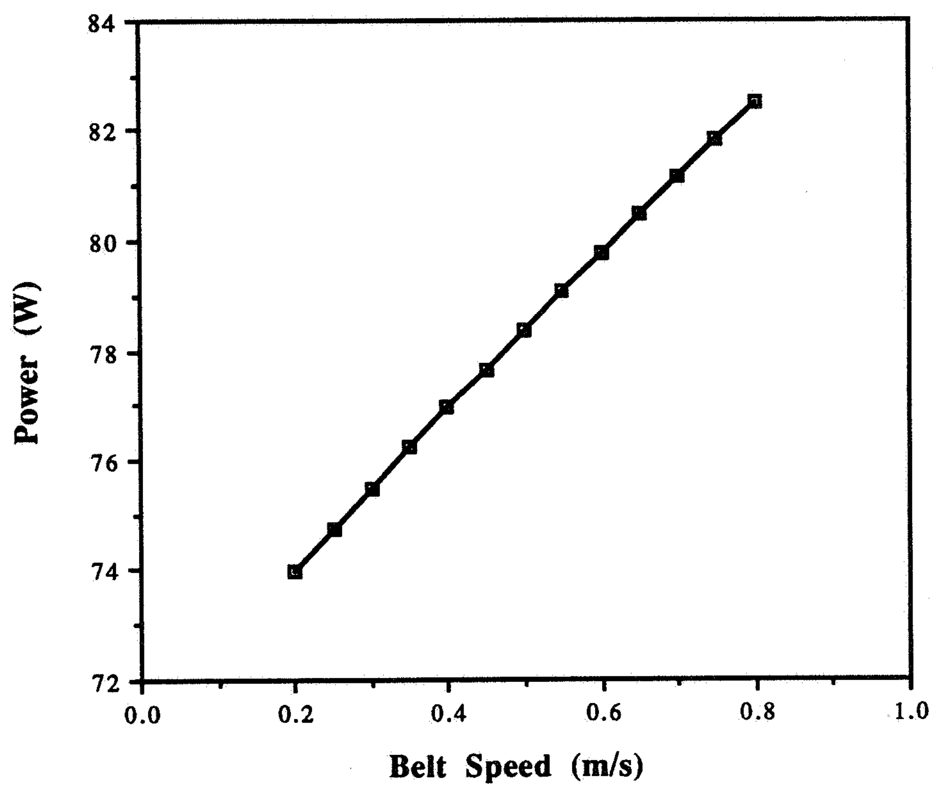


Figure C12. VARIATION OF POWER WITH SPEED OF BUCKET CONVEYOR BELT

C.3 Transporter

The Haul-Dump unit selected to move the collected regolith from the excavation site to the processing site consists of the Main Drive Units and regolith bins (MDU-Bin).

In this section, the payload capacity, number of MDUs, and power requirement will be calculated. A spread sheet will be used to generate these values. By plotting the appropriate graphs, the optimum operation conditions can be determined. Traction analysis will be discussed briefly. For a more detailed traction analysis, refer to the Supplementary Report..

C.3.1 Equation Derivation

The required traction force on each hemispherical wheel of the MDU-Bin is given by

$$H = Ac + Mg\mathrm{Tan}\,\phi \qquad \text{(C15)}^{5}$$

where

H	= traction force developed
A	= area of wheel-soil contact
c	= the coefficient of cohesion of regolith
M	= MDU mass with regolith and regolith bin
g	= moon's gravitational acceleration

The rolling resistance per wheel of the MDU-Bin is given by

$$R_c = \frac{\left[\frac{3Mg}{\sqrt{D}}\right]^{\frac{2n+2}{2n+1}}}{[3-n]^{\frac{2n+2}{2n+1}}[n+1][K_c + bK_\phi]^{\frac{1}{2n+1}}} \quad \text{(C16)}^{6}$$

where

D	= hemispherical wheel diameter
n	= soil deformation exponential factor
K_c	= coefficient of cohesive deformation modulus
K_ϕ	= coefficient of frictional deformation modulus
b	= wheel width

To propel the vehicle forward

$$H \geq \frac{R_c}{0.75} \quad \text{(C17)}^{7}$$

assuming that 25% of additional force is needed for acceleration and going up inclines.[8]

The power required to haul a filled bin depends on the total force required to propel the MDU-Bin and the velocity of the MDU-Bin. The power required is given by

$$P = FV \quad \text{(C18)}$$

where

P	= power required
F	= total force required to propel the MDU-Bin
V	= velocity of the MDU-Bin

The total force required to propel the MDU-Bin, F is

$$F = \frac{R_c}{0.75} \qquad \text{(C19)}$$

The power is then

$$P = \frac{R_c V}{0.75} \qquad \text{(C20)}$$

The energy required to operate the MDU-Bin for a day is then

$$E = Pt$$

$$E = \frac{R_c V t}{0.75} \qquad \text{(C21)}$$

where

t = time

The MDU-BIN payload is calculated based on the power-to-mass ratio of the hydrogen-oxygen fuel cells. A fuel cell of mass 20 kilogram can generate one kilowatts of electricity. Hence, the payload of the MDU-Bin is

$$M_p = M - \left(\frac{20\ \text{kg}}{\text{kW}}\right)(P) \qquad \text{(C22)}$$

The amount of regolith moved in a 24 hour period is

$$M_l = \frac{V t M_p}{d} \qquad \text{(C23)}$$

where

d = distant travel by the MDU-Bin

The number of MDU-Bins required to achieve a volume rate of 62.5 m^3/hr is given by

$$N = \frac{V_r t \rho}{M_l} \tag{C24}$$

where

N	= number of MDU-Bin, rounded to tne next round number, N_r
ρ	= density of loosened regolith

The energy required to operate one MDU-Bin is

$$E = Pt \tag{C25}$$

The total energy energy required to run the mining operation at the required rate of 62.5 m^3/hr will be

$$E_t = EN_r \tag{C26}$$

where

E_t	= total energy to run the mining operation
N_r	= total number of MDU-Bins required

Finally, the total mass of the transportation system to be shipped to the lunar outpost from the earth is

$$M_T = MN_r \tag{C27}$$

C.3.2 Calculations

The variation of power, energy, and number og MDU-Bin required was analysed by varying the MDU-Bin mass. The following are the constants used in generating the spread sheet.

1) d = 6 km (3km between the sites)
2) V = 50 km/hr [4]
3) D = 2 m [7]
4) b = 0.2 m [4]
3) t = 24 hours [5]
4) ρ = 1300 kg/m^3
5) c = 1600 Pa [5]
6) g = 1.624 m/s^2
8) n = 1 [8]
9) K_c = 20855 Pa [9]
10) K_ϕ = 8100 Pa/m

C.3.4 Results

The following is a discussion of the results obtained from the spread sheet simulation. The total mass of a single MDU-Bin is varied from 100 kg to 10000 kg. The net traction force is plotted as shown in Figure C13.

The ideal operating condition is at the maximum net traction force. At this condition, the supplied energy is equal the energy consumed. Hence, the equipment is said to be working at its highest efficiency. However, as shown in Figure C13, the maximum net traction force requires a large mass. As a result. it is not practical to operate the MDU-Bin at the optimum condition. As shown in Figure C13, the MDU-Bin will have to operat at a point lower than optimum. The team decided to limit the range of evaluation to 10000 kg. The energy expended and number of MDU-Bins required were used to determined the optimum operating conditions within the mass range mentioned above.

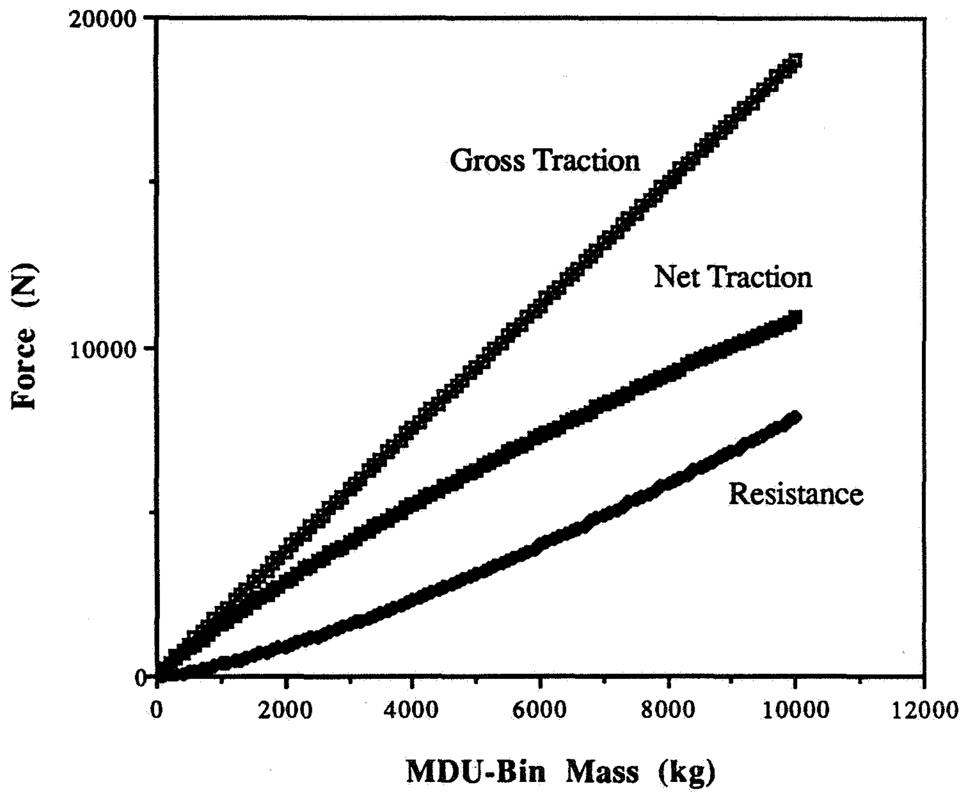


Figure C13 VARIATION OF GROSS TRACTION, RESISTANCE, AND NET TRACTION WITH MDU-BIN MASS

Figure C14 shows the variations in the total energy consumed due to the variation in the MDU-Bin mass. For a mass less than 800 kg, the MDU-Bin will not be able to work because of lack of traction, as shown by the negative values of energy in Figure C14. Above 2000 kg of mass, the energy required is almost in the same order of magnitude.

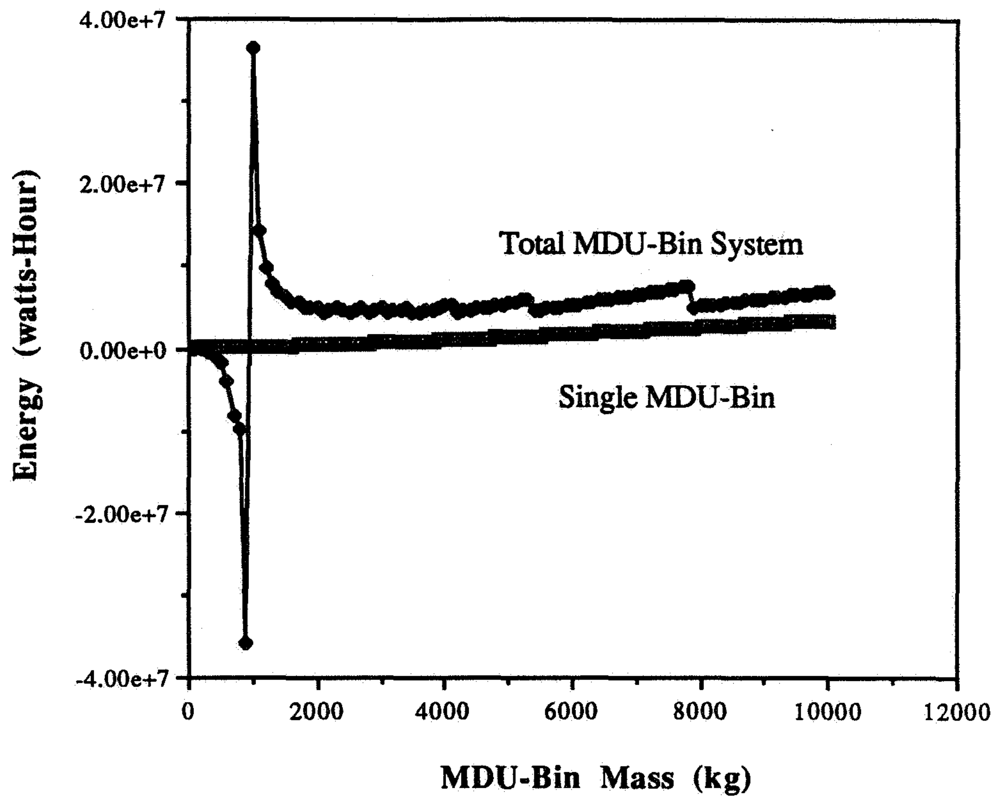


Figure C14 VARIATION OF ENERGY REQUIREMENT FOR THE TOTAL SYSTEM AND A SINGLE MDU-Bin

Next, the design team analysed how the the MDU-Bin mass affect the number of MDU-Bins needed to accomplish the mining operation. The team found that there are five viable groups of number of MDU-Bins, namely two, three, four, five, and six MDU-Bins. Within each group, there are a number of possible MDU-Bin mass choices. For example, in the six MDU-Bins group, the MDU-Bin mass ranges from 3100 kg to 3400 kg. The team found that the MDU-Bin with the least mass within each group consistently has the lowest power and energy, as shown in Figure C15 to C24.

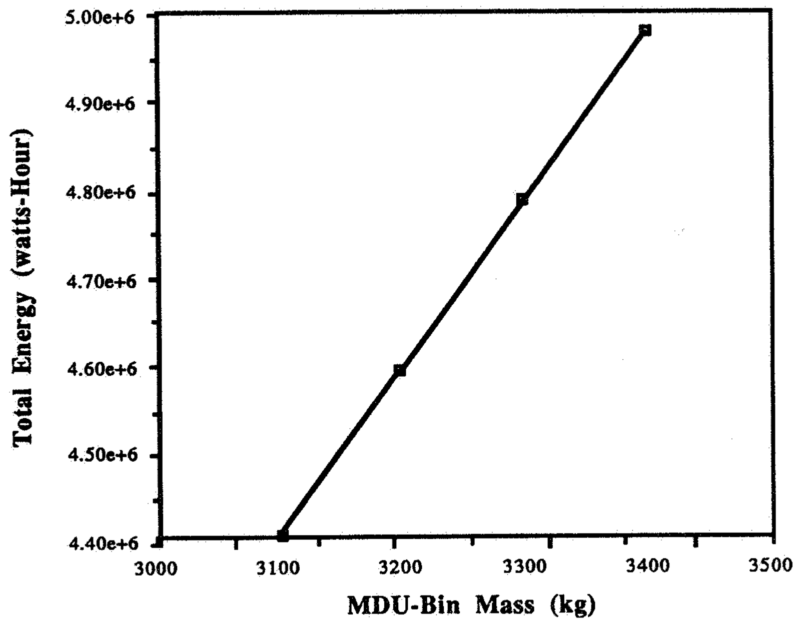


Figure C.15. VARIATION OF TOTAL ENERGY WITH MDU-Bin MASS (GROUP 6)

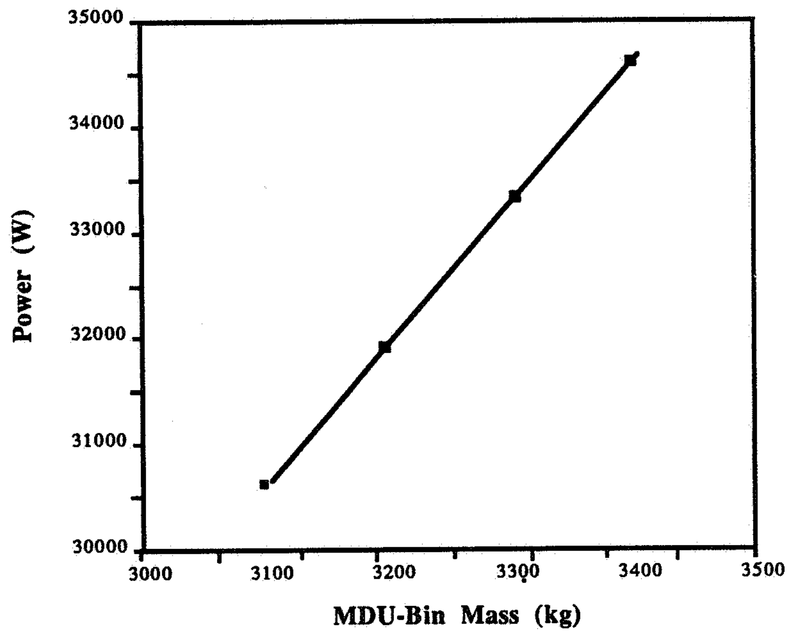


Figure C16. VARIATION OF POWER REQUIREMENT WITH MDU-Bin MASS (GROUP 6)

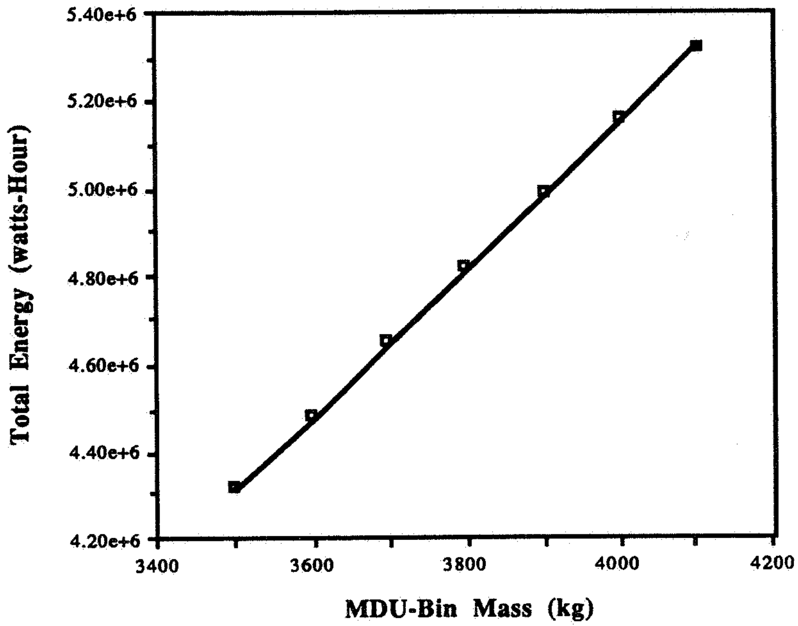


Figure C17. VARIATION OF TOTAL ENERGY WITH MDU-Bin MASS (GROUP 5)

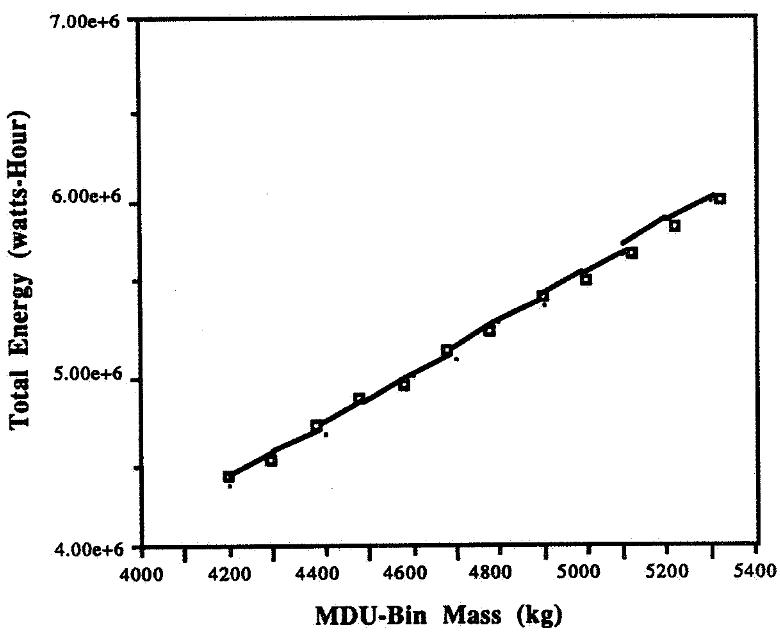


Figure C18. VARIATION OF POWER WITH MDU-Bin MASS (GROUP 5)

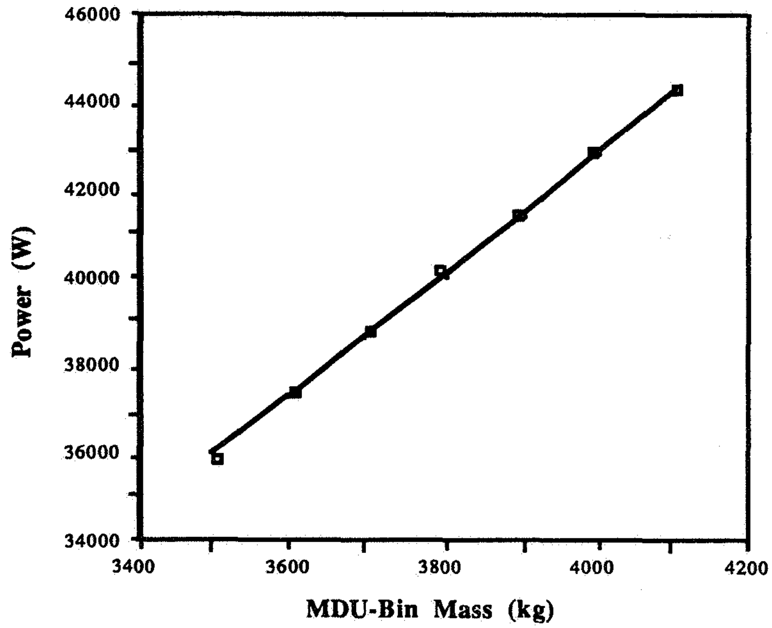


Figure C19. VARIATION OF TOTAL ENERGY WITH MDU-Bin MASS (GROUP 4)

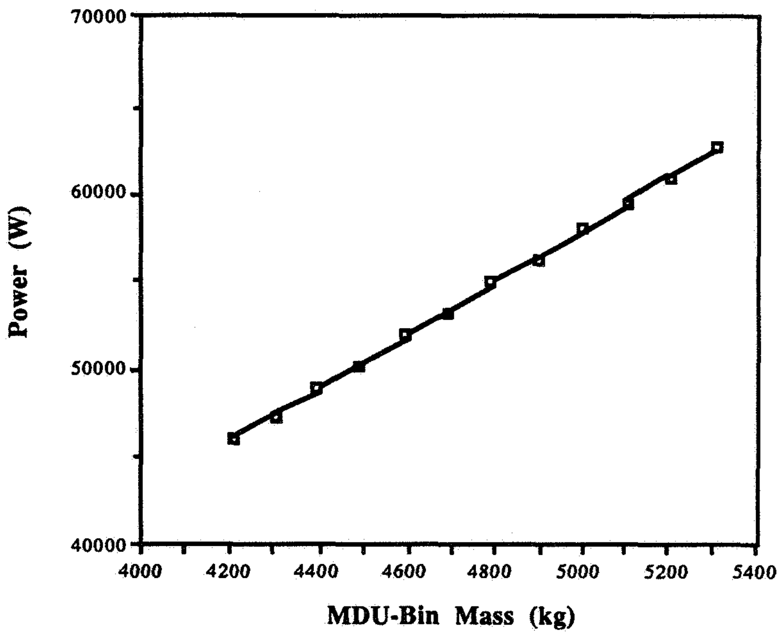


Figure C20 VARIATION OF POWER WITH MDU-Bin MASS (GROUP 4)

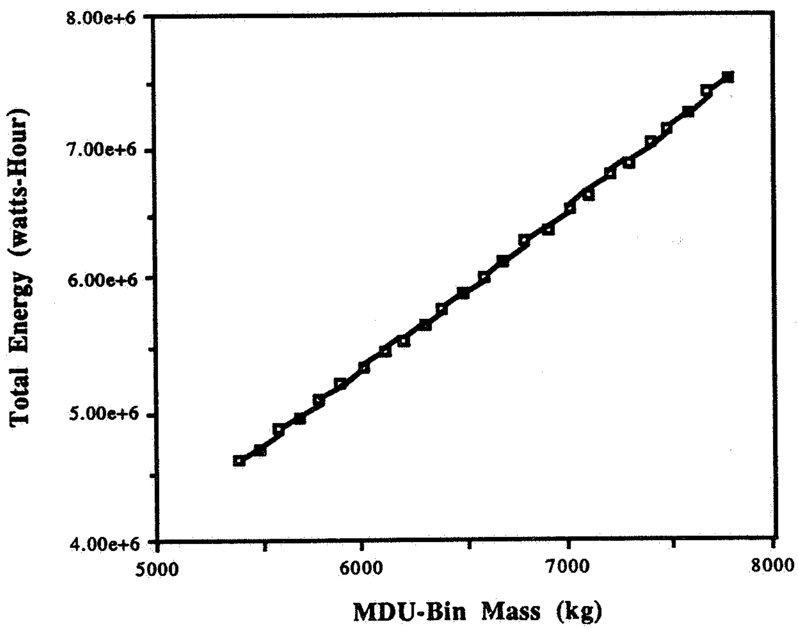


Figure C21. VARIATION OF TOTAL ENERGY WITH MDU-Bin MASS (GROUP 3)

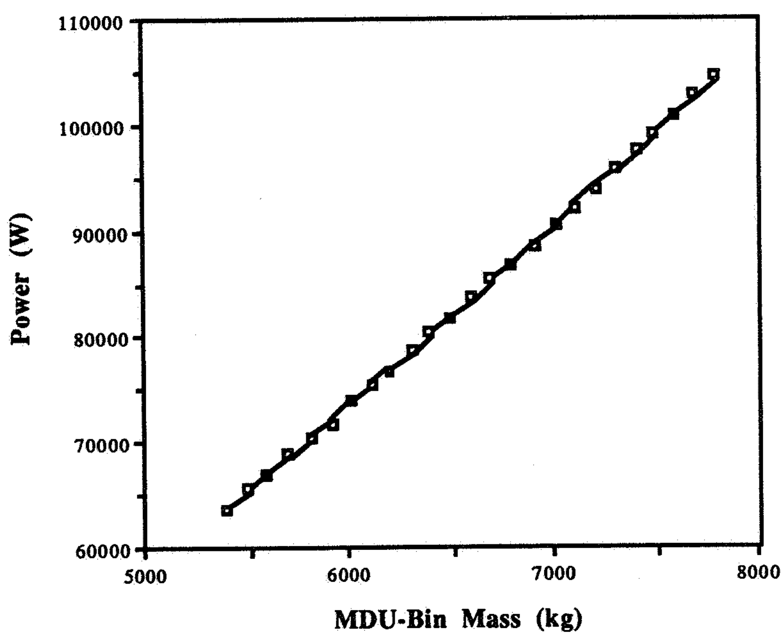


Figure C22. VARIATION OF POWER WITH MDU-Bin MASS (GROUP 3)

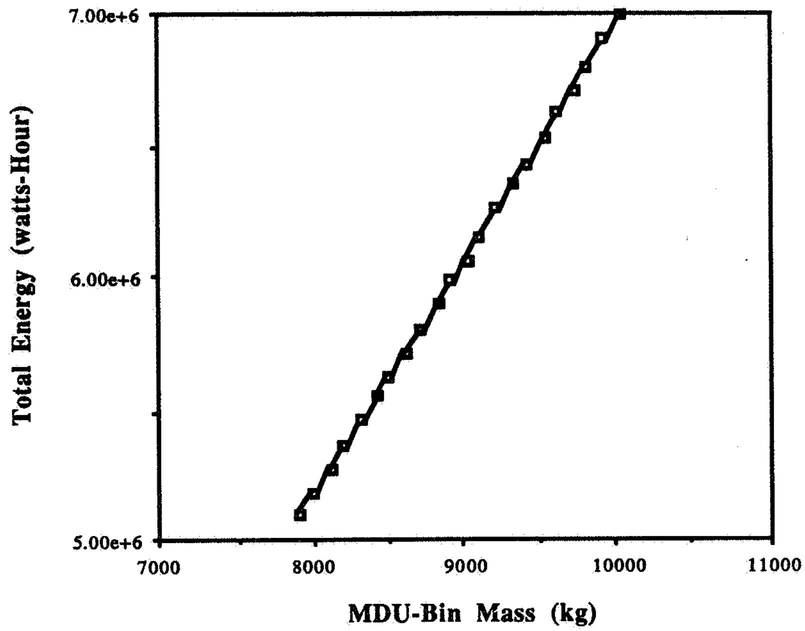


Figure C23. VARIATION OF TOTAL ENERGY WITH MDU-Bin MASS (GROUP 2)

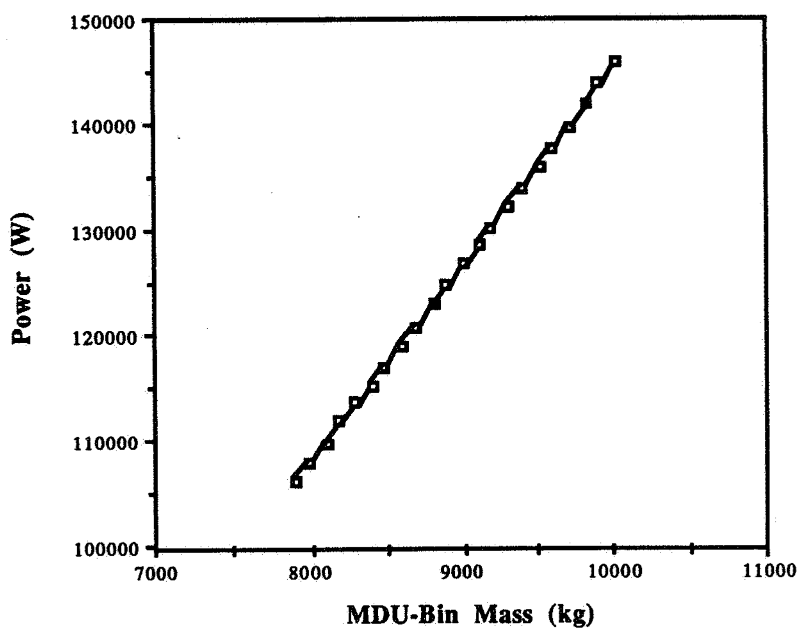


Figure C24. VARIATION OF POWER WITH MDU-Bin MASS (GROUP 2)

The next step the team took was to compare MDU-Bin with the least mass of each group in terms of total energy expended and total mass to be shipped. Figure C25 shows the relationship between the energy, mass, and number of MDU-Bins required.

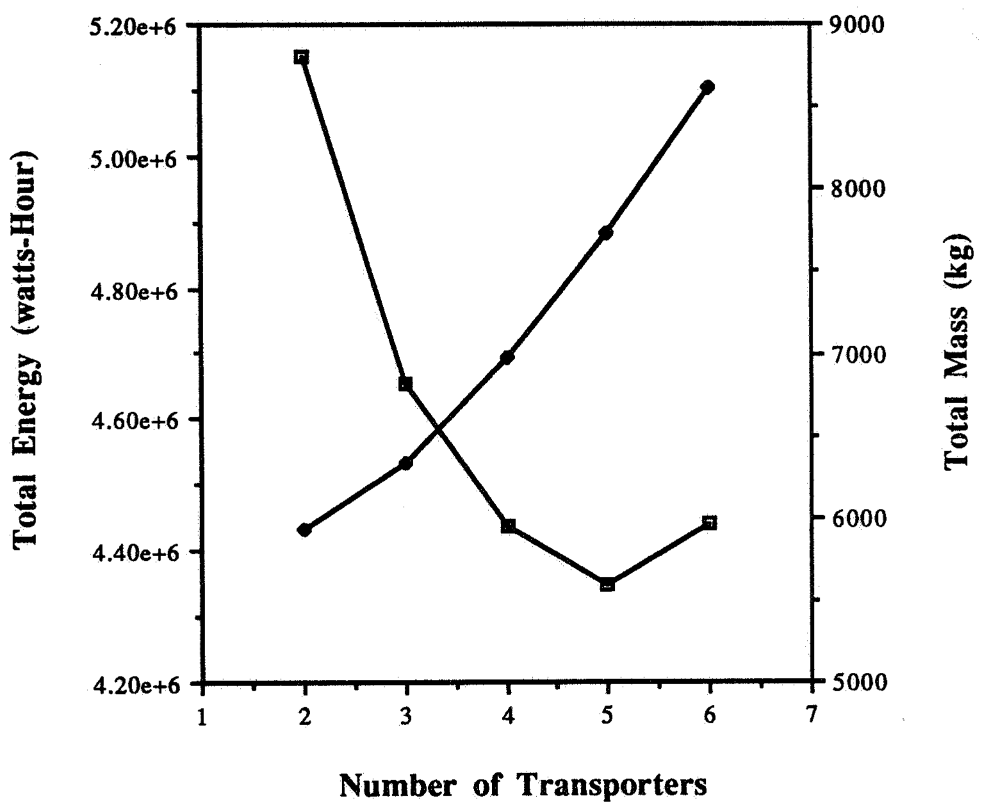


Figure C25. VARIATION OF TOTAL ENERGY AND TOTAL MASS WITH NUMBER OF MDU-Bin

Since the shipping cost is a one-time cost, the design team decided to choose the five MDU-Bins group because it requires the least energy to operate. Based on this selection, the following are the results of the analysis.

Table C7

Results of Parametric Analysis

Number of MDU	5
Power Required	35 kW
Payload	1960 kg
MDU-Bin Mass	1539 kg
Bin Volume	1.5 m^3

designs. However, dimensions will be given based on spatial requirement, as shown in the Design Solution Section. Based on these dimensions, the mass of the components were calculated. The following is the summary of the component masses.

Table C8

Component Mass of MDU and Regolith Bin

Component	Mass (kg)
Regolith Bin	103
Wheels	538
Frame	145
Fuel Cells	725
Control Unit	20

References

1. Mitchell, J. K, et al, "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction", Proceedings of the Third Lunar Science Conference, Criswell, David R.,(MIT Press: Cambridge, MA, 1972), p. 3249.

2. Balovnev, V. I., New Methods for Calculating Resistance to Cutting of Soil, (Amerind Publishing: New Dehli, 1983), pp.22-35.

3. Ibid (2), p.27.

4. Wood, Stuart , Jr, Heavy Construction: Equipment and Methods, (Prentice-Hall: Englewood Cliffs, NJ), pp. 182-183.

5. Bekker, M. G., Off-the Road Locomotion: Research and Development in Terramechanics, (University of Michigan Press: Ann Arbor, MI, 1960), p. 68.

6. Ibid (5)

7. Kraushaer, Jack J., Energy and Problems of a Technical Society, (John Wiley and Sons: New York, 1988), p. 335.

8. Ibid (7)