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TWO WHEELED LUNAR DUMPTRUCK

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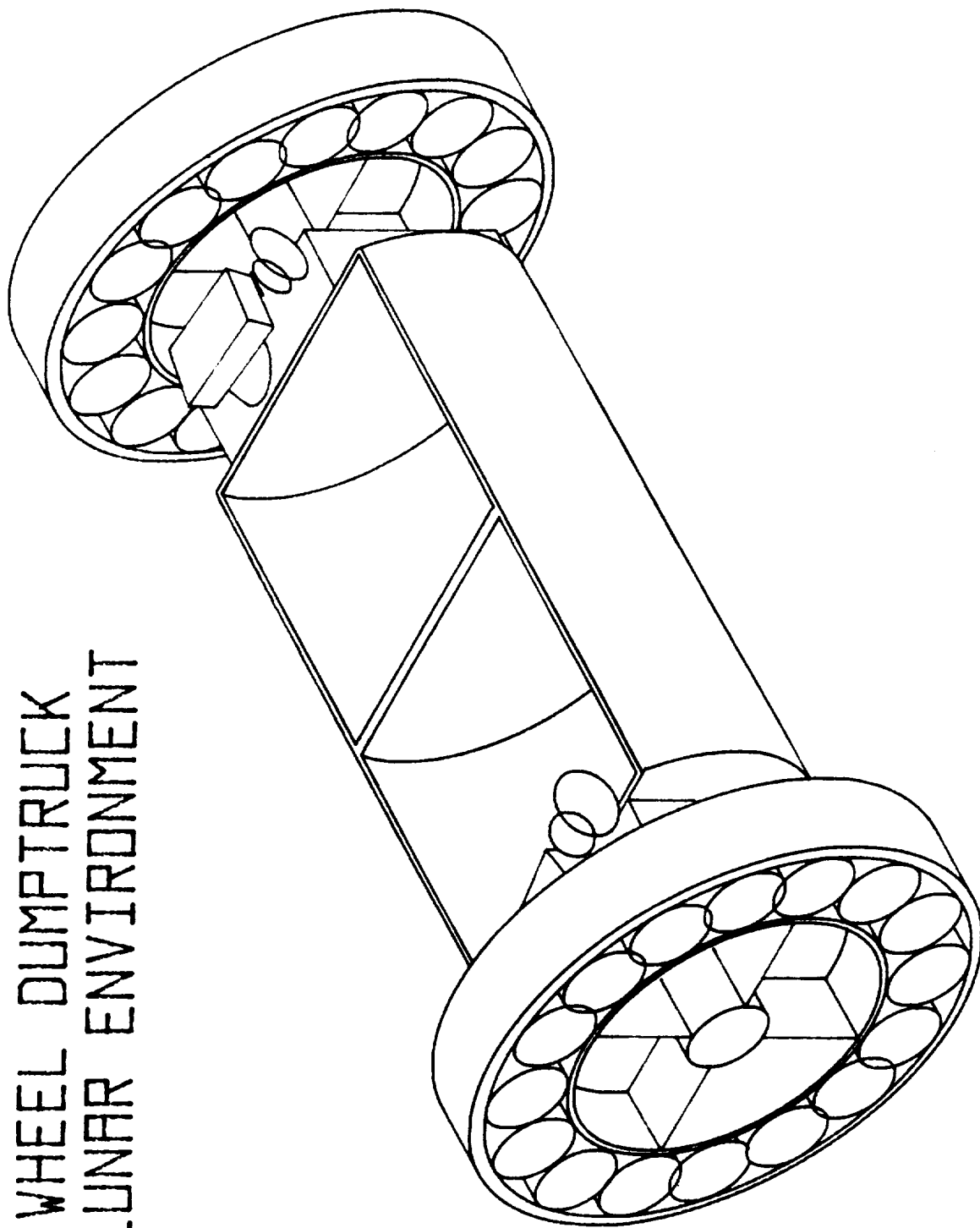Alan G. Shuman

TWO WHEEL DUMPTRUCK
FOR LUNAR ENVIRONMENT

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ABSTRACT

This report describes in detail the design of a two wheel bulk material transport vehicle. The design consists of a modified cylindrical bowl, two independently controlled direct drive motors, and two deformable wheels. The bowl has a carrying capacity of 2.8 m (100 ft) and is constructed of aluminum. The low speed, high HP motors are directly connected to the wheels , thus yielding only two moving parts. The wheels, specifically designed for lunar applications, utilize the chevron tread pattern for optimum traction. The vehicle is maneuvered by varying the relative angular velocities of the wheels. The bulk material being transported is unloaded by utilizing the motors to oscillate the bowl back and forth to a height at which dumping is achieved.

The analytical models provided in this report were tested using a scaled prototype of the lunar transport vehicle. The experimental data correlated well with theoretical predictions. Thus, the design established in this report provides a feasible alternative for the handling of bulk material on the moon.

PROBLEM STATEMENT

The objective of this project was to design a two-wheeled dumptruck to be used in lunar excavation operations. This design was to be a feasible alternative to conventional earth moving equipment, but was constrained to use only two moving parts. The vehicle must be able to transport 2.8 cubic meters of payload and successfully travel on various terrains of the lunar surface.

In order to be successful, the vehicle must be able to travel at a top speed of 15 km/hr, climb slopes of 25 degrees, and traverse inclines of 45 degrees. The vehicle must posses a configuration that cannot be permanently turned over. In addition, it must be able to accept guidance signals relayed from a remote location.

DESCRIPTION

The two wheeled lunar vehicle's primary components are a cylindrical aluminum bowl, two independently controlled direct drive motors, and two deformable wheels.

The shape of the bowl is an extended half cylinder with a length of 2.76m, a radius of 0.8m, and a thickness of 2.54 cm. The bowl is constructed of AA336 aluminum having a density of 2740 kg/m and a coefficient of thermal expansion of 0.00003 cm/C . A divider located in the center of the bowl reduces deformation and keeps the load distributed evenly. The opening, for the loading of soil, is 1.393 m across and 2.76 m long. These dimensions will allow the transport of 100 ft^3 or 2.8 m^3 of lunar soil.

Rigidly attached to each side of the bowl is a low speed, high torque synchronous motor. The stator is mounted on the bowl and the rotor is attached to the wheels. The motors are powered by three phase current which has been converted from direct current supplied from the batteries. The motors are housed in shells located on each side of the bowl. These shells also house the batteries and control system. All of these components are readily accessible by an access panel on the shell.

The wheels proposed for this design have a radius of 1.14 m (90 in.) and have a width of 0.46 m (18 in.) and will follow U.S. Patent #3,493,027. The deformable wheel, made from aluminum and titanium, deforms proportional to the applied load, thus providing good traction. A chevron tread

pattern is utilized for traction purposes.

The visual guidance system to be utilized will consist of an 8 - 12 micron infrared camera for resolution and a laser rangefinder for depth perception. These two pieces of equipment will be mounted on top of the motor housings. Control of the vehicle will be accomplished via radio singles from earth or some other remote location.

A summary of the design specifications and critical performance characteristics is provided in the following table.

SPECIFICATIONS

BOWL

CARRYING CAPACITY:	2.8 cubic meters
LENGTH:	2.76 m
RADIUS:	0.8 m
THICKNESS:	2.54 cm
MATERIAL:	AA336 aluminum
MASS:	969 kg

WHEELS

RADIUS:	1.14 m
WIDTH:	0.46 m
MATERIAL:	aluminum and titanium
MASS:	75 kg

MOTORS

MAX. POWER:	9.5 hp per motor
MAX. TORQUE:	2400 ft-lbs
MASS:	200 kg

ENTIRE VEHICLE

MASS UNLOADED:	1244 kg
MASS LOADED:	6695 kg

VEHICLE PERFORMANCE

MAX. ACCELERATION FULL: 0.762 m/s

MAX. ACCELERATION EMPTY: 0.642 m/s

MAX. VELOCITY :   15 km/hr

UPHILL MAX. GRADE :   25 degrees

DOWNHILL MAX. GRADE :   36 degrees

MAX. TRAVERSE ANGLE :   45 degrees

DYNAMICS

The dynamic analysis concentrates on stable linear propulsion of the bowl with no payload loss. As such, two modes of failure exist. First, the torque requirements for acceleration, climbing hills, and crossing obstacles may cause the bowl to tilt at an angle which causes spillage. Second, the torque requirements may exceed that which is obtainable from the given soil, causing excess slippage or immobilization. Both of these modes will be discussed in detail, however, it should be noted that "bowl tipping" is the failure most likely to occur and, therefore, sets the design criteria.

Soil Mechanics

Soil mechanics theory to date is based primarily on empirical data. The compound problems due to different soil types, terrain, and environments have allowed only limited use of theory. The most complete set of relations used are those developed by M.G. Bekker during the late 60's and early 70's. These relations are primarily "curve fits" to experimental data. They do, however, produce fairly accurate results and, therefore, are extremely useful in design.

Soil Thrust

When a rotating wheel is loaded with a vertical force W
a tractive effort or "soil thrust " H develops as a result of
the shearing strength of the soil. This force is
schematically shown in (figure 1).
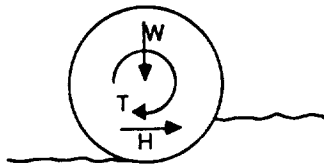
(Figure 1)

The soil thrust may remain constant or it may vary with
vehicle weight depending on the soil type. For wet clay or
snow the soil thrust is constant with respect to W due to
cohesive forces which bind soil grains together. This
bondage remains constant irrespective of the pressure exerted
on the ground by the wheel. For dry sands, however, soil
thrust is developed as a result of friction between the
grains. These forces obey Coulombs Law of friction and,
therefore, change with respect to pressure. Most soils have
both cohesive and frictional forces acting on the grains.
Thus, the soil thrust can be expressed by the following
relation:

$$H = Ac + W \tan \emptyset \quad \text{where } A = \text{contact area}$$

$$W = \text{weight}$$

$$c, \emptyset = \text{soil parameters}$$

A plot of H versus W for a soil with both cohesive and
frictonal forces is given in Figure 2a.
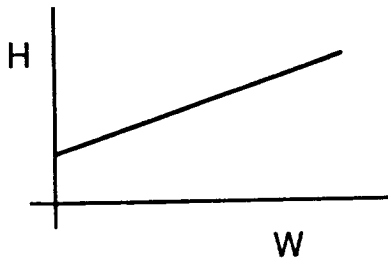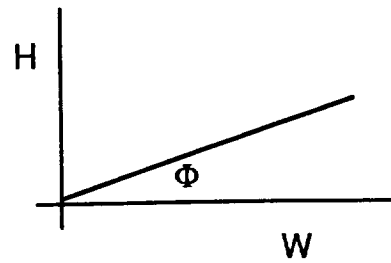
Figure 2a   Figure 2b

Since the moisture content of lunar soil is approximately
zero, c = o thus giving the graph of H versus W shown in
figure 2b.

Resistance

External motion resistances are forces which are created
by soil deformation and, therefore, do not produce soil
thrust. The major motion resistance is due to soil
compaction and is given by Bekker as:

$$Rc = \frac{1}{(3-n)^{\frac{2n+1}{2n+1}}\ (n+1)(Kc+bK\phi)^{\frac{1}{2n+1}}} \times \left(\frac{3W}{\sqrt{D}}\right)^{\frac{2n+1}{2n+1}}$$

where   W = total weight (lb)

        D = wheel diameter (in)

        b = equivalent wheel width (in)

   kc, kϕ, and n are all soil parameters which relate flat
plate sinkage to pressure by:

$$Z = \left(\frac{P}{Kc/b + K\phi}\right)^{1/n}$$

           where p = plate pressure (psi)

If vehicle parameters are used, the sinkage equation

becomes:

$$Z = \left(\frac{3W}{(3-n)(Kc+bK\phi)\sqrt{D}} \right)^{\frac{Z}{2n+1}}$$ (Bekker 1966)

which accounts for the curvature of the wheel. The
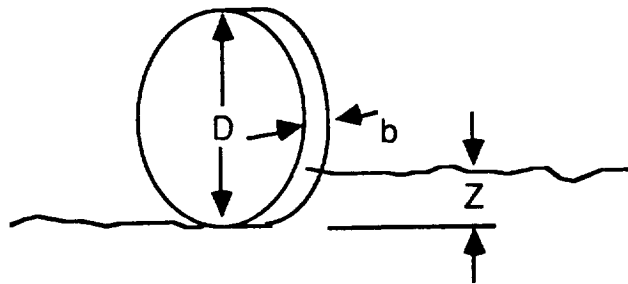parameters are shown in (figure 3).

Figure 3

kc and ko are constants describing the cohesive and
frictional forces respectively.

Sinkage versus payload for the lunar design is shown in
Appendix A Figure 1. Since kc, kϕ, and n are empirical
constants, values for lunar soil are not readily available.
Thus, the values for play sand which has a moisture content
of zero and a density comparable to that of lunar soil has
been used.

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Drawbar Pull

The ability of a vehicle to move depends upon difference
between the soil thrust H and the resistance R . It is
customary to refer to this difference as drawbar pull
indicating that force which would be directly measured on a
tow hook or trailer hitch. Mathematically, drawbar pull is

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expressed as:

$$DP = H - ?$$

In the lunar design, drawbar pull is the force parallel to the ground which is applied to the bowl. This force is used for both acceleration and hill climbing. A drawbar pull of zero indicated that the bowl has become immobilized while a negative drawbar pull indicates that a force must be applied in order to keep the bowl from moving in the opposite direction, for example, back down a hill. For a rigid wheel in dry frictional soil, (Poletayer 1964) expressed drawbar pull as follows:

$$DP = W\left(\phi\left(1+ \frac{\phi^2}{3}\right) + \frac{4\phi(5-3n)Z}{5(3-n)\,D} - \frac{1.5(1+\phi^2)(2-n)Z^{1/2}}{(3-n)\,D^{1/2}} - \frac{2(3-2n)Z^{3/2}}{3(3-n)D^{3/2}} \right)$$

A plot of DP versus weight is given in Appendix A Figure 2, and DP versus hill incline is given in Appendix A Figure 3 for the lunar design. Figure 3 of Appendix A indicates that the maximum hill which the lunar design can climb is approximately .44 radians (25°).

Torque Requirements

Although drawbar pull is useful in design, a stress analysis of the wheel is a much more useful approach.

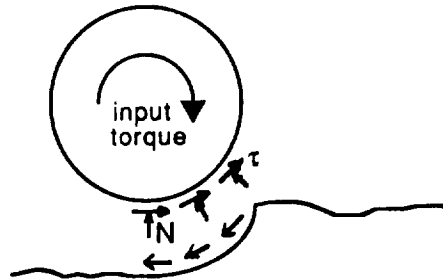Figure 4 indicates the stresses acting on a wheel in rotation.

Figure 4

Shear stress acts tangent to the tire, opposite the input torque direction, while normal forces act normal to the tire toward the center. Since the normal stress has an equivalent force which runs through the tire center, it contributes no torque about the center of the wheel. The shear stresses act in such a way as to propel the wheel along the surface. Thus drawbar pull originates from the shear stresses acting on the wheel.

Like drawbar pull, the shear stress has two components, one which propels the vehicle, the other which represents resistance. Bekker gives the shear stress as follows:

$$\tau = p \tan \phi \quad - \quad \frac{K \, Z^{(n+1)}}{1(n+1)}$$

propulsion   resistance

where P = pressure exerted on the ground
      K = kc/b + kφ
      Z = sinkage
      n = soil exponent
      0 = angle of friction
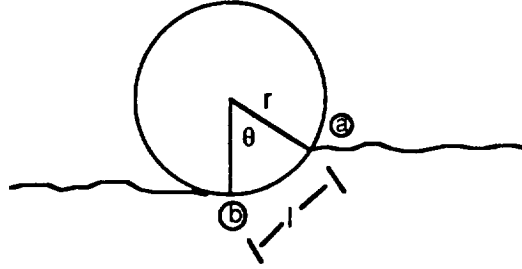   1 = track length

Track length l is defined in (figure 5).

Figure 5

Since the diameter is large (i.e. small curvature), l is approximately equal to the arc length between points a and b. Thus,

$$l = r\theta$$

from previous discussion,

$$P = K z^n$$

Thus the shear stress can be represented as:

$$\tau = Kz^n \tan \phi - \frac{K\, z^{(n+1)}}{r\theta(n+1)}$$

The torque which must applied is then defined by:

$$T = \int D/2\,\tau\, dA$$

assuming τ to be constant.

$$T = D/2\, \tau\, A$$

$$A = bl \qquad \text{where } b = \text{tire width}$$

Thus,

$$T = (D/2)\cdot b \cdot (D/2)\cdot \theta \cdot \tau$$

$$= \frac{D^2 b\theta\, \tau}{4}$$

The starting torque, defined as the torque required to begin movement, is equal to the torque produced solely by the resisting shear.

$$TS = \frac{D^2 b\theta}{4} \cdot \tau_R$$

$$= \frac{D^2 b\theta}{4} \frac{KZ^{(n+1)}}{r\theta}$$

$$= \frac{DbKZ^{(n+1)}}{2}$$

while the maximum torque obtainable from the soil is given by

$$TM = \frac{D^2 b\theta}{4} \cdot \tau_r$$

$$= \frac{D^2 b\theta}{4} \left(KZ^n \tan \phi - \frac{KZ^{(n+1)}}{r\theta(n+1)} \right)$$

Starting torque vs weight and maximum torque vs weight are both plotted in Appendix A, Figures 4 and 5 respectively, for the lunar design.

Bowl Tilt

When a torque is applied to the wheels in order to propel the bowl, an equal and opposite torque is applied to the bowl as shown in (Figure 6).
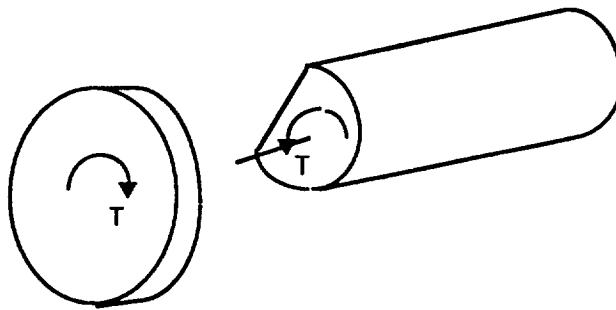

Figure 6

Thus, while moving, a torque is applied which tilts the bowl "toward" the direction of movement. In steady state,

the bowl tilt will remain constant. Thus, the input torque
will be balanced by a torque due to the mass of the bowl and
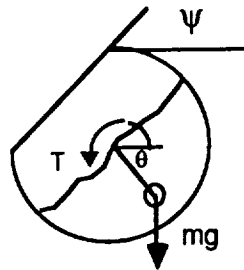the angle of tilt. This is shown in (Figure 7).

Figure 7

or,

$T = mg \cos \theta$

$\theta = 90 - \Psi$

$T = mg \sin \Psi$ $\qquad$ Ψ = angle of tilt

This analysis assumes that the soil does not shift in the
bowl appreciably. This was experimentally determined to be
accurate up to a tilt of about .7 rad (45). Torque vs
bowl tilt is plotted in Appendix A Figure 6. The maximum
torque that can be applied by each motor (full bowl) is
approximately 1400 ft-lb while the maximum torque (empty
bowl) is approximately 300 ft-lb. The results of the torque
- bowl tilt analysis is given in the table below.

	starting torque	bowl tilt	45 torque
full	520 ft-lb	15	1400 ft-lb
empty	40 ft-lb	6	300 ft-lb

Thus an additional 880 ft-lb of torque per motor is
available for acceleration, hill climbing, and obstacle

crossing when the bowl is full, while an additional 260 ft-lb is available when the bowl is empty.

SYSTEM EQUATIONS

Applying Newton's Laws to the free body diagram of the bowl yields the following governing differential equations:

$$J \frac{d^2 Y}{dt^2} = Ti - Mg \cos(Y)$$

and

$$\frac{d^2 X}{dt^2} = r \frac{d^2 Y}{dt^2}$$

where Y = angle of bowl tilt (+ uphill, - downhill)
J = polar moment of inertia of the bowl
M = mass of the vehicle
x = position parallel to the surface

Although the form of these two equations is simple, the solutions are complex. This is primarily because of the non-linearity of the torque equation. The conventional method of solving this equation is to assume that sin(Y) is approximately equal to Y. However, this is only valid for small changes in Y which is not applicable in this case since the bowl tilts $\pm$ 45°.

In addition to the above problem, the nature of the damping ratio is not known and, therefore, has been omitted. With out damping, the bowl tilt would oscillate even in steady state, which was found not to be the case during experimentation.

Although the solutions to the above equations are complex, there is an alternative method of describing the bowl acceleration paralell to the surface. Since the drawbar

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pull represents the net force acting on the bowl paralell to the ground. this force multiplied by the mass yields the acceleration of the bowl along the surface. When the vehicle is climbing or traveling down a hill, the net force along the surface equals the drawbar pull and the component of the vehicle weight along the surface.

Thus, the acceleration can be expressed as

$$\frac{d^2 X}{dt^2} = M \ (DP - \sin(Y))$$

where M = mass of the vehicle
DP = total drawbar pull from both wheels
Y = angle of bowl tilt (+ uphill, - downhill)

DESIGN OF LUNAR DUMPTRUCK BOWL

Perhaps the main component of the lunar dumptruck design is the bowl. The bowl, or hopper, is responsible for holding the lunar soil which is to be transported. The bowl must be able to accept soil through an opening at the top, transport the payload without losing any out the same opening, and dump the soil through the opening upon arriving at the designated dump site.

The considerations involved with the bowl are obvious. The shape of the bowl must lend itself to the desired tasks. The bowl must be capable of transporting a certain set volume of lunar soil during each trip to the dump site. The bowl must also be capable of sustaining the harsh lunar environment, particularly the temperature extremes and thermal gradients involved. Lastly, the bowl must be designed

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to withstand problems associated with the dumptruck's motion.

The first of these considerations is very important. The shape of the bowl will determine such things as the dimensions of the vehicle, weight and thus cost, and performance capabilities. The volume which the dumptruck is designed to carry also determines to a great extent these specifications. It is desirable to carry as much lunar soil as possible, but one sacrifices weight, cost, and performance to obtain a large capacity.

As with all materials involved in the design, the bowl must be made of metals capable of withstanding the lunar environment. The main problem with the bowl will be the presence of temperature gradients, which can cause thermal stresses in the bowl, possibly leading to failure. Corrosion is not a problem in the lunar environment because of the vacuum condition. This precludes the necessity of finding a type of paint that is capable of protecting against corrosion.

In order to deliver its capacity to the dump site, the bowl must be able to withstand the disturbances incurred in the motion of the truck. The loss of lunar soil could come from jolts to the dumptruck as it passes over small obstacles and from random swinging of the bowl when there is a shift in the payload. Another criteria of the design is that the dumptruck must be capable of righting itself should it flip onto one of its wheels while in the process of traversing an incline.

To begin the design of the bowl, many shapes and capacities were examined. A decision was made on the basis of each shapes advantages and disadvantages. Professor Brazell suggested a range within which to have the capacity, the final volume being chosen to give reasonable hauling capabilities. The bowl was chosen to be able to carry 2.8 cubic meters (100 cubic feet) of payload. After setting the volume, exact dimensions were chosen which were a compromise between weight, cost, and manueverability. The bowl material was then selected through research and contacting various experts.

The bowl design which is to be implemented can best be described as a cylindrical shape with a 120 degree opening through which soil may pass, as shown in Appendix C Figure 1. The bowl is to have a radius of 0.804 meters and a length of 2.76 meters giving the wheel a radius of 1.14 meter and a 0.34 meter clearance. The advantages of this type of shape are many. The opening, which is 1.393 m across and 2.76 m long, is large enough for another remotely controlled machine to easily load lunar soil. The motors used to drive the wheels can be easily mounted onto the flat sides of the bowl. Also, the proposed bowl shape has better stability in motion than other possible shapes. This is because the center of gravity is lower than other designs and is well below the axle. Also, the long cylinder shape makes the vehicle more stable when traversing hills laterally. This bowl design also has the advantage of being able to keep more soil in the

bowl because the cylinder extends beyond the 180 of a half
cylinder, as will be discussed further below.

The only problem with the 240 design is its use of
large amounts of material, raising the weight and cost of the
design. The excess weight is not advantageous because of the
cost incurred to ship the dumptruck to the moon.

Once the dumptruck arrives on the moon the excess weight
of the bowl will be advantageous. The weight of the bowl
provides the counter-torque necessary to accelerate the
vehicle. If too light, the bowl will simply spin under the
torque of the motors and the wheels will not be forced to
roll forward.

The material of the bowl is to be aluminum, specifically
AA336. The material selection was researched extensively,
information being obtained through literature, graduate
students, professors, and NASA engineers. Ms. Jill Harvey
suggested that we contact Mr. Dennis Matthews of NASA for his
input. He directed the group to a technical report, Design,
Development, and Manufacture of the Lunar Roving Vehicle
Technical Proposal. Through the use of the Materials
Engineering Materials Selector 1986 and a materials selection
data base, the group narrowed the choices to two
possibilities, specifically AA336 and AA390. Dr. Carolyn
Meyers, of Georgia Tech's Mechanical Engineering Department,
agreed that these metals are well suited to the design
criteria. Both of these alloys have low coefficients of
thermal expansion, but the AA336 possessed better high

temperature strength. A T65 heat treatment is also suggested
to improve the strength. The alloys tensile strength of 47
kpsi and a yield strength of 43 kpsi satisfy the design
needs. The results of a stress analysis are given in Appendix
C Figure 2.

It was decided that a an anti-wear laminate was not
needed for the design, because aluminum already has good
resistance to wear. The addition of laminate would improve
the design's anti-wear properties, but sacrificing both
weight and cost.

The bowl design was decided to be a 240 degree cylinder
in which the determined payload is achieved by filling to the
180 degree line. This design is capable of withstanding any
motion incurred by the dumptruck while en route to the dump
site. The main problem is the counter-torque applied to the
bowl by the motors. Although there is sufficient weight in
the bowl so that it won't flip, it will travel at a slight
angle to the normal. Since the bowl design has an opening of
120 degrees, or 30 degrees past a flat top on each side, any
motion of the soil in the bowl will be contained by the
sides. These built-up sides also satisfy the design
consideration of the bowl being able to sustain its load when
any swinging might occur during a sudden change of motion
incurred by the vehicle traveling down an incline or
traveling over an obstacle. Another design consideration, the
ability of the dumptruck to right itself, is satisfied
through a combination of both the bowl shape and the wheels.

The shape of the bowl, possessing a large distance between the wheels, would be inherently unstable if standing on its end due to the high center of gravity that would result. This fact would be combined with the controller turning the wheel on the ground in order to impart some motion to the overall machine causing the truck to fall back into a desirable position.

DESIGN OF LUNAR DUMPTRUCK WHEELS

Aside from the bowl, the other main component of our design are the wheels. The wheels are responsible for supporting the bowl, both empty and full, providing traction to move the machine from the landing site and back again, and aiding in the dumping process. The size of the wheels that must be used have a 1.14 m radius and a 0.46 m width.

The two main constraints involved with the wheels are the environmental effects on the wheels structure and the traction performance of the wheels. Each of these areas had to be studied and a final design had to comprise the best qualities of all designs studied.

Of the environmental constraints which the lunar environment imposes, those which are applicable to the wheel design are the temperature extremes and the hard vacuum. The extreme temperatures present and the temperature gradients which are produced can be withstood by only a select group of materials. The temperatures also cause problems with the possibility of using pneumatic tires because of the pressure

extremes that would be a function of the atmospheric temperature. The hard vacuum combined with the temperature leads to other problems as well. Under these conditions, any surfaces which rub together could possibly cold weld to each other, not allowing any further relative movement.

In order to transport a payload from one location to another, the proposed dumptruck design must incorporate wheels that are able to obtain sufficient traction on the lunar surface. The truck must also be able to successfully navigate inclines which may be encountered while traveling to or from a dumpsite. The properties of the soil, being much like dry sand on earth, dictate that a unique tread design be implemented. This design must be able to aid in traction when passing over small obstacles as well as allowing for a large surface contact area in order to better climb hills.

At the outset of the wheel design, innovative designs were sketched out on paper. The general advantages and disadvantages of each design were established. Based on the choice of what was considered an optimal design, research was performed to establish material and performance parameters. Included in this research was establishing a contact at the Tillage Laboratory at Auburn University in order to obtain vital information concerning tread design. The research process led to a design that optimized the parameters that were deamed as important by the discovery of a patent alternative.

The design which is being proposed is that found in the

United States Patent #3,493,027 for a deformable vehicle wheel. The design was designed by inventors Calvin V. Fern and Donald L. Dewhirst to be used on the lunar surface. The advantages of this design are many, ranging from the materials that are used to enhance the performance of the wheel, to the traction and surface area it provides while in motion. The design incorporates an inner hub assembly connected to an inner rim by a system of spokes. The inner rim is connected to the outer rim by flexible rings.

Most of the wheel is composed of aluminum, including the hub and the connecting spokes. The aluminum provides the design necessary stability while being lightweight and able to withstand the temperature extremes. The connecting rings and the outer rim are made of titanium, which has a superb strength to weight ratio and is also quite flexible.

The performance of this wheel satisfies all of the design criteria set forth. As the wheel traverses a surface, the applied load on the wheel forces the deformation of the outer rim and rings. The rings act as springs, deflecting and supporting the wheel in proportion to the applied load. This distribution of the load allows the surface contact area to increase, improving traction while not allowing the wheel to penetrate the surface to a great degree. In this fashion, the rings serve as shock absorbers, keeping the load in the truck stable. Another advantage of the wheel is that the resilient titanium rings deflect such that the traction performance obtained is comparable to that of pneumatic tires found on

conventional wheels. This likeness will not only aid in realizing possible limitations, but also in earth testing of a final model.

A drawback to this design comes in the varying support found around the wheel. Because the resilient rings act like springs, they will give different support at locations where the rings actually touch the outer rim as opposed to locations on the outer rim that are between the ring contact areas. These differing spring rates found on the outer rim could be unsettling to a load found in the bowl. This problem was overcome by designing the wheel to have more rings at a closer spacing, though not approaching a rigid wheel. Increasing the number of rings along with realizing that, as with knobby tires, off-road vehicles do not experience this problem to any extent, provides an excellent solution to the problem of wheel design.

Having decided on the wheel design, it became necessary to produce a tread design which would aid in the traction of the dumptruck. The designs which were studied included those found on present day earth moving equipment, the tread design utilized on the lunar rover of Apollo missions, and other original designs which were perceived. Since the tread design of the lunar rover had already proven itself, it became the obvious first choice. To obtain a professional opinion on the matter, the Tillage Lab was contacted. The researchers at the lab agreed with our speculation about the lunar rover design. Based on this combined information, the chevron tread design

was chosen. An example of this wheel design tread is shown in Appendix C Figure 3.

MOTORS

Due to the main design constraint faced by this group, incorporate as few moving parts into the design as possible, the motors chosen to drive this vehicle had to be both extremely versatile and durable. Many motor designs and configurations were studied, yet the motor that seems to fit the applications called for is a low speed fractional horsepower motor designed by Dr. Kent Davey of Georgia Tech's Electrical Engineering Department.

Some of the main advantageous of using this type of motor are as follows: i) This design is extremely efficient, by the inherent qualities of the design, many energy losses that effect motors can be neglected (such as eddy current and hysteresis losses). ii) the motor is designed to operate without an unlimited power supply, and iii) the output torque of this motor can be dramatically increased by small increases in its radius.

The rotor of Dr. Davey's motor design can be easily modified to meet the design requirements. A "spoked" design, as shown in Appendix D Figure 1, will be used so that a larger radius can be achieved without significantly increasing the weight of this component. As the radius (r) increases the output torque increases as a function of r^3, while the weight increases as a factor $r^1.5$. Therefore, the

motors torque to weight ratio becomes greater as the radius becomes larger. In order to obtain the torque the vehicle requires a radius of 0.6 meters will be used.

Another factor that will enhance the performance of the vehicle is the choice of magnets to be used. Magnets that are being tested in prototype motors have a surface magnetization value of 0.11 webers/square meter, therefore this value must be met in the final design so that performance objectives will be satisfied. There must be a total of 48 magnets on both the rotor and stator, each with a length of 0.2 meters. Also, the magnets must be backed by a highly permeable iron so that a greater efficiency will be obtained. An additional consideration for increasing the efficiency of the motor is the fact that the losses are proportional to the square of the rotor magnet's strength. This means that doubling the strength of the magnets, the losses will be reduced by a factor of four.

Another question that had to be overcome was the question of power to supply these motors. In order to overcome this obstacle, direct current power will be supplied in the form of four batteries. This D.C. energy will be fed into a "black box" so that the output power is in the form of three phase alternating current. This power is then fed into the motor which inherently makes the machine more efficient. This "black box" design has been successfully implemented by Dr. Davev in applications involving smaller motors.

The actual configuration of the motor will be quite

simple, as depicted in Figure 2 of Appedix D. The stator will

be rigidly attached to the bowl and the rotor will be

attached to the wheel, constituting the only moving parts in

the design. The motors will be housed in a shell to

accomplish three important parameters. These parameters are

i) to protect the motor from the lunar environment, ii) to

establish a constant configuration of the motor (by using

bearings), and iii) to house the power and control systems of

the vehicle.

Inside the housing, the batteries will be mounted below

the motor in order to keep the overall length of the vehicle

down. Also, the power converter and control systems will be

mounted below the motor for both protection from the elements

and easier accessibility for maintenance via a hinged door at

the bottom of the housing.

CONTROLS

Many advantages are derived from testing a scale model

of a design, not only is experimental data is obtained, but

also control methods can be scaled up from a model to an

actual product. One extremely important observation that was

made by testing the model is that it is much easier to

control the movement of the vehicle by keeping the speed of

one wheel constant and varying the relative velocity of the

second wheel in order to turn the vehicle. This philosophy

was used in developing the control system for the lunar

version of the dumptruck.

This type of design can be implemented by utilizing a proportional feedback controller to vary the output torque, and therefore the speed, of one of the wheels relative to the constant output wheel. This method of maneuvering the vehicle proved to be much more efficient than attempting to simultaneously control the output of both wheels.

In addition to the proportional controller that will be used in this system, another important piece of electronic equipment must be incorporated. This component is an optical encoder that can measure the position of the rotor relative to an established position on the stator which will give the instantaneous speed output which can then be used to determine the torque output. By utilizing this combination of equipment, the vehicle can be driven from a remote location by varying only one controller.

As depicted in the schematic of the control system, Appendix D Figure 3, the entire control system is quite simple. A signal from the controller is first received by the system, it is then changed into predetermined values of the constant in the proportional controllers of both motors, for either a straight path or a turn. Next, it is passed through a comparator. The comparator then feeds a power interface to control the input to the motor to set the desired output. After the motor has been input with the new control sequence the optical encoder reads the position of the rotor. This information is then passed through an input/output card to obtain the instantaneous readings of speed and torque.

Finally, this information is fed back into the comparator so that more modifications to the input signal can be made to position the vehicle along the desired path.

VISUAL GUIDANCE SYSTEM

Since the two-wheeled dumptruck design will be used in the construction of lunar bases and will not be directly controlled by men on the lunar surface, there is a need for visual information to be sent to the earth from the lunar surface. The vision system will serve as an integral part of the overall guidance of the vehicle, either as an aid to the controller on earth or as a check of the dumptruck's progress on a particular mission.

Because one of the overall design constraints of the vision system is simplicity, an elaborate system can therefore not be implemented. The mounting locations on the dumptruck for the system are also limited. The best location being on either side of the bowl in the space between the bowl and the wheels.

If the vision system is be used by a controller on earth, the vision system employed must be capable of generating an accurate picture of the terrain in the path of the vehicle. This is not only to serve as basic guidance, but also to give the controller time to maneuver the dumptruck away from large obstacles given the communication time delay that exists between the earth and the moon. This delay is comprised of three seconds for the signal to come from the

moon to the controller's screen and three seconds for the controller's return signal to reach the moon and maneuver the dumptruck.

Another possibility for the vision system is that of acting as a monitor. This would be the case if the dumptruck utilized an onboard computer which carries a particular task program. A scientist on earth could monitor the performance of the dumptruck as it completes its program. This method would entail the use of communication beacons would be placed in triangular form around the area in which the tasks were to be carried out. The dumptruck would maneuver by way of receiving various tones from the beacons.

The first task accomplished was a decision concerning the type of control to be implemented. A final decision was made following numerous brainstorming sessions. After performing some preliminary research. the subject of lunar vision was found to be extremely complex due to the severe intensity of the sun. or lack thereof. Therefore, Mr. John Gilmore of the Georgia Tech Research Institute, an expert in the field was contacted to make a final decision.

It was decided that the dumptruck would be controlled remotely from earth, and that the visual system employed would serve as a way for the controller to maneuver the dumptruck through its tasks. This decision was made because of the obvious advantage of being able to get the truck out of difficult situation which may arise. For example. if the dumptruck was turned on its side. standing on one wheel. the

only way for the controller to right the dumptruck would be for the controller to spin the wheel that was in contact with the ground. The other possibilities of control limit the potential for rescuing the dumptruck from these types of situations.

A system satisfying the above needs was then decided upon. Mr. Gilmore explained that there are four pieces of equipment that could be used in the system. These are: 1) a video camera (color or black and white), 2) an 8-12 micron wavelength infrared camera (for resolution), 3) a 3-5 micron wavelength infrared camera (for depth resolution), and 4) a laser rangefinder (for depth perception). Because the dumptruck design can only utilize two of these, we decided suggested that the best possible combination would be the 8-12 micron wavelength infrared camera coupled with the laser rangefinder. These two pieces of equipment will give good acuity along with necessary and accurate depth parameters.

As stated before, the mounting positions will be on either side of the bowl. In order to obtain an unobstructed view, the laser rangefinder and infrared camera will sit atop the motor and power supply housings.

STEERING

After a desired path has been identified, by either a computer program or human controller, the vehicle can be successfully maneuvered by varying the input to certain components. For instance, if the vehicle needs to progress in

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a straight path the output of the variable wheel is set to be equal to the output of the constant output, or reference wheel. Likewise if a turn needs to be made, the variable controller is set to feed either a larger or smaller input signal into the variable wheel's control system to provide the desired turn.

Also, depending on the severity of the desired turn that must be made the controller will be held in the "non-equilibrium" position for a certain period of time. Approximations of these settings have been made and are included in Appendix E Figure 1. These values are guidelines to be used when controlling the actual vehicle. Experiments were attempted to verify these values, but due to the inconsistency of the controls used on the prototype, exact data could not be obtained.

This type of control is also advantageous when a change of speed is desired. In this case the reference wheel is either speeded up or slowed down while holding the output of the variable wheel equal to the same speed. This method leads to smooth acceleration and velocity changes so that the payload will not be adversely effected.

DUMPING METHODS

Two methods of dumping for the wheeled lunar vehicle have been examined. The first method utilizes the momentum of the vehicle to dump the lunar soil. The second method utilizes an intermittent torque from the motor to slowly

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swing the bowl over.

At a given velocity, the two wheel lunar dumptruck possesses kinetic energy that can be used to dump the material in the bowl. This can be accomplished by locking the motors at a given velocity allowing the wheels and bowl to act as one rigid body. The linear momentum of the bowl is transferred into angular momentum and linear momentum when the motors are locked up.

The easiest way to examine the feasibility of this method is to use a conservation of energy approach. When the motors are locked up the transfer of kinetic energy is given by the following equation:

$$KEi = DE + PEf + KEf$$

where KEi = kinetic energy initial

DE = dissipated energy

PEf = potential energy final

KEf = kinetic energy final

At the dumping point we will assume the wheels and bowl will come to rest, therefore the final kinetic energy is zero. The dissipated energy consists of the friction that occurs in the motors when locking the wheels and that from the rolling friction. The final potential energy is simply due to the gravity acting on the mass of the bowl and load. The initial kinetic energy is determined by:

$$KEi = 0.5 \ M \ V^2$$

where M = mass of bowl and wheels

V = velocity of the vehicle

The final potential energy is given by the following

equation:

$$PEf = M \, g \, l \, (\, 1 + \sin(\text{theta}) \,)$$

where l = distance from axle of bowl to center of
gravity of entire vehicle
g = lunar gravity (1.63 m/s^2)
theta = the angle the line from the center of gravity
to the axle of the wheel makes with the
horizontal

Using these relations, we can simplify our equations to:

$$0.5 \, M \, V^2 = DE + m \, g \, (\, 1 + \sin(\text{theta}) \,)$$

In our design, the mass of the wheels is negligible compared

to the bowl. If we assume the dissipated energy is small and

that the bowl will be completely empty when theta = 90, we

have the following equation:

$$0.5 \, V^2 = 2 \, g \, l$$

For a completely full cylindrical bowl, the following

equation will give the distance from the center of gravity to

the axle.

$$l = 4 \, r \, / \, 3 \, Pi$$

where r = radius of cylinder

Substituting and solving for velocity,

$$V = (\, 5.33 \, g \, r \, / \, Pi \,)^{(0.5)}$$

Our design utilizes a bowl with a 0.8 m radius. Using the

above equation, a velocity of 4.95 mph is obtained. This is

the minimum velocity necessary to dump a full load of lunar
material. Note that this velocity does not depend on the
mass of the load but only the radius of the cylinder. In
addition, this velocity is well within the design criteria of
10 mph.

The second method of dumping is swinging the entire
bowl. This method intermittently applies a torque on the
bowl in opposite directions. This reversing torque will
swing the bowl back and forth very much like a baby would be
rocked in a cradle. If a constant torque is applied during
each swing, the bowl will reach a greater height each cycle
and eventually the bowl will be flipped over completely.

In order to prevent the wheels from rolling, the torque
applied should be below the minimum amount needed to initiate
rolling. The number of swings are related to torque and are
shown in Figure 2 of Appendix E.

The amount of torque needed to dump depends on the
friction caused by the windings and bearings in the motors.
In theory, if the energy applied by the motors exceeds the
energy dissipated, the bowl can be flipped.

The swinging method is difficult to mathematically model
because it is difficult to determine the amount of resistance
in the motors and it is hard to determine the amount of
torque that can be applied to a swinging mass. If we assume
the resistance is proportional to the square of angular
velocity and that the motors have constant torque regardless
of angular speed, the number of swings to dumping can be

calculated for different applied torques. A program was
written to solve these equations and the results are plotted
in Figure 3 of Appendix E. A copy of the program is provided
as Figure 4 in Appendix E.

In order to make the swinging method operational, a
method of instantaneously reversing the motors at maximum
height must be developed. One method to accomplish this task
recognizes the fact that the acceleration of the bowl becomes
zero at the maximum height. An accelerometer can be mounted
to the bowl so that every other time it reads zero the motors
are reversed. This reversal is done at for every other point
of zero acceleration reading.

RIGHTING AN UPTURNED VEHICLE

There is a small possibility of the truck coming to rest
in an upturned position; that is resting only on the outside
of one wheel. The total length of the design is approximately
4 meters, while the wheel diameter that this displaced
vehicle would be resting on is only 2.25 meters. This makes
this position inherently unstable. The other source of static
comes from the fact that the bowl position will make location
of the center of gravity off the center line of the wheel
hub.

The combination of these two factors makes for little
possibility of the truck staying in this upturned position.
If this does occur, however, a method of increasing the
instability is needed. This may be accomplished by inputting

a signal to turn the wheel in contact with the ground. By turning this wheel, the motion imparted to the overall machine will cause enough instability to right the dumptruck.

EXPERIMENTAL VERIFICATION

A scaled prototype was designed and built to test the validity of the analytical models. Pictures of the prototype performing various tasks are presented in Appendix F Figures one through four. Three parameters were tested, drawbar pull, starting torque, and sinkage. The results are plotted in Figures 5 through 7 also in Appendix F.

The drawbar pull produced by a single motor was determined by placing an extension string on the axle of one wheel and measuring the maximum deflection of the spring. The spring rate was then calculated by hanging a known weight on the spring and measuring the deflection. The results, plotted in Figure 5, are promising although expected error is present. The primary source of error is due to the difficulty of accurately measuring the deflection.

Starting torque was measured by determining the angle of the bowl (i.e. the tilt) at the instant when the bowl began to move parallel to the surface. Again the primary source of error was the inability to accurately determine this angle.

The sinkage was determined by direct measurement of the track depth. However, the theoretical curve plotted in Figure 7 assumes "flat" wheels. The actual wheels on the prototype have curvature along the width.

Other inaccuracies can be contributed to the fact that the tests were run on outdoor sand which did not have a moisture content of zero. Thus, cohesive bondage was present between the sand grains which was not accounted for in the analytical model. The measured sinkage would, therefore, be expected to be lower than that indicated by theory.

Thus, although the analytical model appears to be accurate, more experimentation is needed before any broad conclusions can be made.

SITE SELECTION

Just as it not would be feasible to design a vehicle to efficiently travel on all surfaces on earth, the same is true for lunar applications. There is a limit on the amount of grade that can be climbed along with the type of terrain that can be traversed. Since certain vehicles are made for specific jobs, a determination must be made on where the vehicle will operate. Many sites were examined in order to determine the areas where the truck would most efficiently operate. Among those selected were several of the Apollo landing sites. The reason these sites were selected was because of the vast information known about the terrain from the previous missions. Since many other parts of the lunar surface have undesirable regions for lunar development, the operation of the dumptruck would be less efficient. The more information that is known about the working areas of the excavation equipment gives any mission a much greater chance

for success.

After researching many Apollo sites, it was determined that the Apollo 11, 15, and 16 sites could be used with a high success rate of the truck. The main Apollo landing site that has been studied is that of the Descarte, the landing site of Apollo 16. The reason this site is so significant is that Descarte formations cover approximately 11% of the lunar near side. This decision was made after studying photographs of the terrain and the design constraints of the vehicle. Typical terrain that is found in these areas can be found in Appendix G.

CONCLUSION

After reviewing the design considerations of the bowl, it is evident that the proposed design is satisfactory. The aluminum bowl is capable of transporting 2.8 cubic meters (100 cubic feet) of lunar soil in an environment containing large temperature extremes. The modified cylindrical shape of the bowl allows for shifting of the payload while in motion, as well as, providing a sufficient opening for loading. The flat sides of the bowl are a convenient location to mount the motors and thus, eliminating the need for gear trains.

The design of the wheel, a U.S. Patent, is well-suited for the design specifications. The deformable vehicle wheel performs comparable to pneumatic tires while being able to withstand the lunar environment. In addition, the titanium

rings of the wheel provide shock absorbtion for the vehicle. Traction is enhanced by the use of the chevron tread design.

The low speed, high horsepower motors to be used to drive the vehicle are extremely versatile in their operation. With the stator rigidly attached to the bowl and the rotor attached to the wheel, the vehicle can be operated with the minimum number of moving parts. These motors are also capable of creating enough torque to drive the vehicle on the rugged terrain of the lunar surface in addition to performing the dumping process.

The simple control system employed in this design makes it extremely easy to control the vehicle in order to perform the desired tasks. Steering, by changing the relative velocity of one wheel proved to be the easiest method of controlling the vehicle.

The visual guidance system will aid a controller in remotely manuevering the vehicle. The infrared camera will give the necessary resolution while the laser rangefinder provides depth perception. These two pieces of equipment, mounted on either side of the bowl, can be used in conjunction with the existing topographical knowledge to direct the vehicle through its tasks without encountering difficulty.

Overall, this design proves to be an extremely effective alternative to conventional earth moving equipment.

RECOMMENDATIONS

In the course of preparing this report, many areas of further research and design have been identified. These areas deal with the vehicle dynamics, motor design, wheel design, bowl design, and control.

One suggestion that surfaced during the design of the two wheeled vehicle was the feasibility of linking several trucks together and forming a train. The linking together of two of more of these vehicles bowls will immediately solve the problem of the bowl flipping. In addition, a train of vehicles will be more stable when traversing over rough terrain. This adds stability without sacrificing system simplicity and reliability because if an individual unit fails it can easily be removed from train. This linking should not hinder the dumping ability of the trucks or cause the control system to become extremely complex.

Several gaps were discovered in our wheel and traction dynamics. First, there is a shortage of data dealing with lunar soil microscopic and microscopic characteristics. This lack of data cast doubt on the validity of our lunar surface performance calculations. Second, the effects of surface roughness on torque requirements and controls needs to be investigated. The equations developed in this report have assumed uniform soil conditions. Finally, the energy lost in the deformation of the tires needs to be more accurately determined.

Several assumptions were made in determining the torque

requirements to dump the bowl that may not be valid. In this mathematical model, the torque was assumed to be constant throughout the swing even though the angular speed is varying. At this time, the performance characteristics of the design motors is not known. When this data becomes available, it should be applied to this model. Also, the friction in the motor needs to be more accurately determined.

The motors proposed for this design are currently in the design stages. For this reason, the test results of these prototype motors should be examined closely. Also, a means of dissipating heat from the motor needs to be developed.

Although the wheel design proposed is a design patented for use on the moon, this design has not been tested in the lunar environment and wear and durability data is not available. Wear and durability data needs to be obtained before these wheels can be confidently specified.

Composite materials should be investigated further for possible bowl materials. Composite material are desirable for their high strength to weight ratio but the composite materials examined for this report either had low strength or they could not withstand the extreme temperatures.

At the present time, little can be done to improve the visual guidance system of the vehicle. Remote vehicle guidance is a major research topic in the military today. Hopefully technological breakthroughs will be made from this research and this technology can be applied to the two wheeled lunar vehicle.

ACKNOWLEDGMENTS

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APPENDIX A

SINKAGE VS. WEIGHT

LUNAR VERSION

SINKAGE (IN)

WEIGHT (LB)
(Thousands)
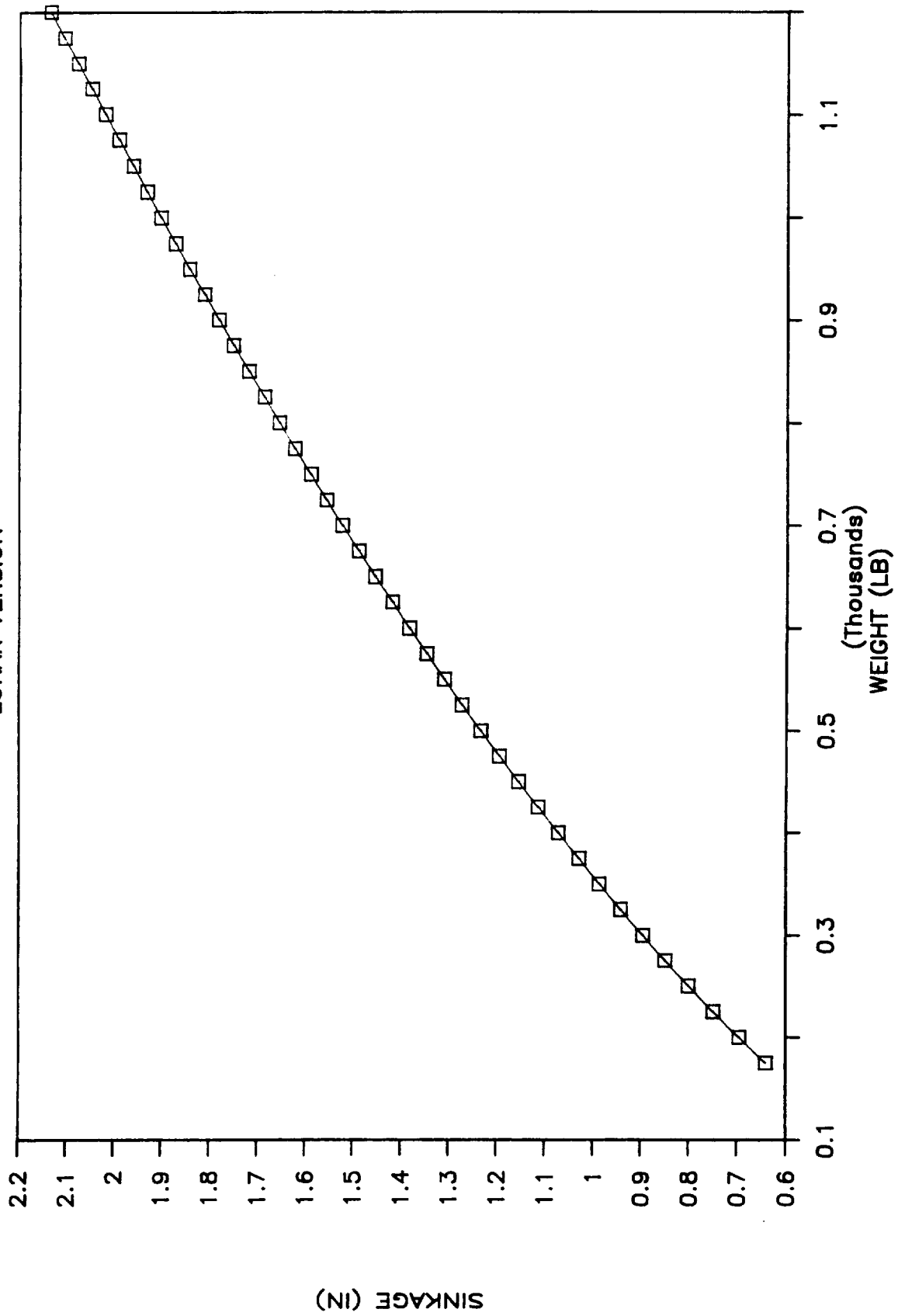
Figure 1.

DRAWBAR PULL VS. WEIGHT

LUNAR VERSION

DRAWBAR PULL (LB)

WEIGHT (LB)
(Thousands)
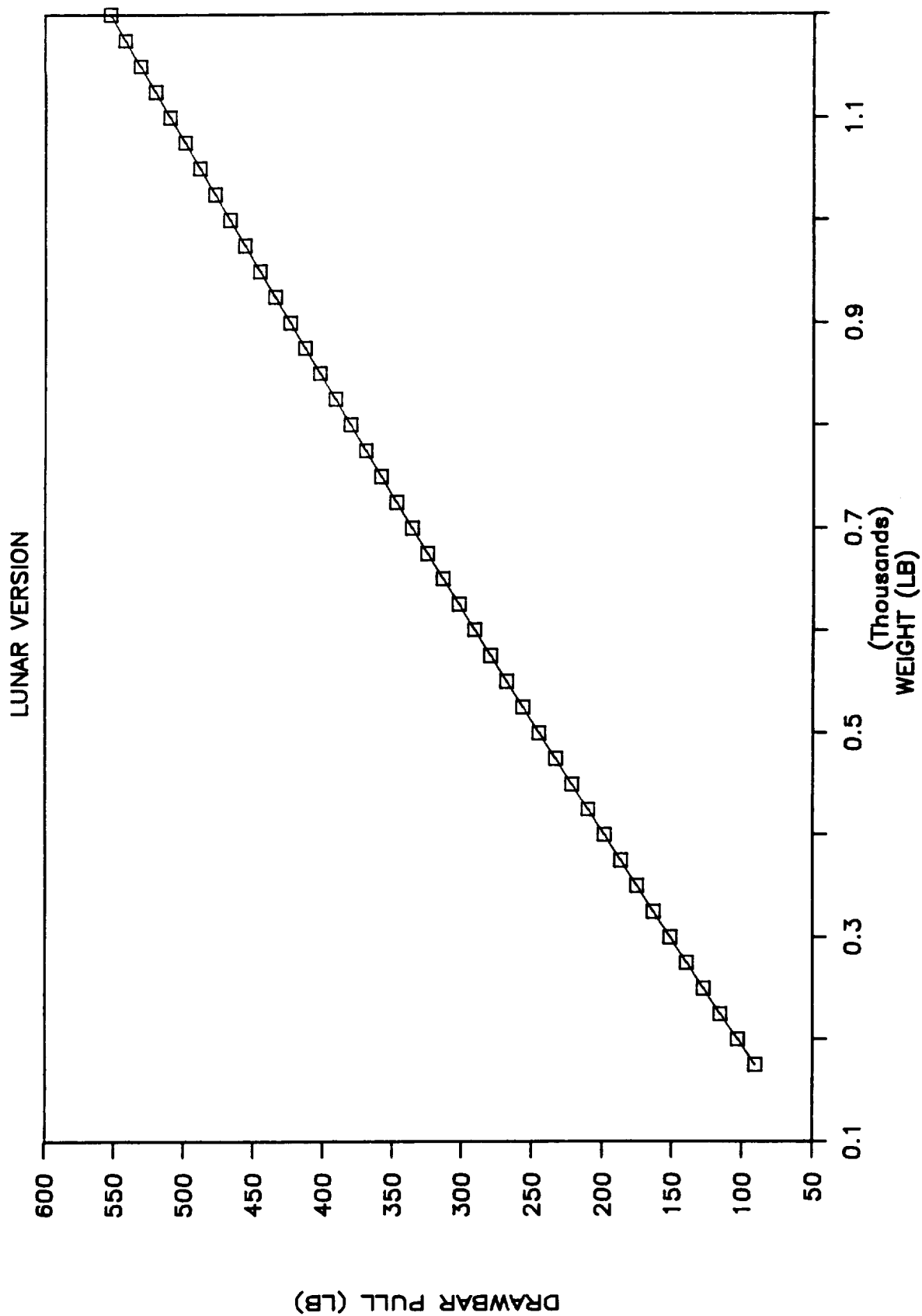
Figure 2.

DRAWBAR PULL VS HILL INCLINE

LUNAR VERSION

DRAWBAR PULL (LB)

INCLINE (RAD)
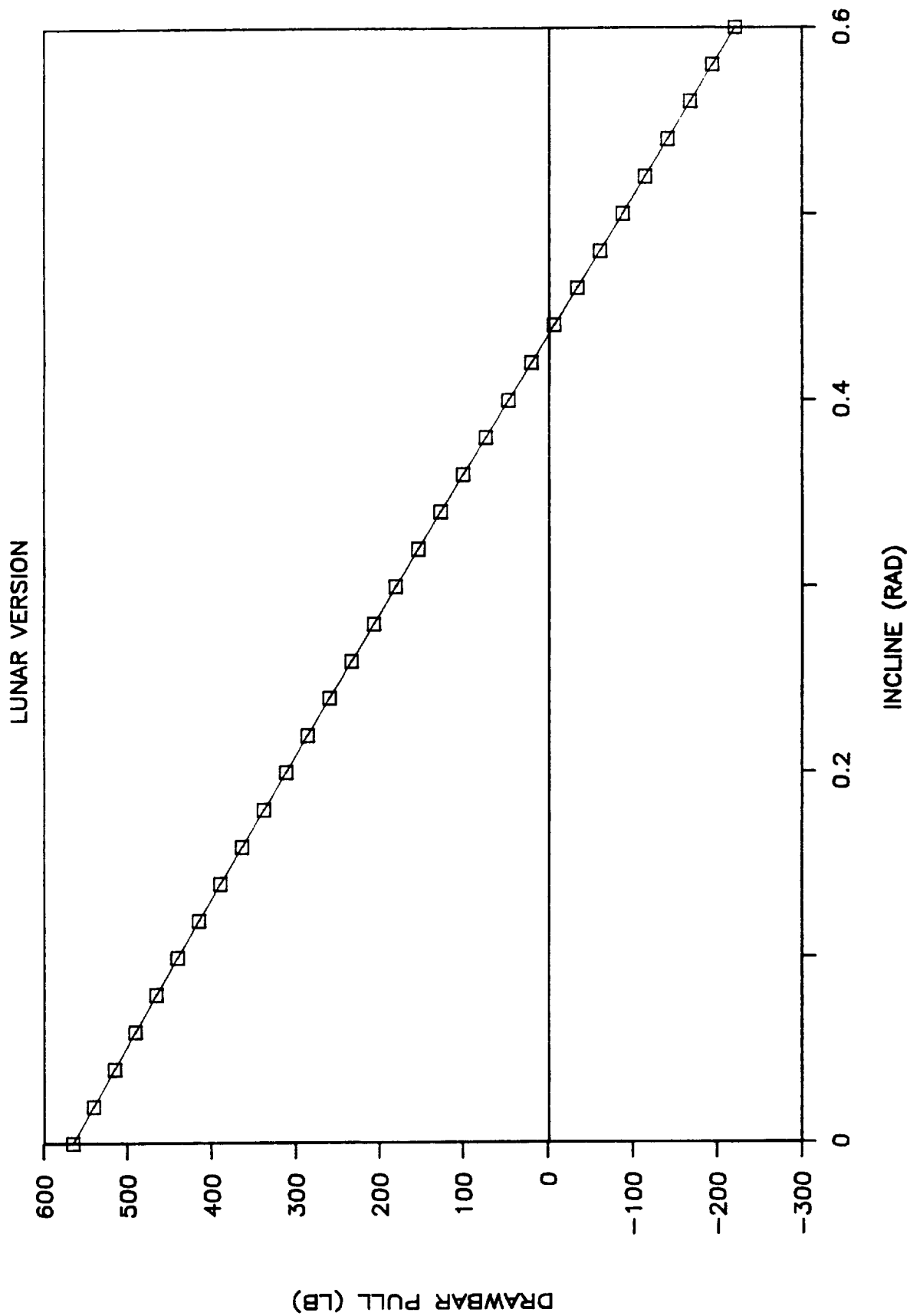
Figure 3.

STARTING TORQUE VS. WEIGHT

LUNAR VERSION

TORQUE (FT-LB) vs. WEIGHT (LB) (Thousands)
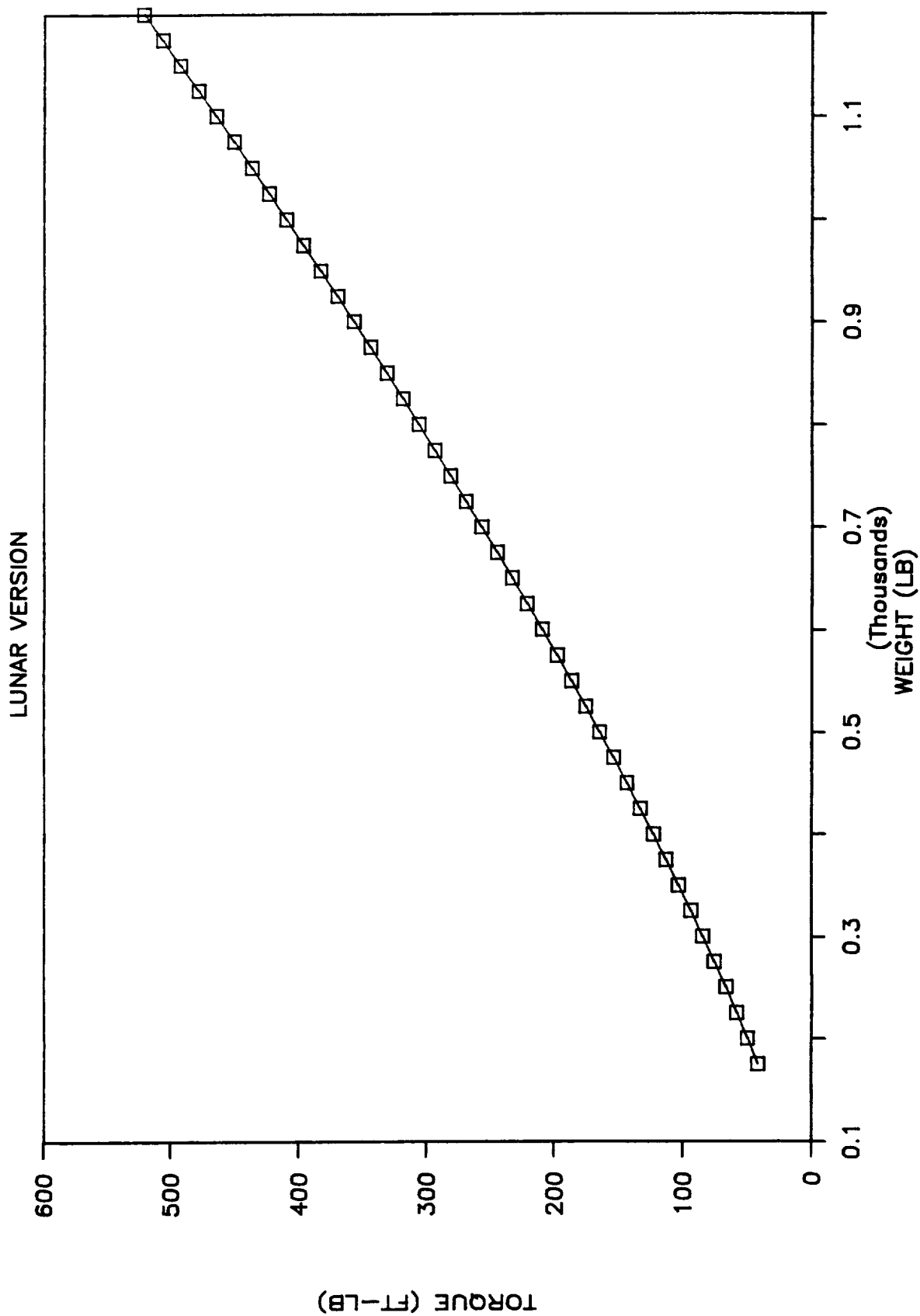
Figure 4.

MAX TORQUE VS. WEIGHT
LUNAR VERSION

TORQUE (FT-LB)
(Thousands)

WEIGHT (LB)
(Thousands)
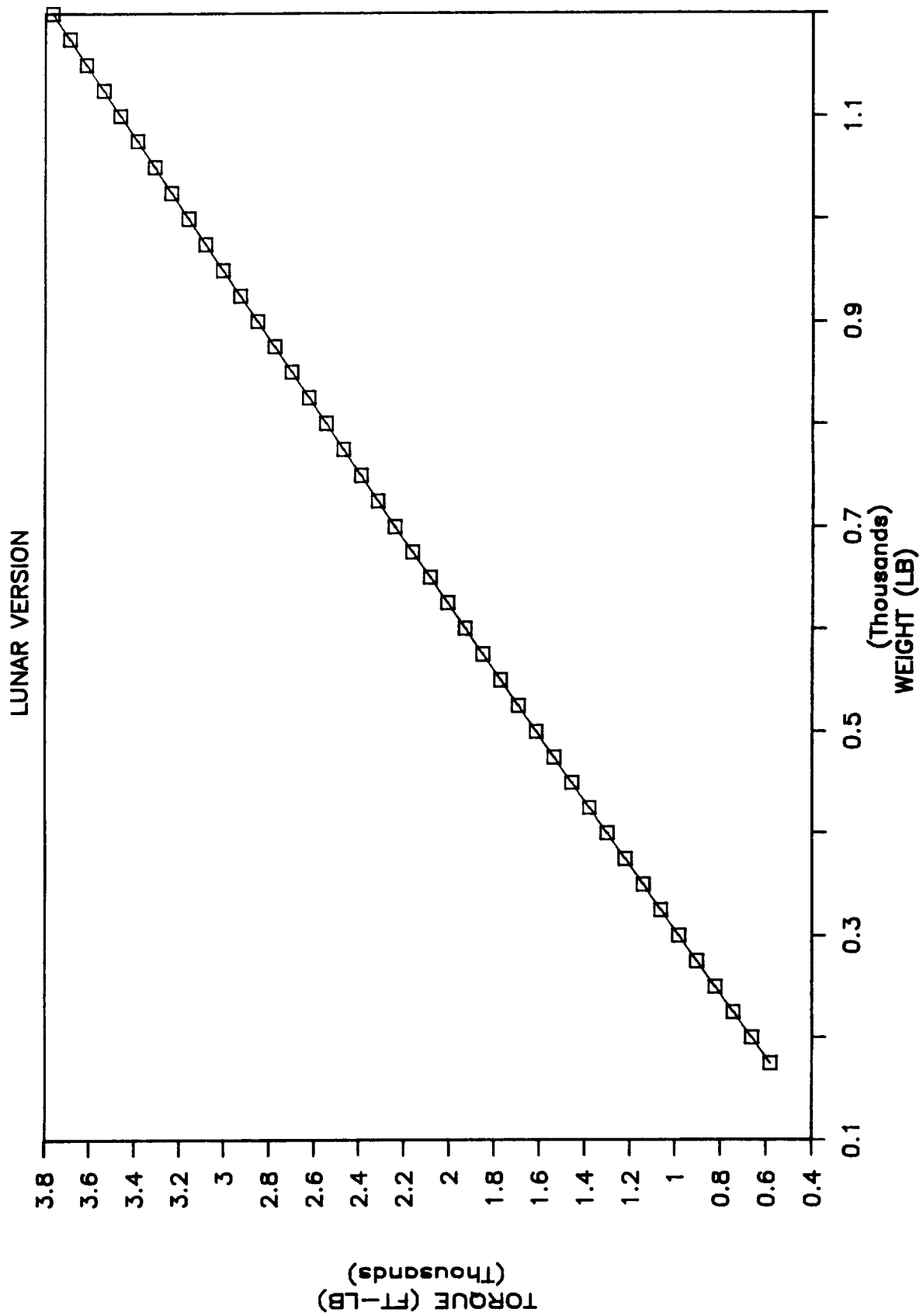
Figure 5.

TORQUE VS BOWL TILT

LUNAR VERSION

TORQUE (FT–LB) (Thousands)

TILT (RAD)

□ EMPTY   +   FULL
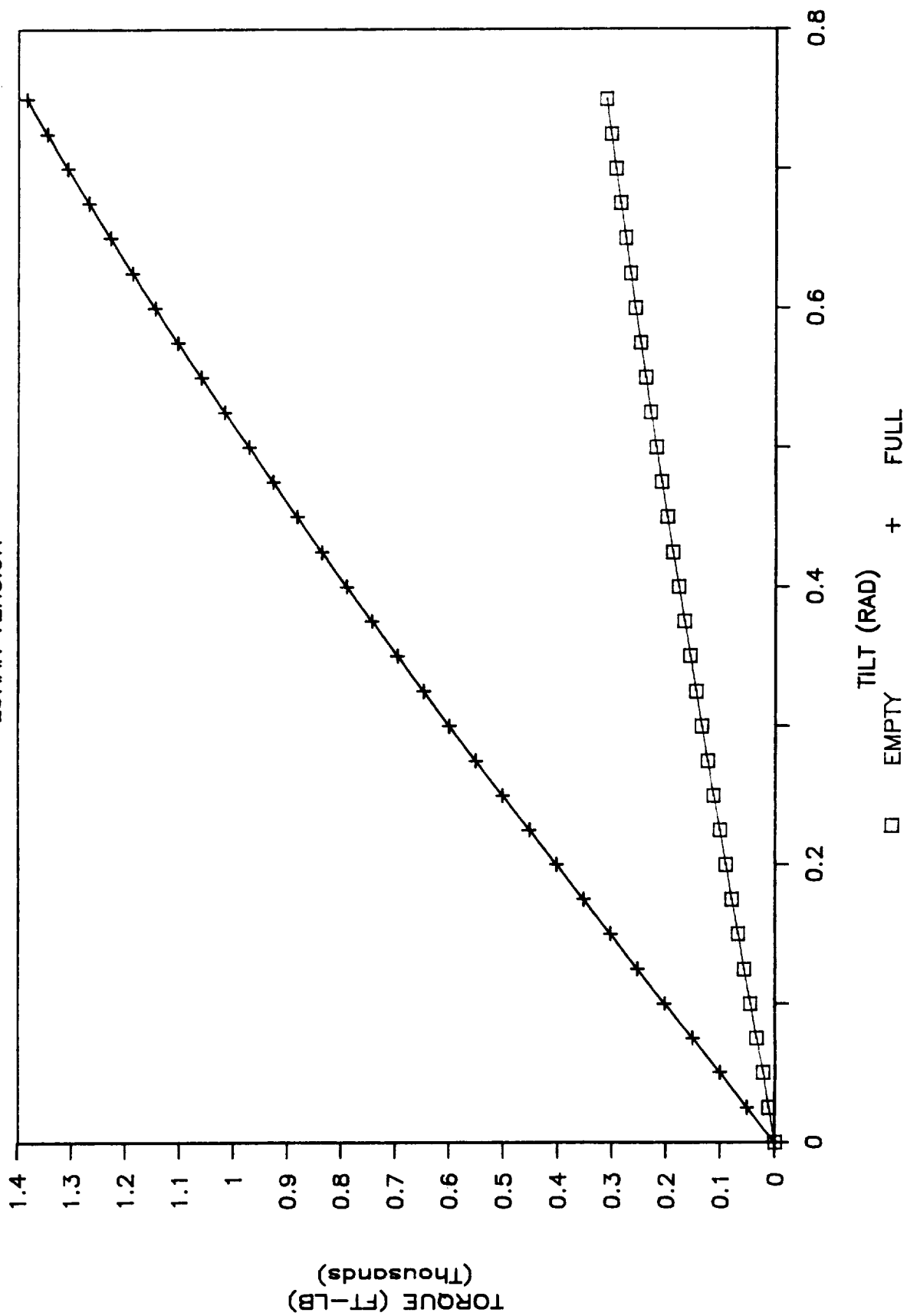
Figure 6.

```
1    REM PROGRAM CALCULATING DRAWBAR PULL, SINKAGE, STARTING TORQUE,
         AND MAX TORQUE VERSUS WEIGHT.
5 OPEN "O",1,"A:\DATAA"
10 KPHI = 3.3
20 N = 1.1
30 P = .541
35 D = 90
37 B = 18
40 FOR W = 175 TO 1216 STEP 25
70 X = 2*N+2
80 Y = 2 * N +1
90 R = (1/((3-N)^(X/Y)*(N+1)*(B*KPHI)^(1/Y)))*((3*W)/D^(.5))^(X/Y)
100 Z = ((3*W)/((3-N)*(B*KPHI)*D^(.5)))^(2/Y)
110 DP = W*((P*(1+(P^2)/3)) + (4*P*(5-3*N)*Z)/(5*(3-N)*D)
    - (1.5*(1+P^2)*(2-N)*Z^(.5))/((3-N)*D^(.5))
    - (2*(3-2*N)*Z^(3/2))/(3*(3-N)*D^(3/2)))
122 DY = ((D/2)^2-((D/2)-Z)^2)^(1/2)
123 T = ATN(DY/((D/2)-Z))
133 TAUM = KPHI*Z^N*TAN(P)-(KPHI*Z^(N+1))/((D/2)*T*(N+1))
134 TAUS = (KPHI*Z^(N+1))/((D/2)*T*(N+1))
135 TS = (D/2)^2*B*TAUS*T*(1/12)
137 TM = (D/2)^2*B*TAUM*T*(1/12)
140 PRINT #1,USING"#####.###": W;Z;DP:TS:TM
170 NEXT W
```

```
1 REM PROGRAM CALCULATES THE EMPTY BOWL TORQUE AND FULL BOWL TORQUE
         VERSUS BOWL TILT.
5 OPEN"O",1,"A:\TILT"
10 A = 3.1416
15 D = 63
20 DB = .043
30 DS = (2/3)*(1/A)*D
35 FOR PSI = 0 TO .75 STEP .025
40 CGBX = ((D/2)-DB)*COS(4.712-PSI)
50 CGSX = ((D/2)-DS)*COS(4.712-PSI)
60 WB = 175
70 WS = 1040
80 TF =-1* (CGBX*WB + WS*CGSX)/12
90 TE =-1* CGBX*WB/12
100 PRINT #1,USING"#####.###";PSI,TE,TF
110 NEXT PSI
```

```
1 REM PROGRAM CALCULATES THE DARWBAR PULL VERSUS HILL INCLINE
5 OPEN "O",1,"A:\DATAA"
10 KPHI = 3.3
20 N = 1.1
30 P = .541
35 W1 = 1216
37 B = 18
38 D = 90
40 FOR U = 0 TO .6 STEP .02
50 W = W1*COS(U)
70 X = 2*N+2
80 Y = 2 * N +1
90 R = (1/((3-N)^(X/Y)*(N+1)*(B*KPHI)^(1/Y)))*((3*W)/D^(.5))^(X/Y)
100 Z = ((3*W)/((3-N)*(B*KPHI)*D^(.5)))^(2/Y)
110 DP = W*((P*(1+(P^2)/3)) + (4*P*(5-3*N)*2)/(5*(3-N)*D)
    - (1.5*(1+P^2)*(2-N)*2^(.5))/((3-N)*D^(.5))
    - (2*(3-2*N)*2^(3/2))/(3*(3-N)*D^(3/2)))
120 DP = DP - W1*SIN(U)
122 DY = ((D/2)^2-((D/2)-Z)^2)^(1/2)
123 T = ATN(DY/((D/2)-Z))
133 TAUM = KPHI*Z^N*TAN(P)-(KPHI*Z^(N+1))/((D/2)*T*(N+1))
134 TAUS = (KPHI*Z^(N+1))/((D/2)*T*(N+1))
135 TS = (D/2)^2*B*TAUS*T*(1/12)
137 TM = (D/2)^2*B*TAUM*T*(1/12)
138 TSH = TS + W1*SIN(U)*(D/2)*(1/12)
140 PRINT #1,USING"#####.###";U,DP,TSH
170 NEXT U
```

APPENDIX B

OPTIMIZATION

Wheel diameter, wheel width, bowl diameter and bowl length were chosen by an optimization process using the governing equations already discussed combined with industry standards.

Drawbar pull

Drawbar pull vs wheel diameter is shown in (figure 1) for full load. It is desired to maximize drawbar pull and thus, maximize wheel diameter.

Torque

Starting torque vs wheel diameter for several wheel widths is plotted in (figure 2). Again, starting torque increases with diameter and decreases with increasing wheel width. Thus it would appear to be desirable minimize diameter and maximize wheel width. However, maximum wheel width is not necessarily desired because of considerations discussed later.

Maximum torque obtainable from the soil is plotted in (figure 3). Maximum torque increases with wheel diameter but is virtually independent of wheel width. Thus, wheel diameter should be maximized to obtain the largest maximum torque. However, from the previous discussion it was shown that the bowl will flip (or exceed the 45° tilt) at a much lower torque than the maximum torque obtainable from the soil. Thus, maximum torque is not considered as an optimization parameter.

Torque versus bowl tilt is plotted in (figure 4) for

several bowl diameters. Torque obtainable increases with

increasing bowl diameter. Thus, it is desirable to maximize

the bowl diameter.

Selection

From the previous discussion it is desirable to maximize

wheel diameter from consideration of drawbar pull and bowl

tilt while minimizing wheel diameter for minimum starting

torque. Thus, there is an optimum wheel diameter.

Since wheel width appears only to be critical for

starting torque, it would seem desirable to maximize the

width. However, large width to diameter ratios are not

generally used in design because the internal work spent on

deformation, which was neglected in the analysis, increases

with width. Thus industry standards were used to determine

the diameter to width ratio.

The diameter to width ratio of terrain vehicles varies

depending upon application and region the vehicle is designed

for. A diameter to width ratio of 5:1 was selected as an

average ratio. This is plotted on (figure 2).

From topography maps of the lunar surface it was

determined that a ground clearance of 13 inches was

needed. Thus, the bowl diameter should be approximately 26

inches smaller than the wheel diameter.

A tilt of approximately 20° was selected as the starting

tilt. This left an additional 25° for acceleration and hill

climbing. The $20°$ vertical line is plotted on (figure 4).

Each intersection of this line with a constant diameter curve defines the desirable starting torque. These points are then plotted on (figure 2).

A width and diameter selection is then made from the intersection of the two lines in (figure 2). This corresponds to a wheel diameter of approximately 90 inches and a width of 18 inches.

DRAWBAR PULL VS DIAMETER

DRAWBAR PULL (LB)
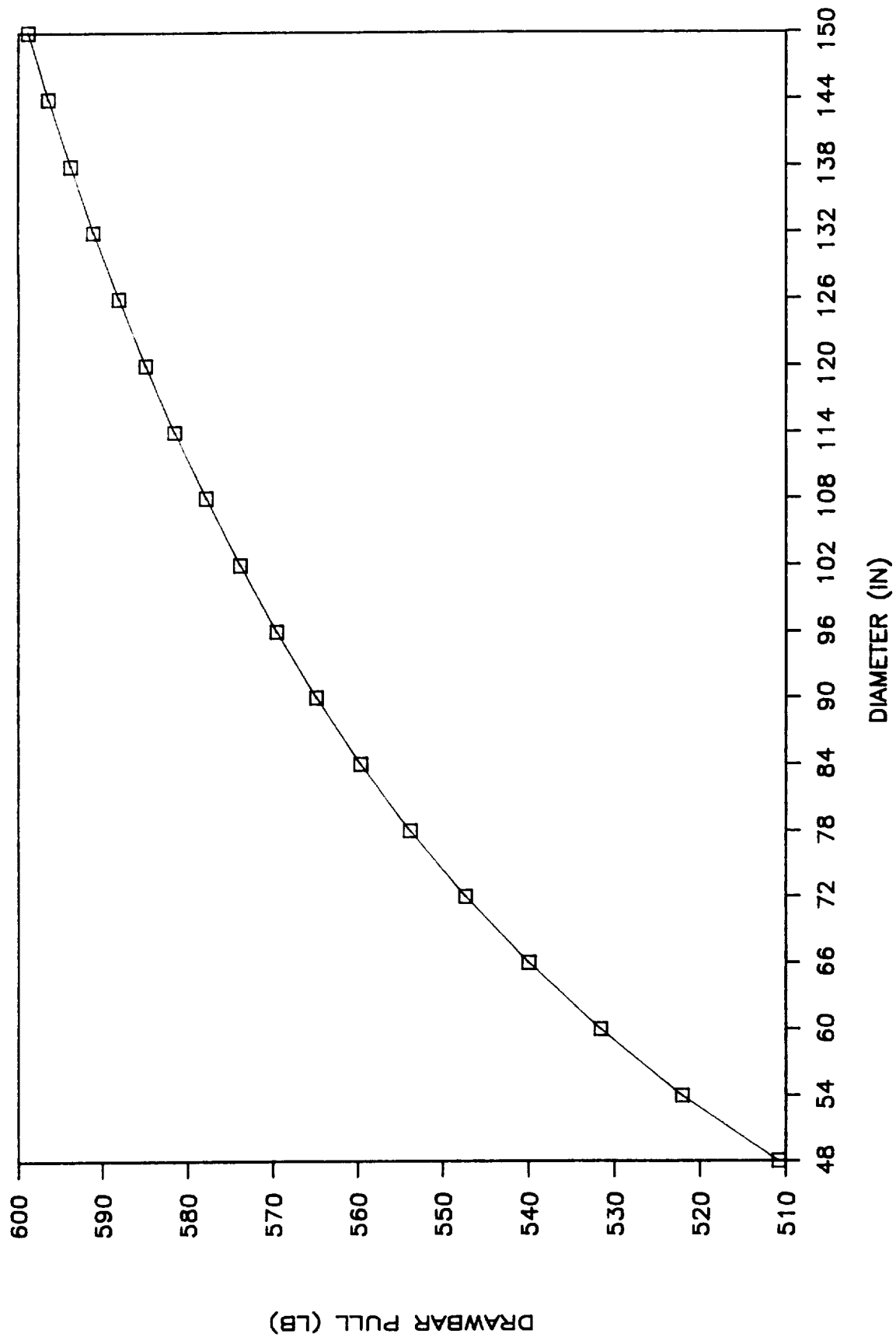
DIAMETER (IN)

Figure 1

STARTING TORQUE VS DIAMETER

FOR SEVERAL WHEEL WIDTHS

TORQUE (FT-LB)

DIAMETER (IN)

□ B=12   + B=15   ◇ B=18   △ B=21   × B=24
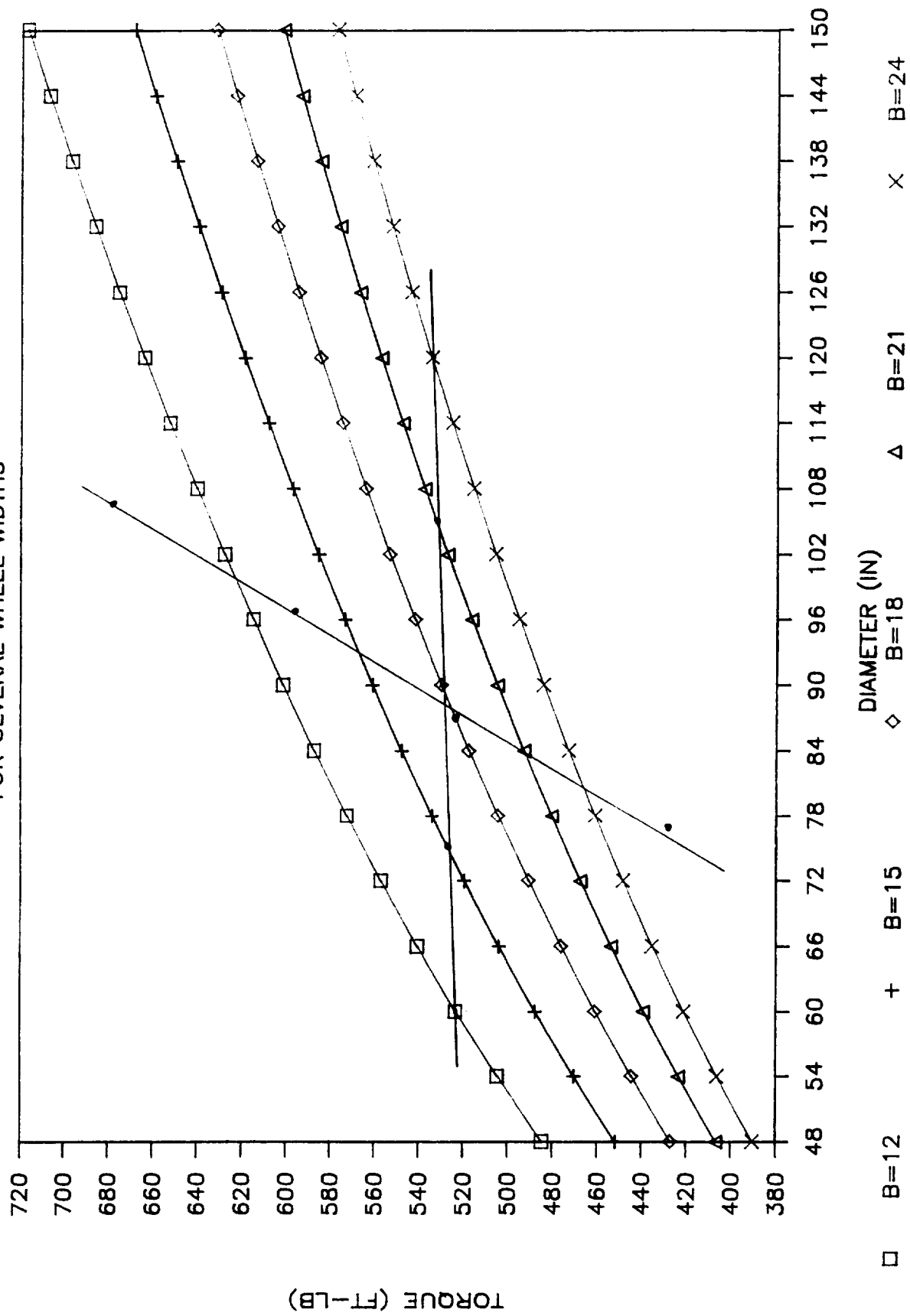
Figure 2

MAXIMUM TORQUE VS DIAMETER

FOR SEVERAL WHEEL WIDTHS

TORQUE (FT-LB)
(Thousands)

DIAMETER (IN)

□ B=12   + B=15   ◇ B=18   △ B=21   × B=24
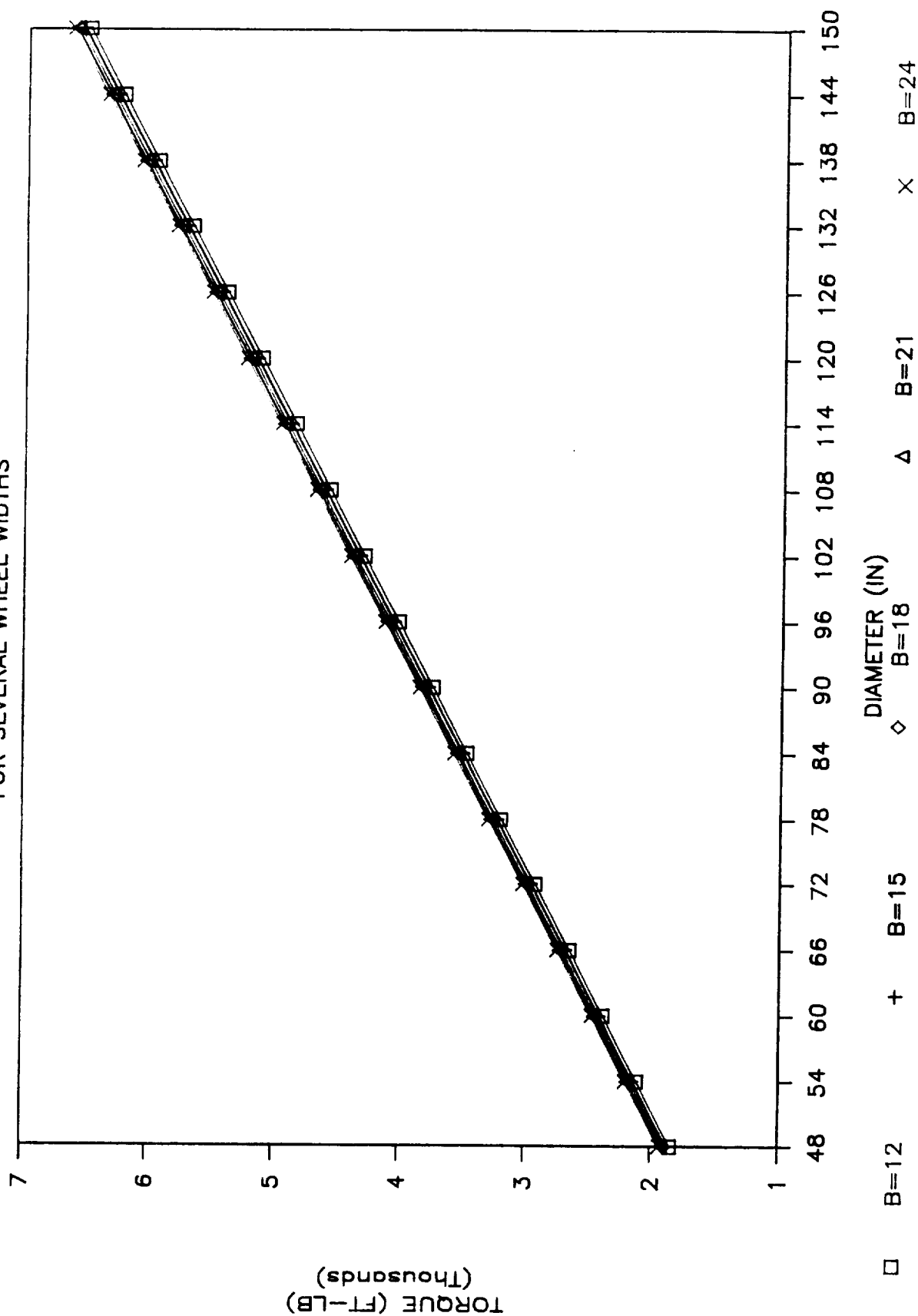
Figure 3

TORQUE VS. BOWL TILT
FULL
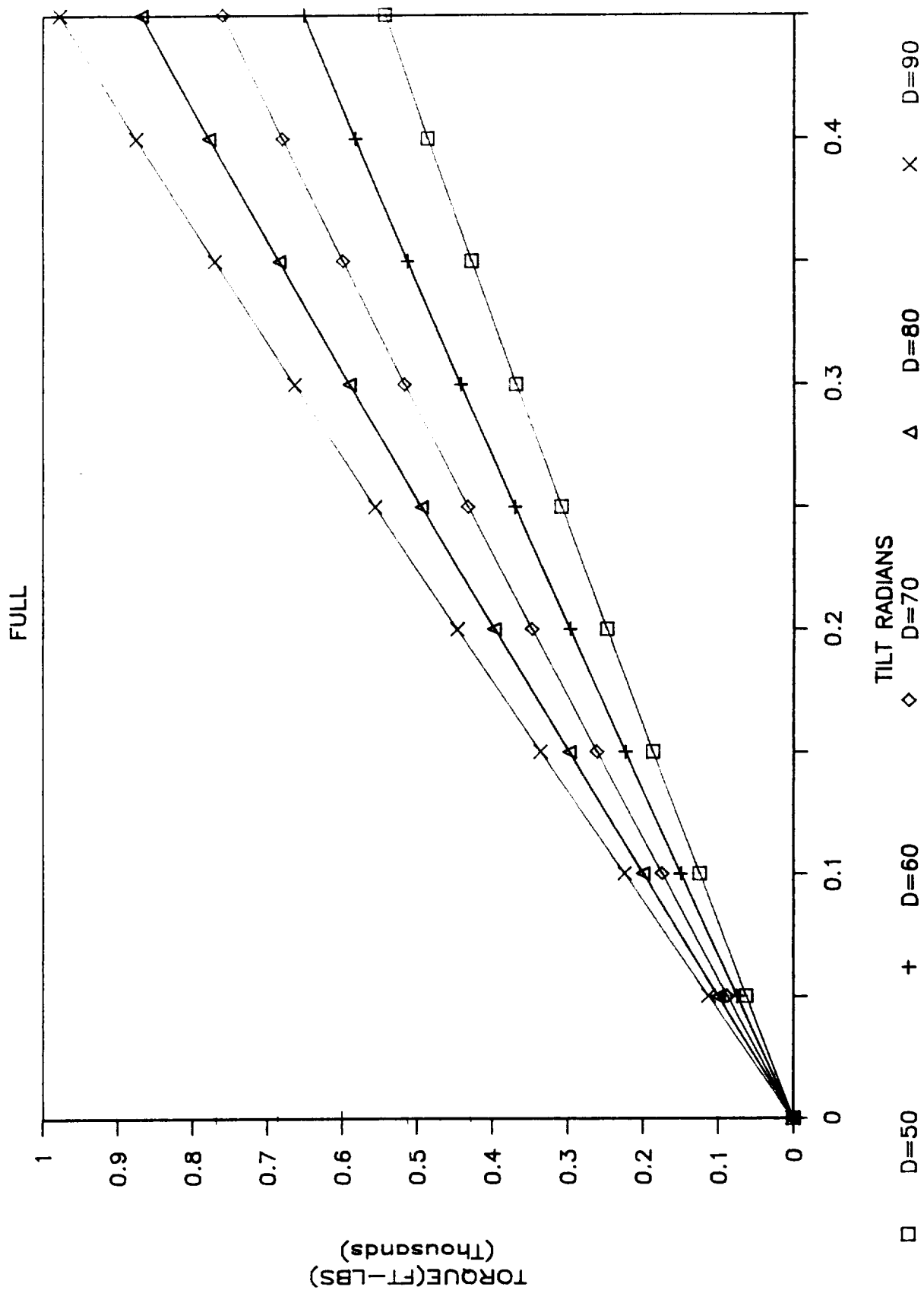
Figure 4

APPENDIX C

240 DEGREE BOWL DESIGN

TOP

276.6

138.6

160.3

FRONT

RIGHT

30 deg.

120 deg.

30 deg.

80.0

all measurements in centimeters
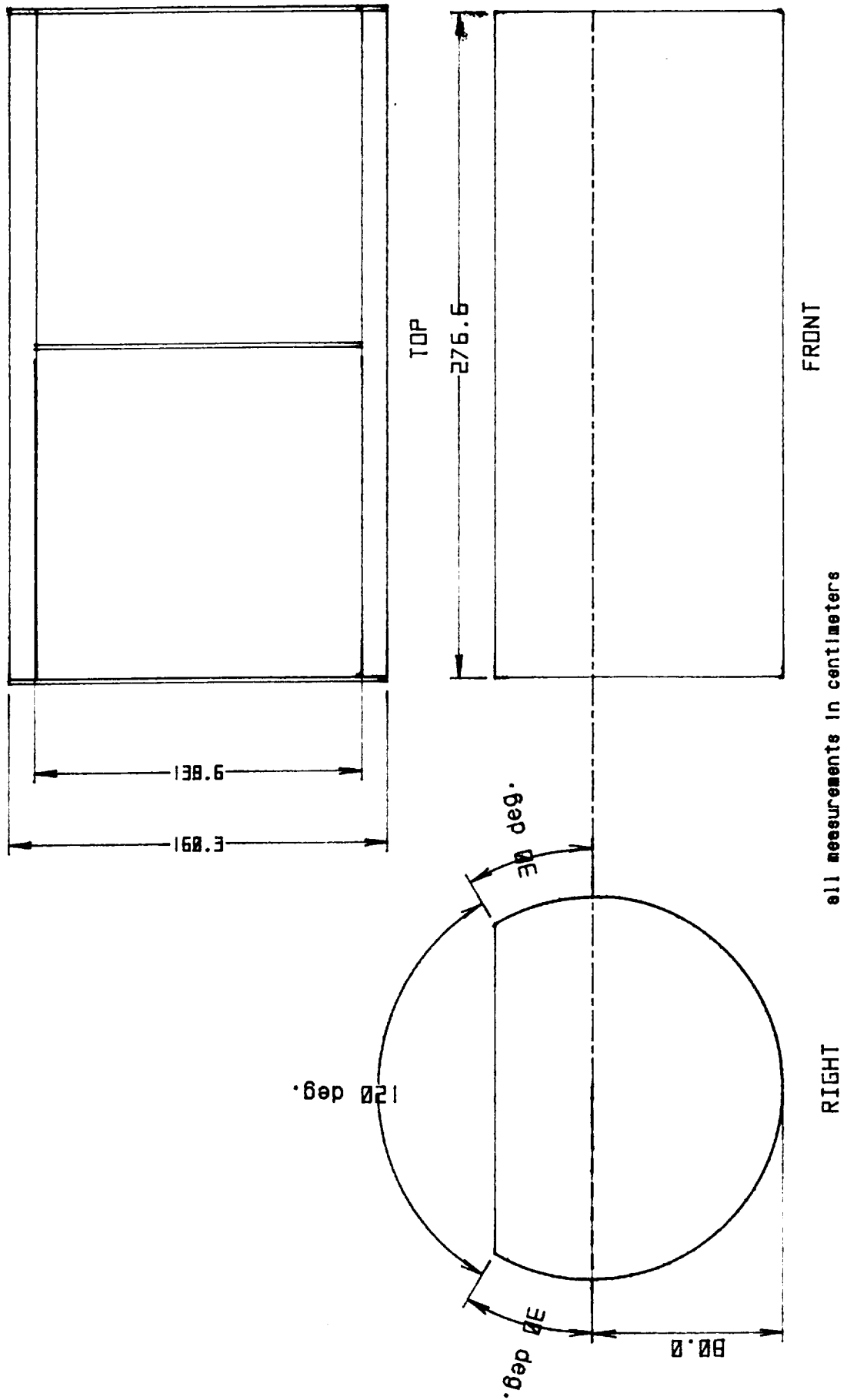
Figure 1.

STRESS ANALYSIS

Notation: $Pi = 3.14159$ $S =$ $= $ stress $R = $ bowl radius
         $d = $ bowl diameter $P = $ pressure $t = $ bowl thickness
         $L = $ bowl length $F = $ weight

Lunar Soil - Weight on earth = 10.000 lbf = 44.500 N

              Weight on moon = 1.667 lbf = 7.417 N

Surface Area of Bowl - $A = (Pi)(R)(L) + (Pi)(R)^2$
(soil loaded to 180)
                        where $R = 0.804$ m
                              $L = 2.760$ m

                        $A = 9.002$ m^2

Pressure On Surface Area - $P = F/A = (7417$ N$)/(9.002$ m$^2)$

                            $P = 823.928$ N/m^2

Hoop Stress Acting On Bowl - $S = (P)(d)/(2)(t) = (P)(R)/(t)$

                              where $d = 1.608$ m
                                    $t = 0.0254$ m

                              $S = 26080.241$ N/m^2
                              $S = 3.78$ lbf/in^2

This is less than the yield and tensile strengths of AA336,
the bowl material.

Figure 2.

WHEEL GEOMETRY

WHEEL PROFILE

228.9

163.6

15.0

TREAD DESIGN

45.7
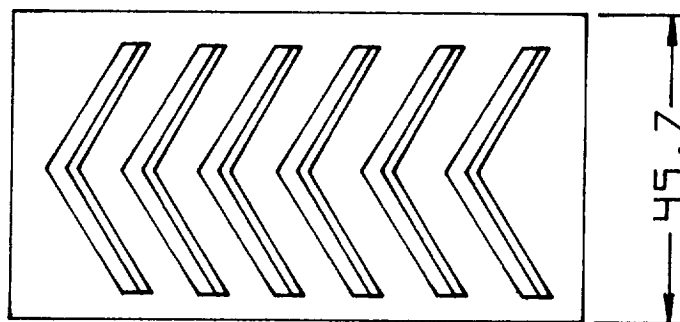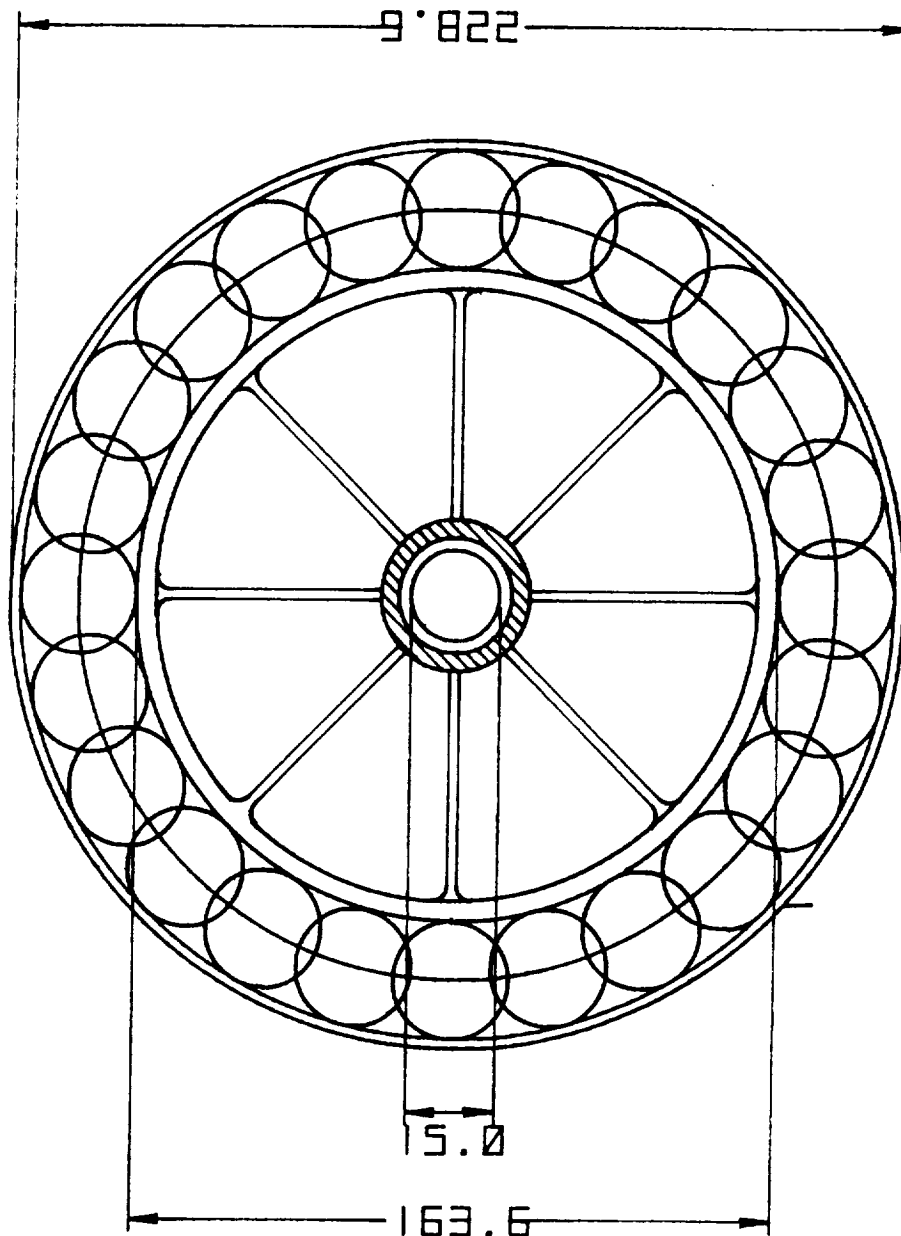
cross-section
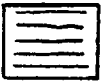
measurements in centimeters

Figure 3.

BOWL DESIGN DECISION MATRIX

	CENTER OF GRAVITY	WEIGHT	MOTOR MOUNTING	EASE OF LOADING	STABILITY CLIMBING	KEEP SOIL IN	TOTA
HALF SPHERE	5	5	3	5	2	2	22
BATHTUB SHAPE	3	1	2	4	4	4	18
HALF CYLINDER	3	3	5	4	5	3	23
240 CYLINDER	3	2	5	3	5	5	23
TRUNCATED CONE	1	4	1	5	1	1	13

WHEEL DESIGN DECISION MATRIX

	SIMPLE DESIGN	ABILITY RIGHT SELF	CONTACT AREA	OVERCOME OBSTACLES	EASE OF STEERING	TOTAL
	1	5	1	1	5	13
	5	2	2	1	4	14
	3	3	3	5	1	15
	3	1	5	4	5	18

APPENDIX D

ROTOR/STATOR ELEMENTS

STATOR

measurements in centimeters

120.0

ROTOR

76.0

phase A

phase B

phase C

phase B

phase A

phase C

30.0

60.0
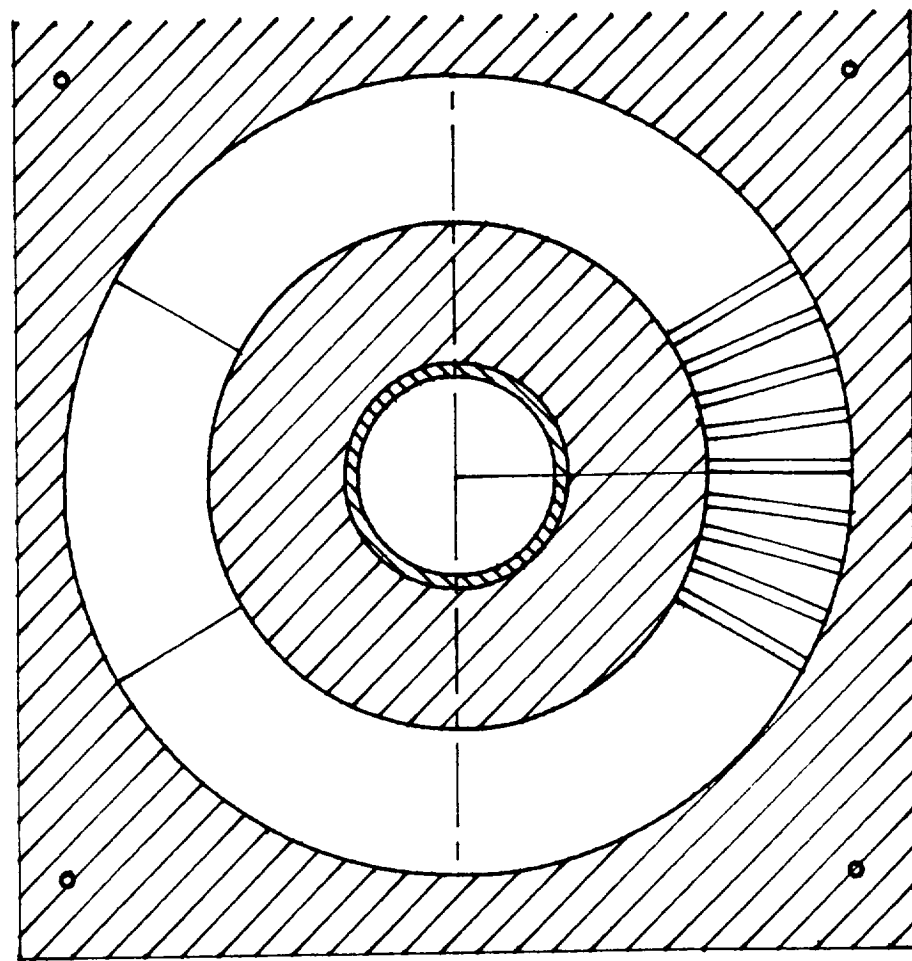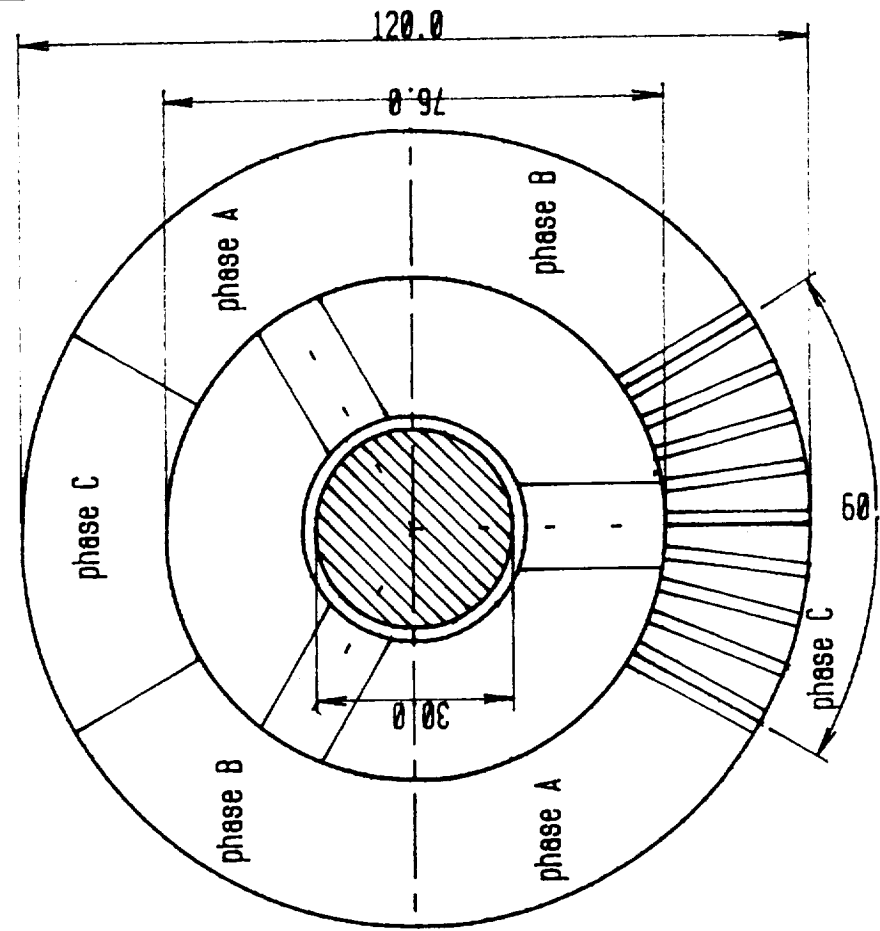
48 magnets - equally spaced

Figure 1.

2 WHEEL LUNAR DUMPTRUCK
MOTOR / SHAFT ASSEMBLY

stator

rotor

120.0

body

IR camera

driveshaft

batteries

units := centimeters

RIGHT

88.8

68.0

64.0

60.0

5.0

89.7

batteries

hinged door

control - 3 phase DC converter

80.0

FRONT
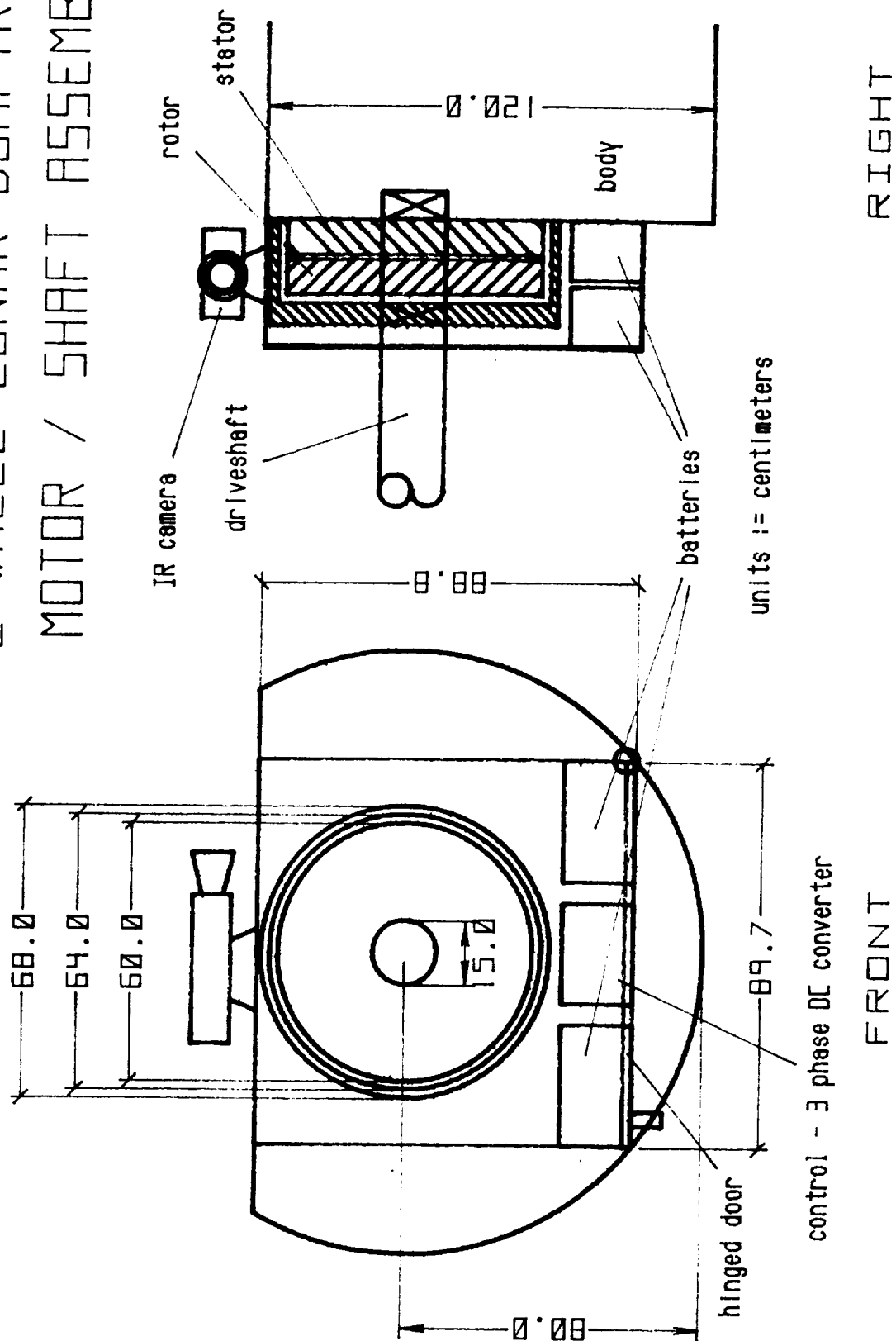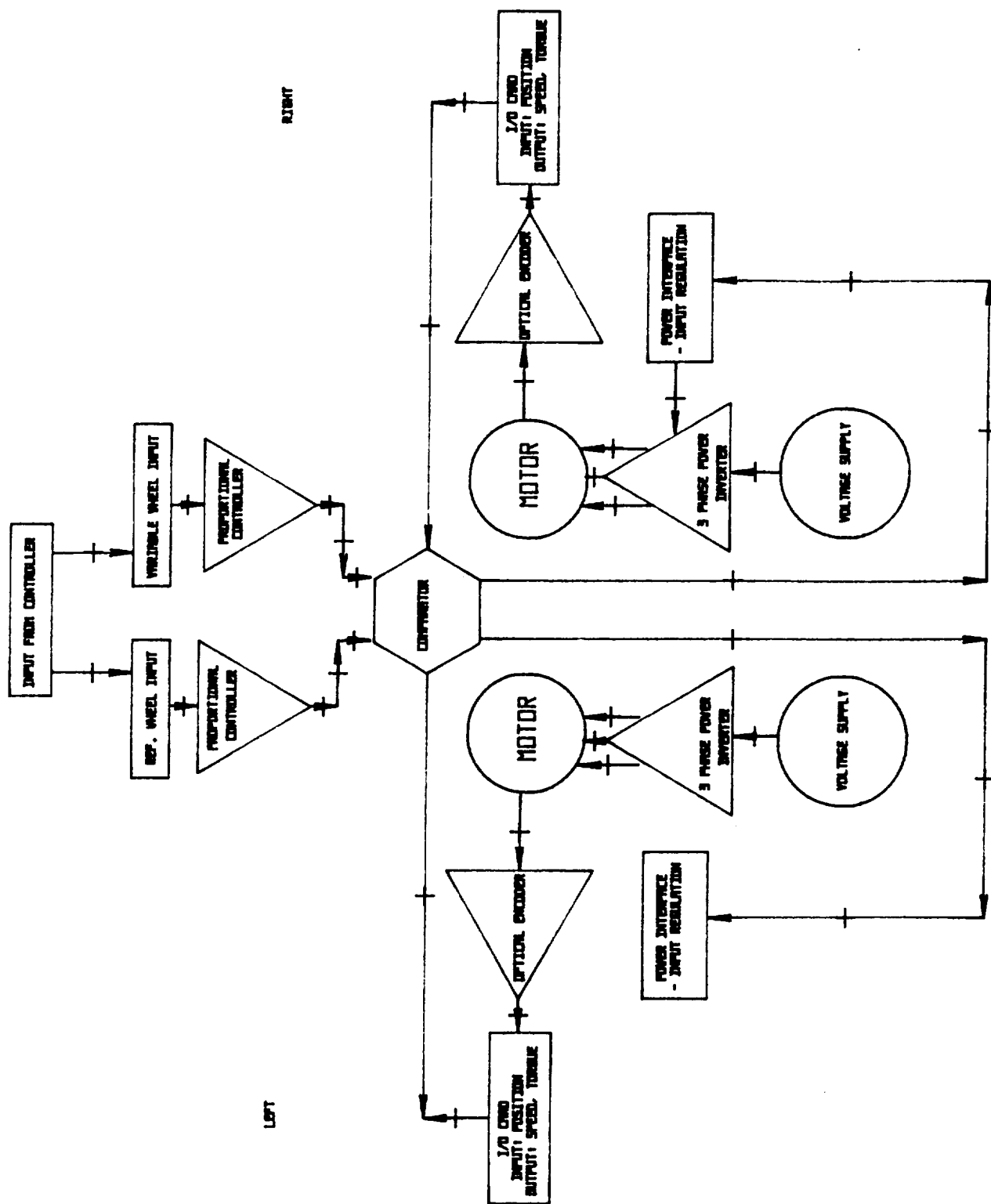
Figure 2.

Figure 3.

HORSEPOWER VS. RPM

ME 4182

HORSEPOWER

SPEED OF MOTOR (RPM)
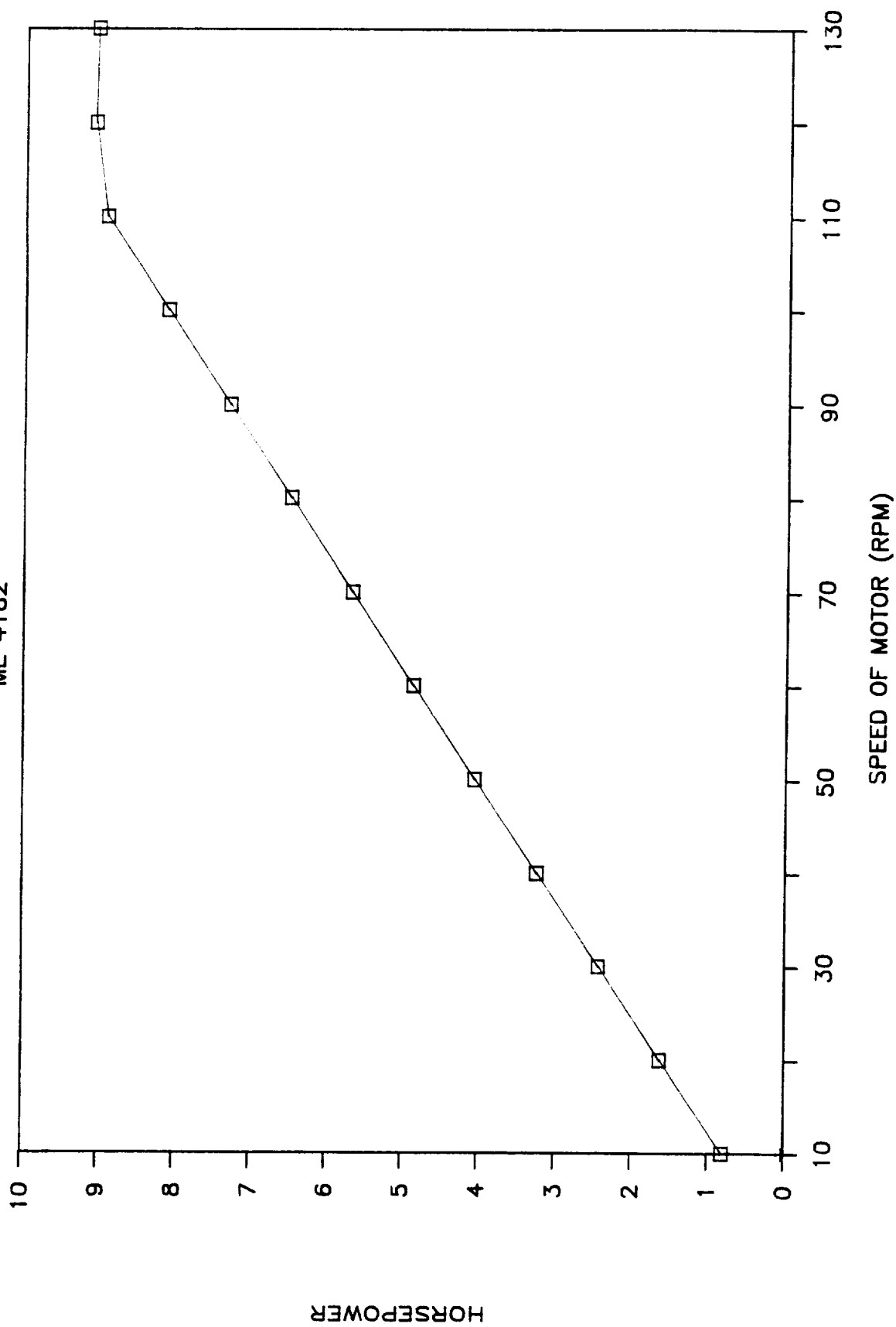
APPENDIX E

VARIOUS TURNING STATEGIES

ASSUMPTIONS:
SPEED OF   SPEED OF
REFERENCE   SECOND
  WHEEL   WHEEL
w1=CONSTANT=100RPM   w2=(2*w1)=200RPM

DESIRED TURN ANGLE (DEGREES)	TIME REQUIRED TO HOLD SECOND CONTROLLER IN ABOVE CONFIGURATION FOR DESIRED TURN (SEC)
10	0.351802
20	0.703604
30	1.055406
40	1.407208
50	1.759010
60	2.110812
70	2.462614
80	2.814416
90	3.166218

THE SAME DEGREE TURN COULD BE MADE IN THE OPPOSITE DIRECTION,
IF THE SPEED OF THE SECOND WHEEL IS CHANGED TO 1/2 THE SPEED
OF THE REFERENCE WHEEL FOR THE SAME AMOUNT OF TIME AS LISTED
IN THE ABOVE TABLE.

Figure 1.

NUMBER OF SWINGS TO DUMP

TWO WHEELED LUNAR DUMPTRUCK 11/24/88

TORQUE

□   friction ignored

NUMBER OF SWINGS
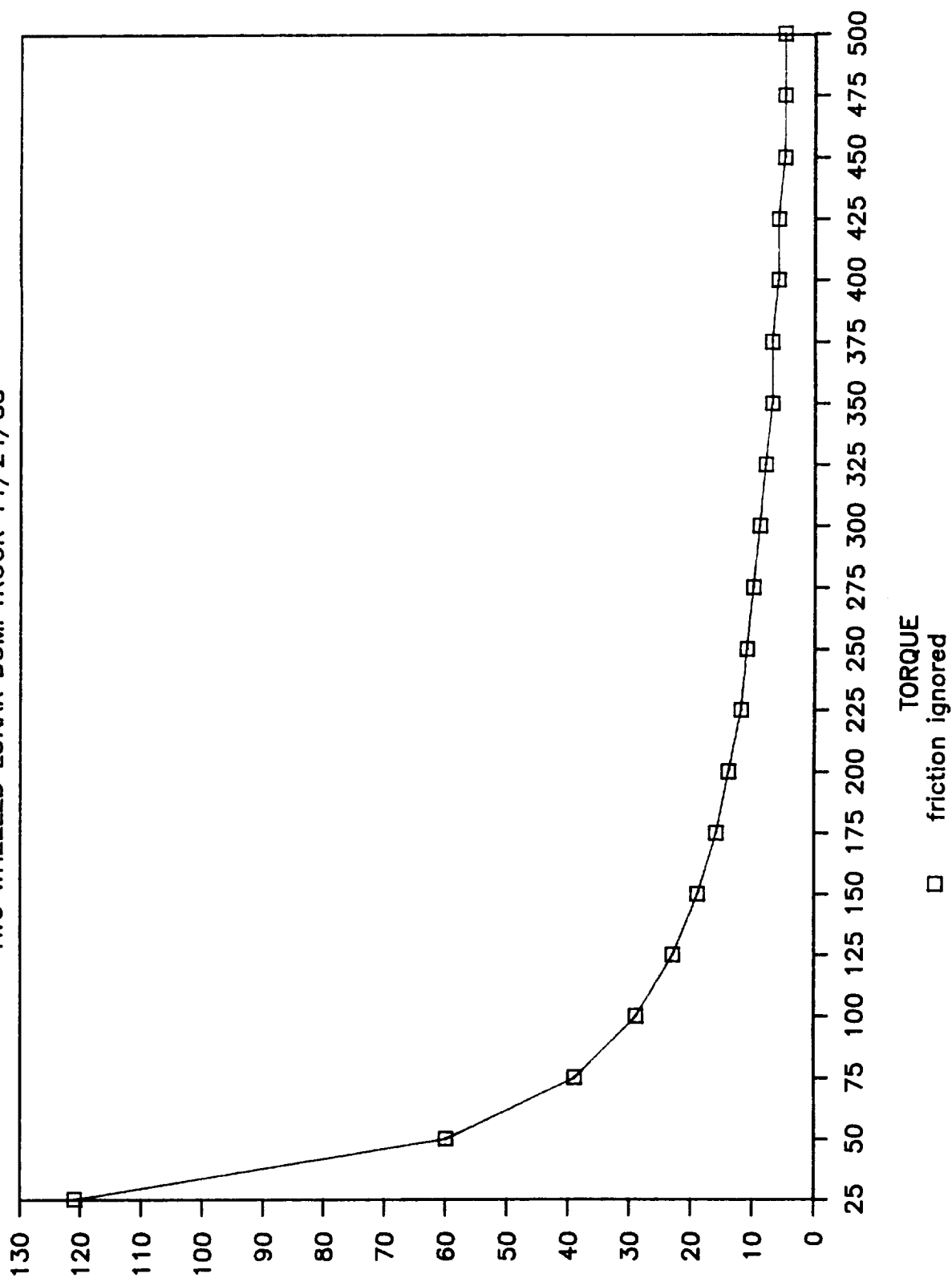
Figure 2.

TORQUE	SWINGS
25	121
50	60
75	39
100	29
125	23
150	19
175	16
200	14
225	12
250	11
275	10
300	9
325	8
350	7
375	7
400	6
425	6
450	5
475	5
500	5
525	5
550	4
575	4
600	4
625	4
650	3
675	3
700	3
725	3
750	3
775	3
800	2
825	2
850	2
875	2
900	2
925	2
950	2
975	2
1000	2

Figure 3.

```
10 REM PROGRAM FLIP
20 REM PAUL JENSEN ME4182
20 REM THIS PROGRAM DETERMINES THE NUMBER OF
40 REM SWINGS TO FLIP THE FULL BOWL AT VARIOUS TORQUES
50 DIM E(1000),THETA(1000)
83 LPRINT "TORQUE          SWINGS"
84 LPRINT
85 FOR T = 25 TO 1000 STEP 25
87 REM START AT A TORQUE OF 25 AND STEP TO 1000
88 PRINT
90 M = 375
100 L = 1.71196 : G = 5.33
110 Y = (T/(M*G*L))
120 X1 = 1 - Y^2
125 X = X1^(.5)
130 THETA(1) = ATN(Y/X)
140 E(1) = M*G*L*(1 - COS(THETA(1)))
150 LET J = 0
160 FOR I = 2 TO 1000
165 REM ADD ENERGY TO PREVIOUS CYCLE
170 E(I) = E(I-1) + 2*T*THETA(I-1)
180 X = (1 -(E(I)/(M*G*L)))
185 IF (1 - X^2) < 0 GOTO 235
190 Y = (1 - X^2)^(.5)
195 REM CALCULATE NEW THETA
200 THETA(I) = ABS(ATN(Y/X))
205 REM COUNT SWINGS
210 J = J + 1
220 IF E(I) > 2*M*G*L THEN GOTO 235
230 NEXT I
235 LPRINT T,J
240 NEXT T
250 END
```
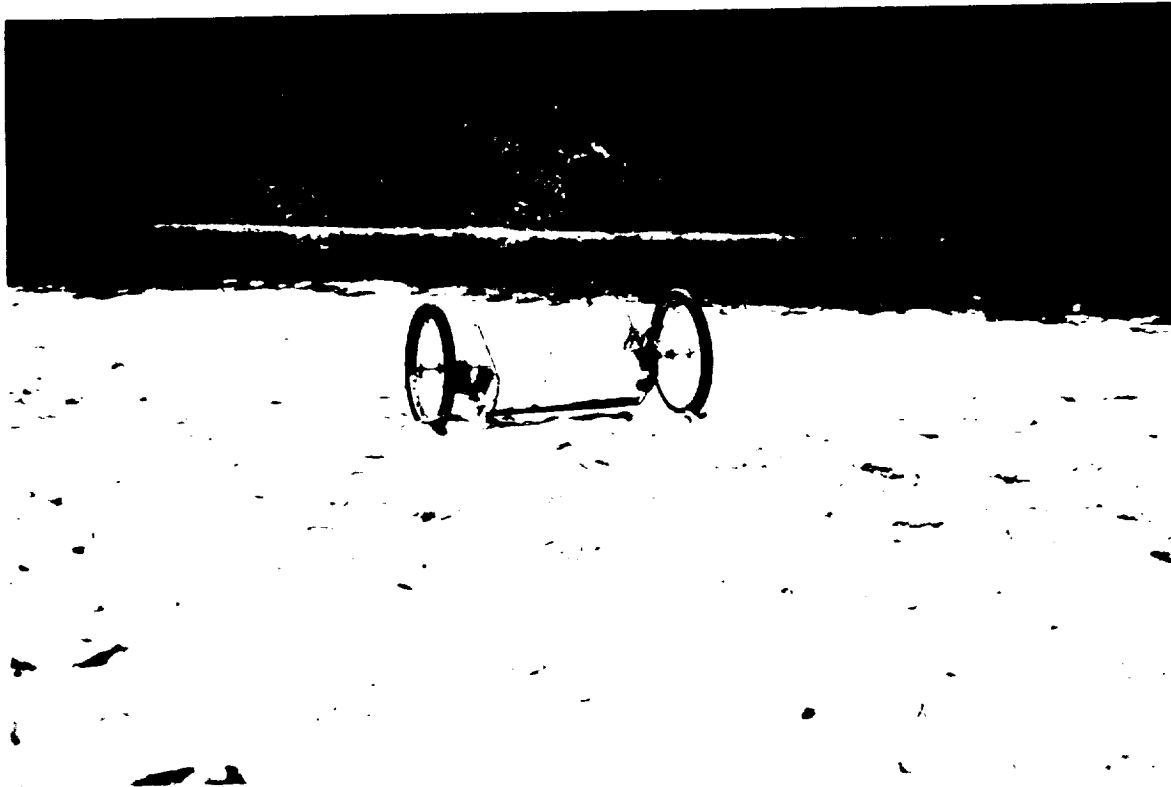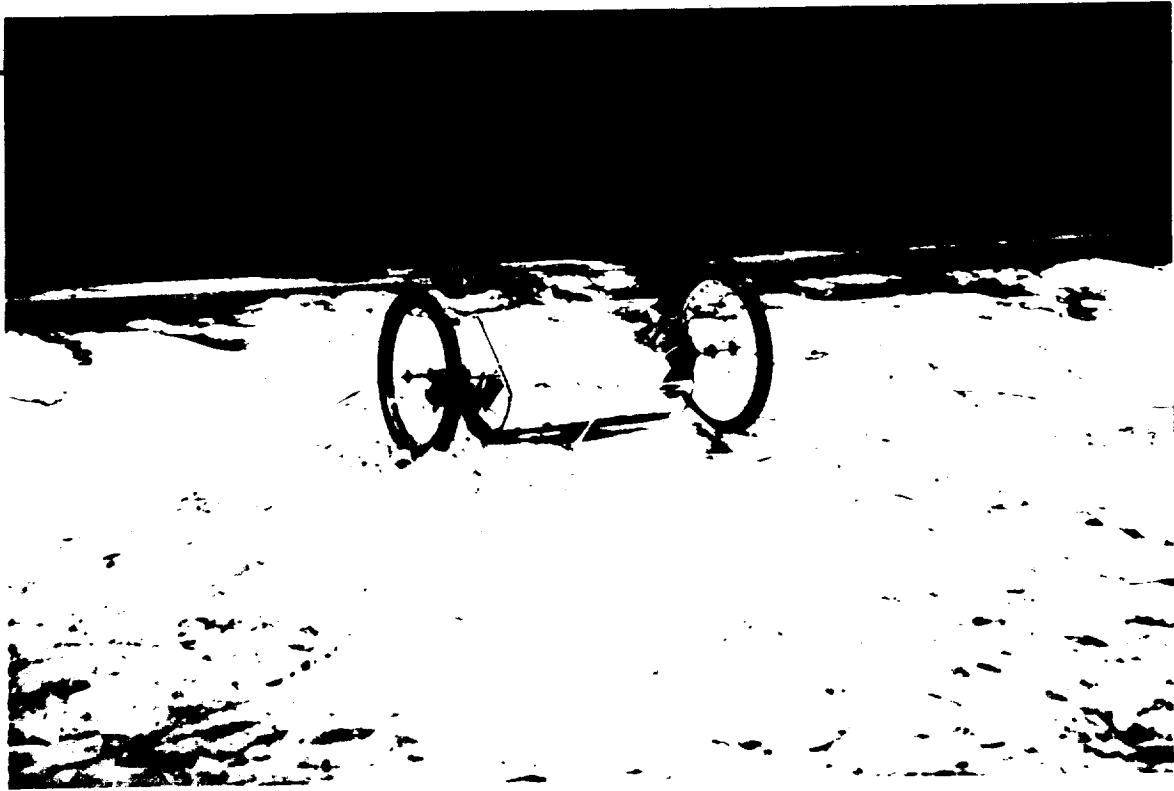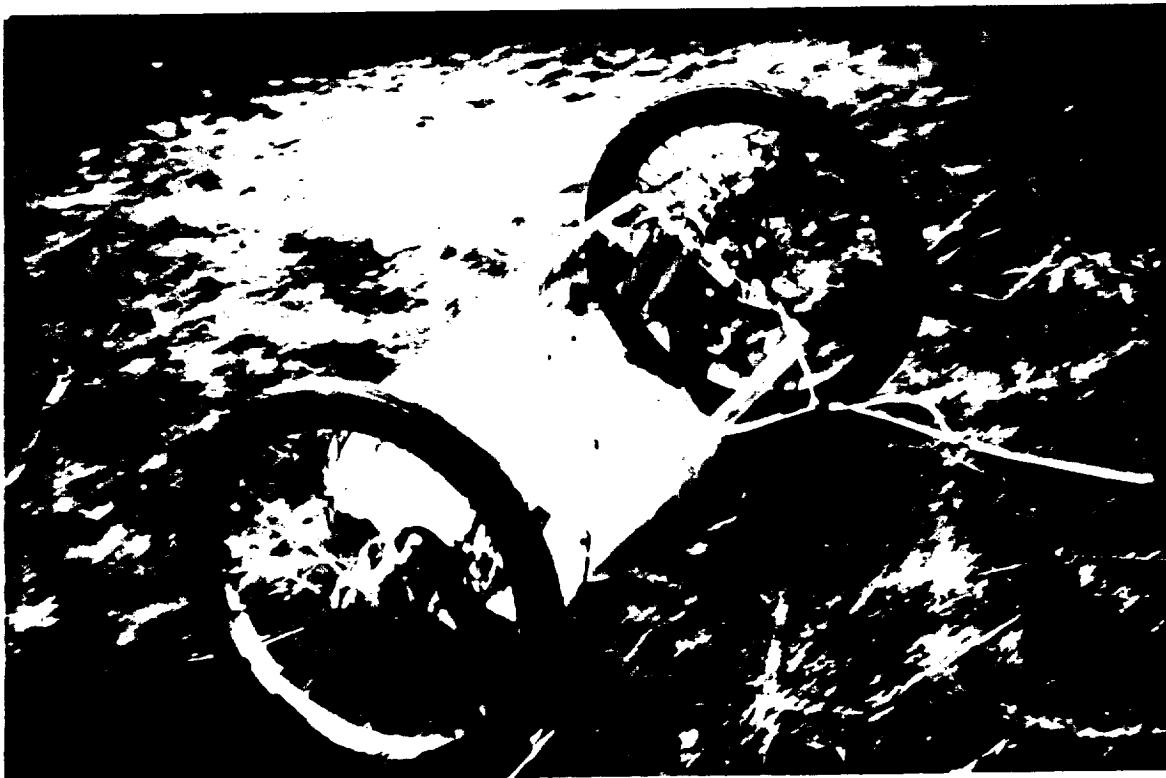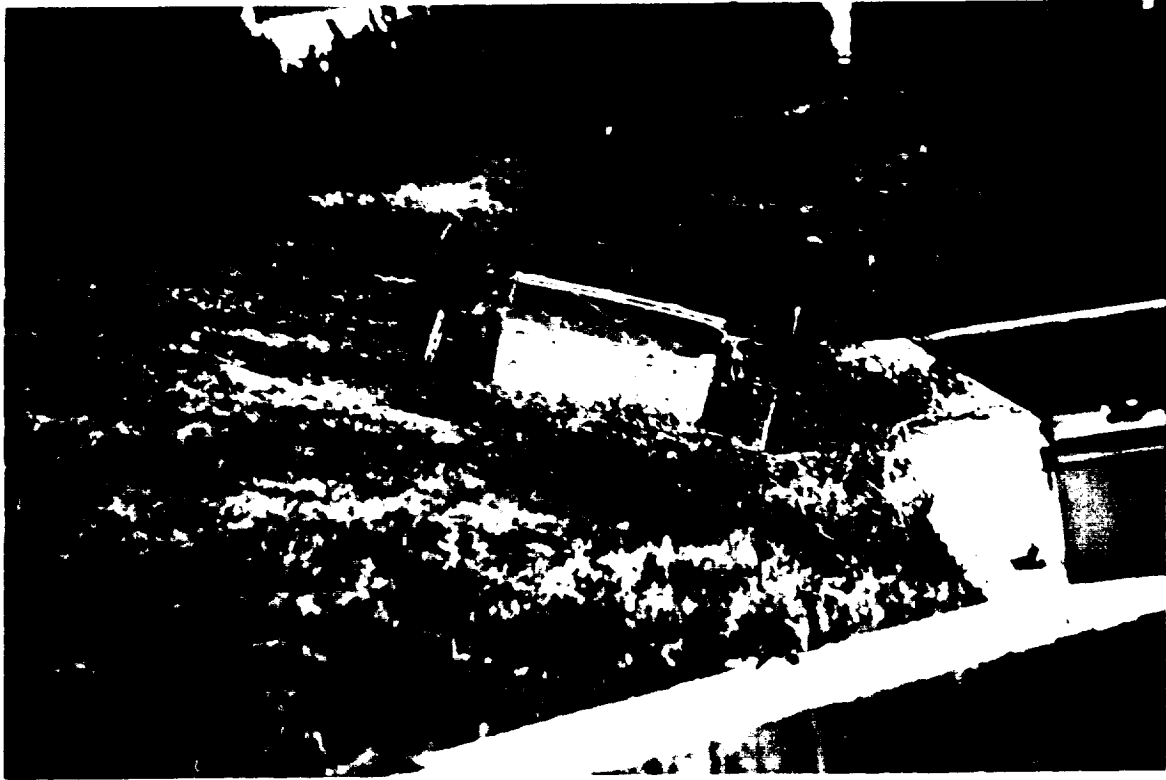
Figure 4.

APPENDIX F

Figure 1.

Figure 2.

Figure 3

Figure 4.

DRAWBAR PULL VS WEIGHT
MODEL

DRAWBAR PULL (LB)
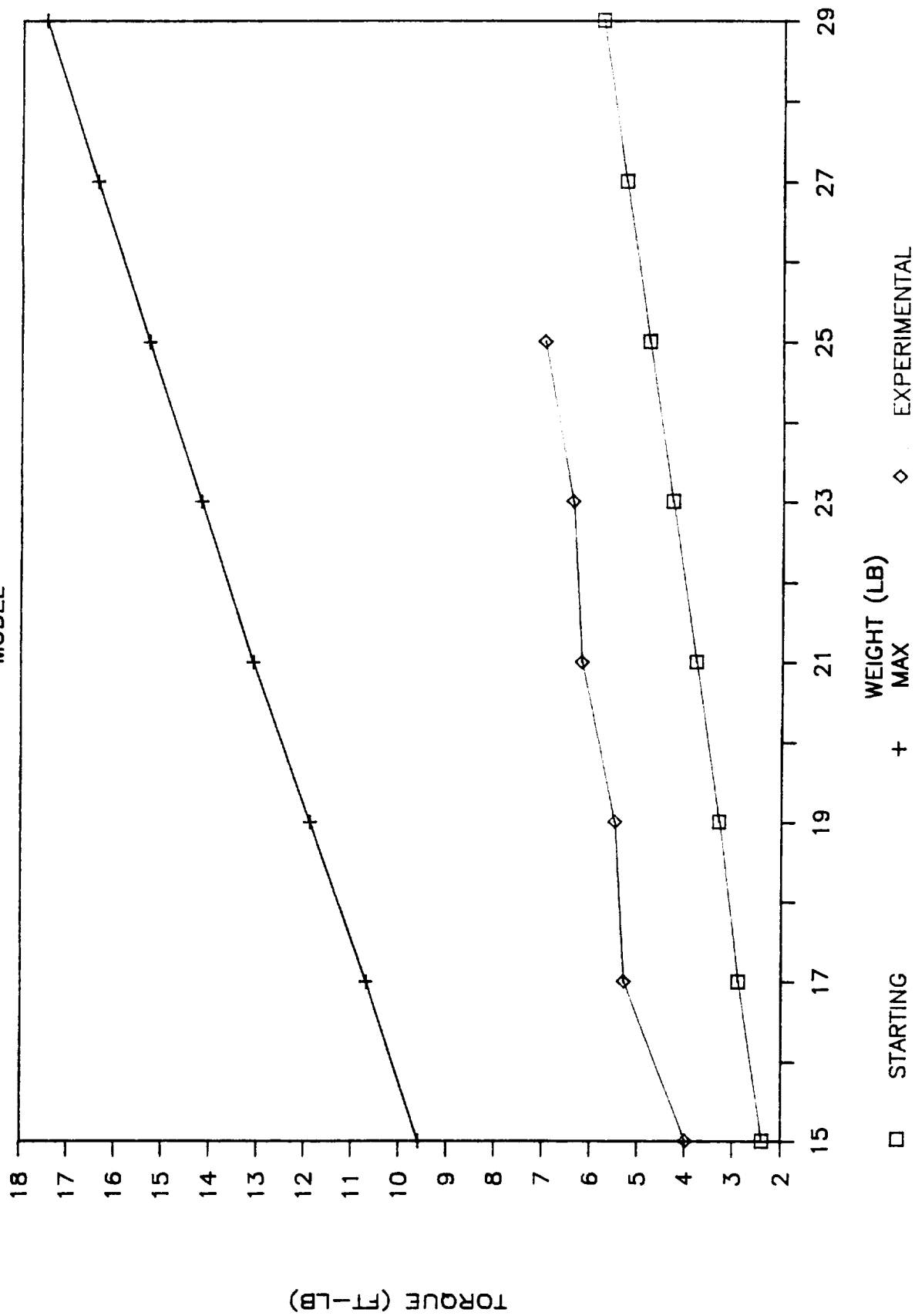
WEIGHT

□ THEORETICAL   + EXPERIMENTAL
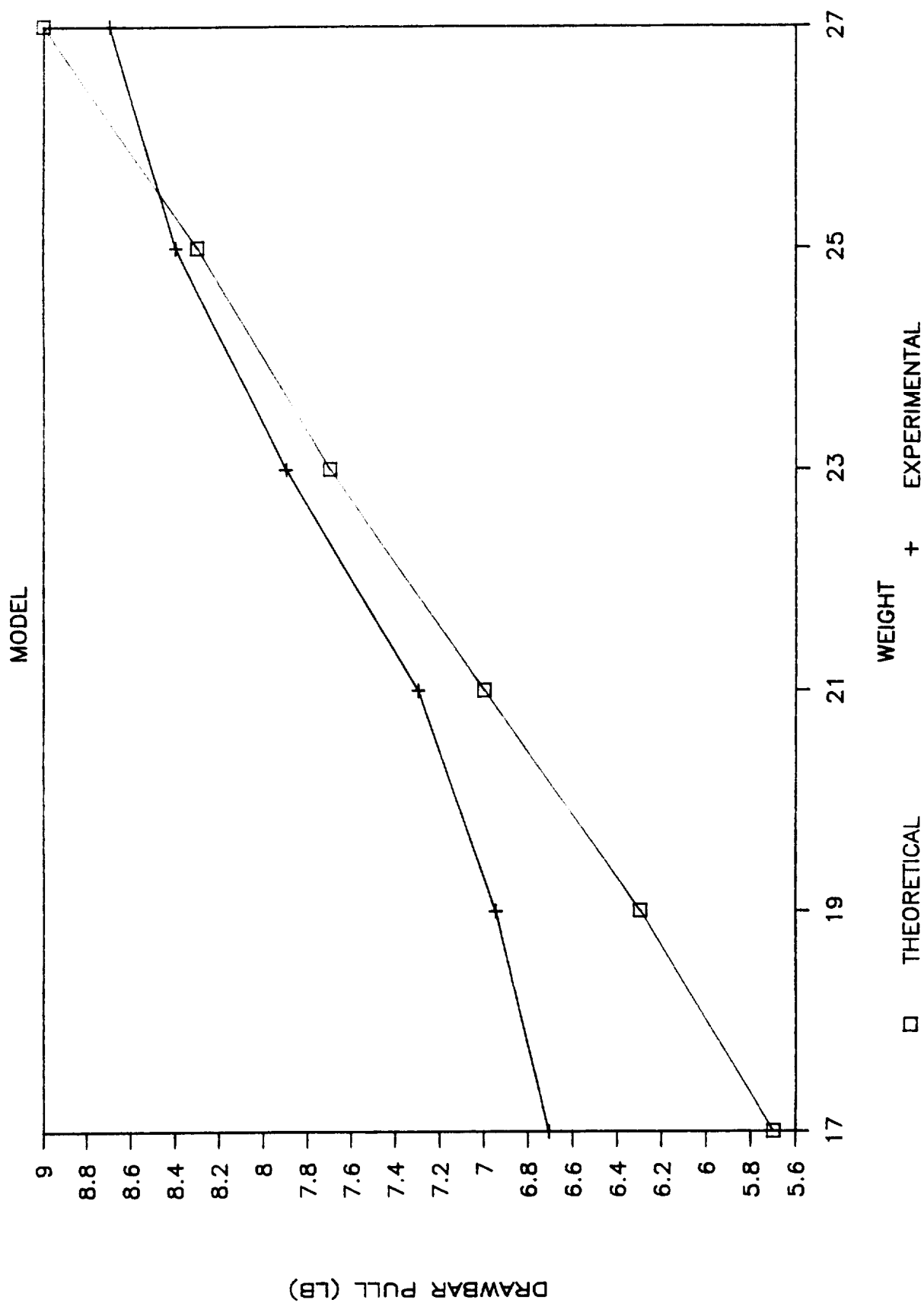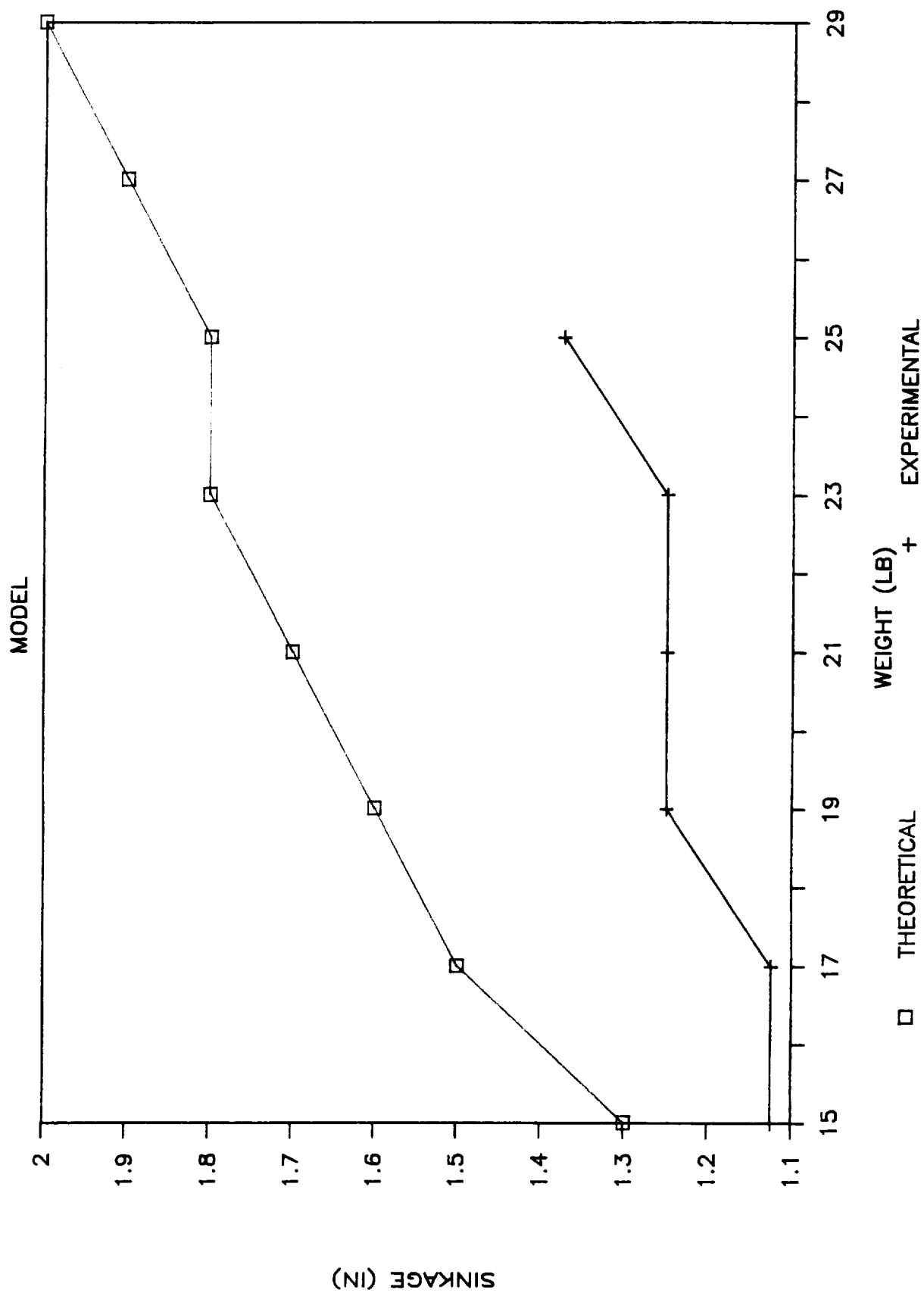
Figure 5.

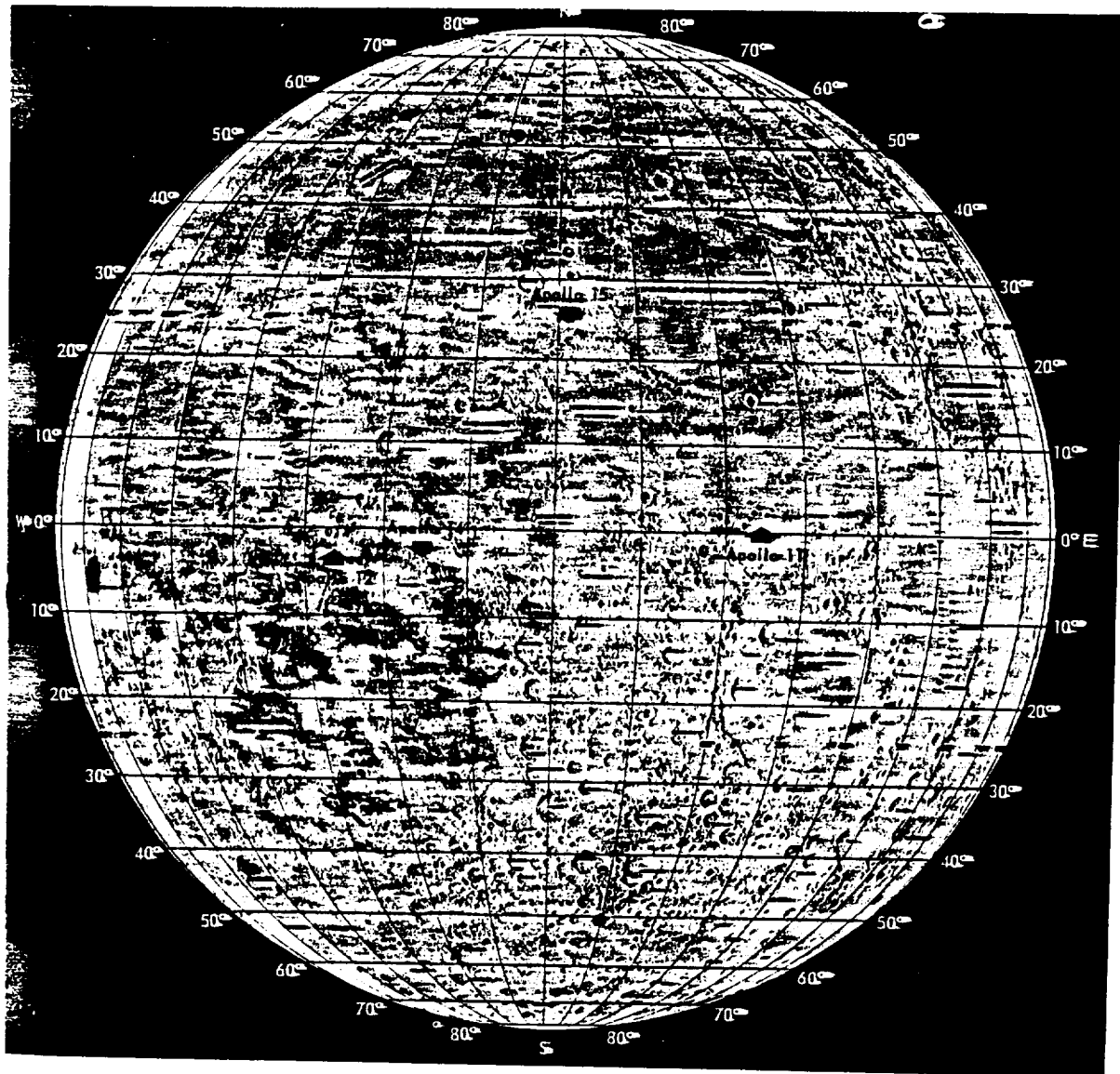TORQUE VS WEIGHT

Figure 6.

Figure 7.

APPENDIX G

FIGURE 1-1.—Landing sites of Apollo lunar-landing missions. Apollo 11 landed in Mare Tranquillitatis on July 16, 1969; Apollo 12 near the unmanned Surveyor III spacecraft on November 14, 1969; Apollo 14 in the Fra Mauro highlands on January 31, 1971; and Apollo 15 in the Hadley-Apennine region on July 30, 1971. Apollo 13 was aborted during translunar coast because of spacecraft-equipment malfunctions.

FIGURE 3-26.—Composite photograph of the LM taken from the ALSEP location. The Apennine Front forms the background behind the LM. Wheel and foot tracks crisscross in the foreground (S-71-51738).

FIGURE 3-28.–The textured pattern in the upper cente
of this photograph was made by the LMP with th
lunar rake. The rake is used to collect a comprehensiv
sample–a selective collection of rocks in the 1- t
3-cm size range. Samples 15600 and 15610 were co
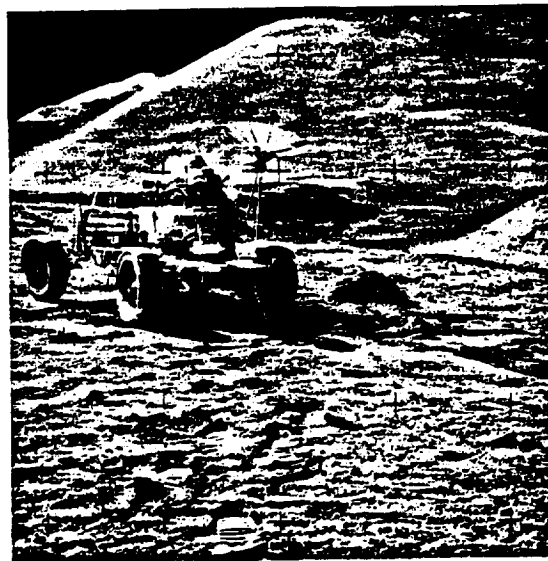lected at station 9A (AS15-82-11155).

FIGURE 3-27.–Hadley Delta, Silver Spur, and St. George
Crater form the skyline in this view toward the south
of Hadley Rille from station 9A. The CDR works at
the Rover to remove the Hasselblad camera for the
telephotographs. It is noteworthy that the front panel
on the left front fender of the Rover has been lost
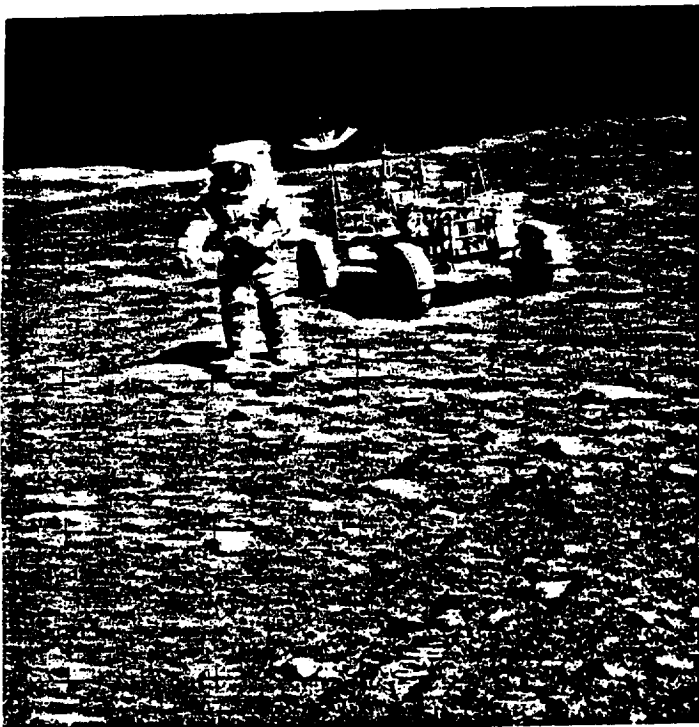(AS15-82-11121).

FIGURE 3-31.–The CDR walks t
Hadley Rille at station 10 to tak
photographs of the far side. He
the Hasselblad camera with a 5C
lens in his left hand as he walks
from the Rover (AS15-82-11168).

APPENDIX H

ME 4182 PROGRESS REPORT #1
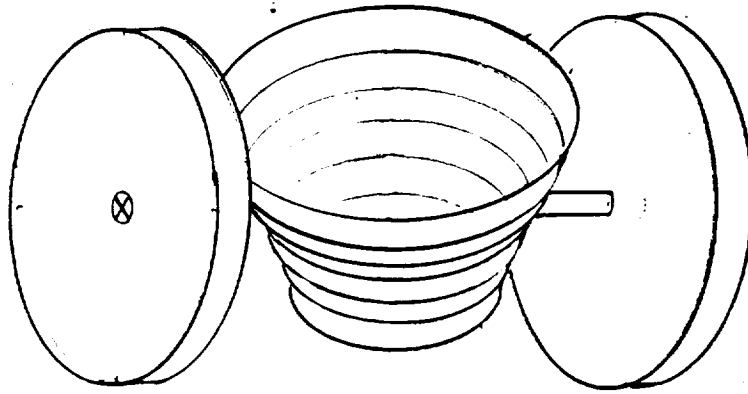TWO-WHEELED DUMP TRUCK
OCTOBER 4, 1988

In order to design an efficient dump truck, the project
has been broken into three distinct categories. Each of these
categories is being investigated by at least two group
members to ensure each decision will be made in an objective
manner.

Tomas Hernandez, Ron Kraynick, and Stan Langley will be
working closely in order to design the wheel mechanism and
the carrying bowl. This portion of the project includes
designing the most efficient wheel system, the shape of the
wheels, and the best bearings to be used for this
application. They will also be investigating the most
efficient shape of the bowl as well as the best material for
this purpose.

The dumping method and the method for "righting" an
over-turned dump truck will be investigated by Paul Jensen
and Ray Haleblian. The most important aspect of this section
is discovering the best way to dump the payload. Both
mechanical actuation and the use of dynamic actuation will be
investigated. Also, determining the most efficient way of
placing the vehicle back in service once it has turned over
will be studied.

Alan Shuman and Michael Brus will be investigating the
best method to control the movement of the truck. This
includes finding an efficient way of mobilizing and steering
the vehicle. Both one and two motor drives will be studied as
well as speed controls of the wheels to find a practical
steering mechanism.

Each sub-group's progress will be discussed in detail at
the weekly group meetings so that a successful design can be
completed for the harsh Lunar environment.

INITIAL CONCEPTION OF

TWO WHEELED DUMP TRUCK

ME 4182 PROGRESS REPORT
PROJECT: 2-WHEEL LUNAR TRANSPORT VEHICLE
DATE: 10/11/88
PREPARED BY: ALAN SHUMAN

CONFIGURATION:

Two different types of bowl configurations are currently being compared, hemispherical and cylindrical (see Figure 1). The hemispherical shape offers better traveling stability due to its large moment of inertia when it is full of material in addition to the best volume to surface area ratio. On the other hand, the cylindrical shape offers better stability on inclines and requires less motor torque because smaller wheels can be used. Therefore, currently neither shape has a distinct advantage over the other. In fact, the final shape may be a combination of the two into a "bath tub" configuration.

Current specifications:

Capacity - 2.1 m^3 (75 ft^3)

Spherical bowl diameter - 2 m (6.5 ft)

Wheel diameter (*for spherical shape*)- 1.8 m (5.9 ft)

DYNAMICS:

Stability and torque requirements are currently being investigated for both the transporting and dumping modes. First approximations assume ideal conditions such as smooth surfaces and inclines, single homogeneous building materials, as well as earth-like conditions (except gravity). Once these initial calculations have been made, the design process will begin with group brainstorming sessions.

Current specifications:

Maximum speed - 15 km/hr (10 mph)

Maximum transverse incline (*for spherical shape*) - 50°
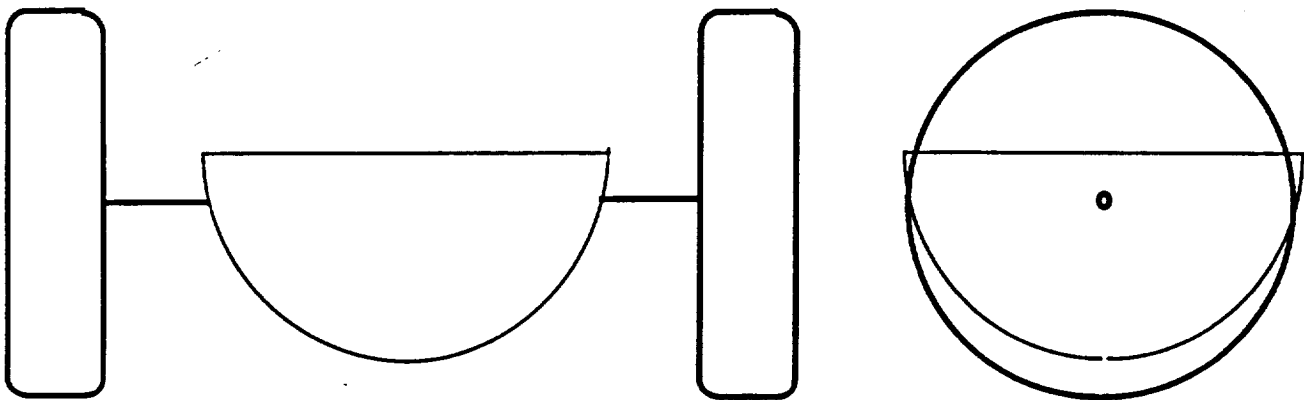
GOALS:

By next meeting time, 10/18/88, we hope to have finished all the necessary initial calculations to begin effective brainstorming. This will conclude the *preparation* stage of our design.
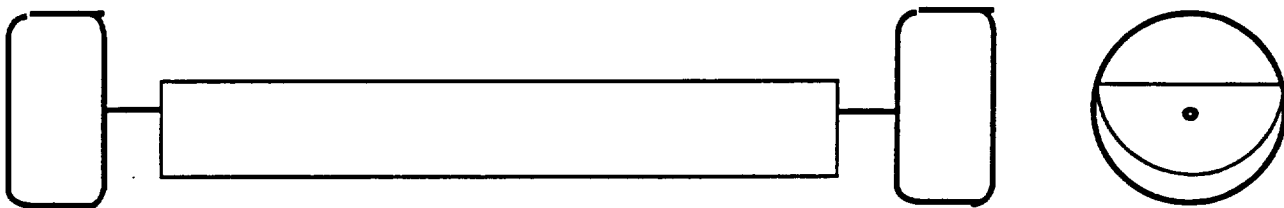
FIGURE 1

A. SPHERICAL CONFIGURATION

B. CYLINDRICAL CONFIGURATION

ME 4182 PROGRESS REPORT
PROJECT: 2-WHEEL LUNAR TRANSPORT VEHICLE
DATE: 10/17/88
PREPARED BY: Paul Jensen

CONFIGURATION:

We have investigated several different bowl types during the past week and we have concluded that a half cylindrical bowl is best suited for this application. The half cylindrical bowl has a low center of gravity and can carry the greatest amount of lunar soil compared to the hemispherical bowl or bath tub type bowl in this particular configuration. Also, we are feel this half cylinder bowl should be fairly long compared to its radius. This will help in a couple of ways. First, a longer cylinder will greatly enhance lateral stability(tendency to roll will be decreased). Second, preliminary calculations are indicating that the wheel moment of inertia should be small compared to the bowl moment of inertia in order to retard bowl flipping. Small wheels and a long bowl will aid this needed relationship.

Current specifications:
Capacity -   2.8 cubic meters
Cylinder length - 3.63 meters
Cylinder radius - 0.70 meters
Wheel radius -   0.80 meters

DYNAMICS:

Progress has been made in the past week in determining a set of dynamic equations that properly model the behavior of a two wheel lunar transport vehicle. These calculations should be complete before the next meeting.

Current specifications:
Maximum speed - 15 km/hr (10 mph)
Maximum transverse incline - 50 degrees

WHEELS:

Several different wheel designs have been conceived that will make the vehicle inherently self righting. Currently, NASA literature is being referenced in order to determine tread design and material requirements.

GOALS:

By next meeting time, 10/25/88, we hope to have a reliable set of dynamic equations that will enable us to calculate performance characteristics such as acceleration, hill climbing and descending ability and lateral stability given various combinations of bowl and wheel size. Also, we want to look further into tire design and bowl material.

ME 4182 PROGRESS REPORT

PROJECT: 2-WHEEL LUNAR TRANSPORT VEHICLE

DATE: 10-25-88

PREPARED BY: STAN LANGLEY

Much of the work done this week has been focused on the design of the wheel and its tread. Many tread designs were examined and of these three final possibilities were chosen. These three include cleats, cheverons, and broken arcs. We are leaning torward the cheveron tread design. The final decision will be made this week.

These decisions were based on research on the lunar rover and a conversation with Dr. Burt of the Tilliage Laboratory at Auburn University. Dr. Burt suggested a pneumatic, non-rigid tire. He suggested calling Royer Klaas of Firestone in Akron, Ohio. Mr. Klaas will be able to help with the material used for the tires.

The cheveron type treads were tested for the lunar rover by the Governments waterways experiment station. With the Cheveron treads covering 50% of the contact area, it was found that a grade of 20-25% could be climbed without slippage.

Work also continued on the dynamics of the system. Also, we worked on the problems of braking and dumping. We also discussed building a working model in the next two to three weeks. We talked to someone in Peachtree City who can get the motors and tires for us cheap.

Next week we will be preparing for our midterm presentation and continuing work on the braking and dumping. We will also make a final decision on much of the hardware involved such as the bowl, tires, and size of motors.

2-WHEEL DUMP TRUCK
PROGRESS REPORT
for week of 10/28/88 to 11/1/88

The high priority of the group is to build a model by which we can test our theoretical design:

Bowl and Wheels

The bowl will be Lexan plastic. 3/8" thickness hemispherical plates will act as ends and divider/supports for the curved outside plate that will be wrapped around them. The overall scale of the model is dictated by a pair of 12" diameter bicycle wheels mounted directly onto the motors.

Motors

Our preliminary research into radio control motors led group members to the local hobby shop. They found that RC motors operate at RPMs too high to gear down to the speeds required by this size model. We decided another option would be to procure variable speed, high torque DC motors like those used in hand drills from Black and Decker Co. which would closely simulate the ideal motor for the full scale truck.

Controls

Since radio control motors appear very unlikely, we will use a drive-by-wire system by which the motor speed is governed by a pair of variable resistors, one for each motor. In this way the operator can adjust the relative speeds of the wheels to turn the model.

The group continued research concerning the various parts of the full scale vehicle:

Materials

Materials Engineerings Materials Selector 1986 was consulted along with a IBMPC metal selector database to decide what materials would hold up to the harsh lunar enviroment. Following the example of the Lunar Rover, various aluminum alloys satisfy the requirements of low coeffecient of thermal expansion and high thermal conductivity while being relatively lightweight. Specifically, cast alloys A03900A, B and C as well as A13320 are being considered due to their wear resistance and high temperature strength.
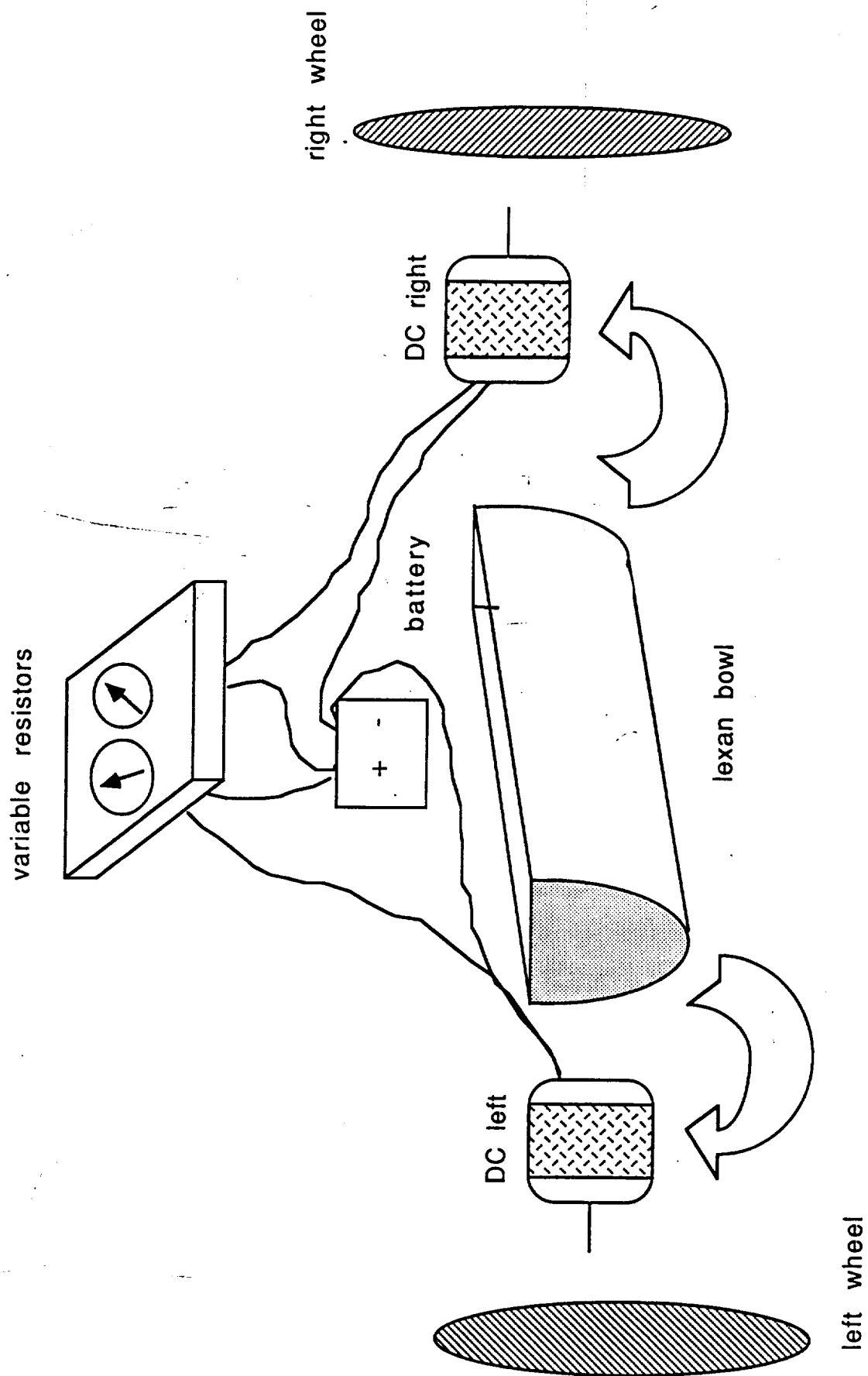
Wheels

On the advice of the Auburn Tillage Laboratory, we have chosen the chevron design (see last report) as the best tread design. We are currently searching for a flexible, wear resistant and thermally stable material for constructing the wheels.

Controls

One possible approach to control has arisen from the SAE Technical Paper 871639: *Automatic Tractor Guidance with Computer Vision* by Reid and Searcy. The paper describes processing camera images by finding outline in contrast difference. Thus, a rudimentary knowledge of surrounding objects can aid a earth based driver or supply enough information to an artificially intelligent machine. To avoid camera problems associated with lunar glare, we have suggested using an infrared camera; our aim is to discover the pitfalls of such a system and how to compensate for lag time in intraplanetary transmission.

MODEL CONTROL SCHEMATIC

variable resistors

right wheel

DC right

battery

lexan bowl

DC left

left wheel

+

ME 4182 PROGRESS REPORT
PROJECT: 2-WHEEL LUNAR DUMP TRUCK
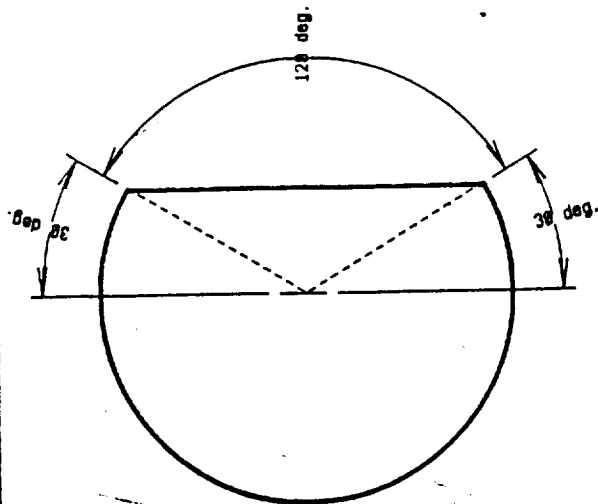### DATE: 11-7-88
PREPARED BY: Tomas Hernandez

BOWL: The bowl design has been altered during the last week in order to make it more stable. It has been decided to close the 180 half-cylinder bowl to a 240 cylindrical bowl. This will allow the bowl to rotate by as much as 30° while carrying the load without causing it to overturn. This closes the mouth of the bowl by 14% but we feel that it is still wide enough to load it without much problem. This makes the bowl about 30% heavier which is bad as far as transporting to the lunar surface but it will help keep the bowl from inappropriately rotating.

WHEELS: A wheel has been found in the U.S. Patent System which was specifically designed for lunar transportation. It has the flexible ability that we were searching for so that it can travel over small rocks without difficulty. It has a flexible outer rim joined to a rigid spoked hub. See the accompaning photocopy. This wheel is being further reviewed.

MATERIALS: A meeting was setup with Dr. Carolyn Meyers to discuss the metals which we had selected by the use of Materials Engineering Materials Selector 1986 and the IBM-PC metal selector. Specifically, AA336(DSG A13320) and AA390 (DSG A03900) were the two main choices. These metals both showed to have high temperature strength, low coefficient of thermal expansion and good resistence to wear. Dr. Meyers was pleased with both metals but suggested the AA336 because of higher ductility. She saw no problem with casting in sand in order to produce our bowl shape. She also suggested the T6 heat treatment in order to improve the strength. We are to meet with her again later this week for further discussion.

GOAL: We are presently looking into purchasing two 115 volt AC/DC motors along with two 12 inch tires. Along with the other materials which we already have, we hope to have a prototype ready by early next week. Other areas of investigation at the present time include the form of steering, the visual guidance system, and detailed maps of the lunar surface.

240 DEGREE BOWL DESIGN
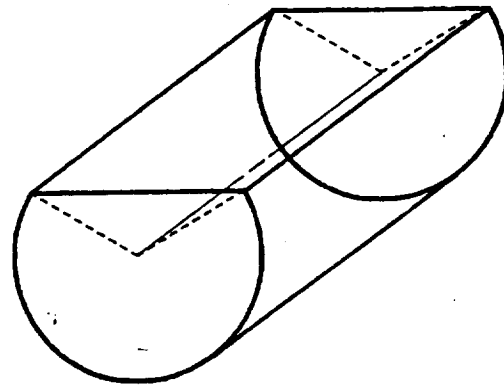
120 deg.

30 deg.

30 deg.

cross-section

isometric
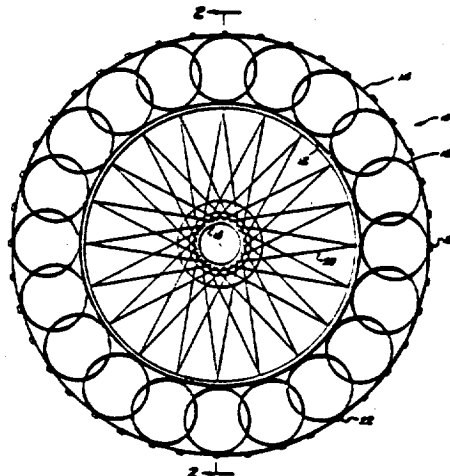
The past week has been spent accomplishing a number of different tasks. These tasks include finalizing details of the lunar dumptruck body design, research on possible types of remote vision, and further efforts in the construction of the dumptruck scale model.

Lunar Model Design

Bowl Design - The design of the bowl presented last week remains the choice of the group, as does the material selection. It was decided, however, that the aluminum material selected would not be laminated with another material to reduce wear. In discussing the possibilities with Dr. Carolyn Meyers, we concluded that our material had excellent wear properties and that a laminate would only raise the total weight and cost of the design.

Wheel Design - The wheel design initially presented last week remains the optimum design. Made of aluminum and titanium, the wheel is well-suited for our requirements of low weight, deformability, and large surface contact area. The wheel design also exhibits traction comparable to that of pneumatic tires, which will aid in traction analysis. Another benefit of the proposed design is that as the load on the wheel is increased, the surface contact area increases so that the wheel does not sink into the lunar soil.

Visual Guidance System - The group was directed to Mr. John Gilmore of the Georgia Tech Research Institute. After presenting our situation to him, he suggested the use of one IR camera and one laser rangefinder since the design limits the number of mounting positions to two, on either side of the bowl.

Scale Model Design

Progress - In the past week, all the necessary supplies have been purchased and/or machined to specifications. The model will be constructed in the next few days, producing a working model by next week. The model will then be tested in order to gather data concerning performance characteristics to be expected on the lunar surface. Sand will be used as the lunar soil simulant in all the experiments.

Goals

Lunar Model Design - In the next week, the areas of steering and dumping will be reviewed. Preliminary ideas have already been presented in group brainstorming sessions. They will now be analyzed to determine the most feasible.

Scale Model Design - As stated previously, the group plans to have a working model which can be tested by next week.
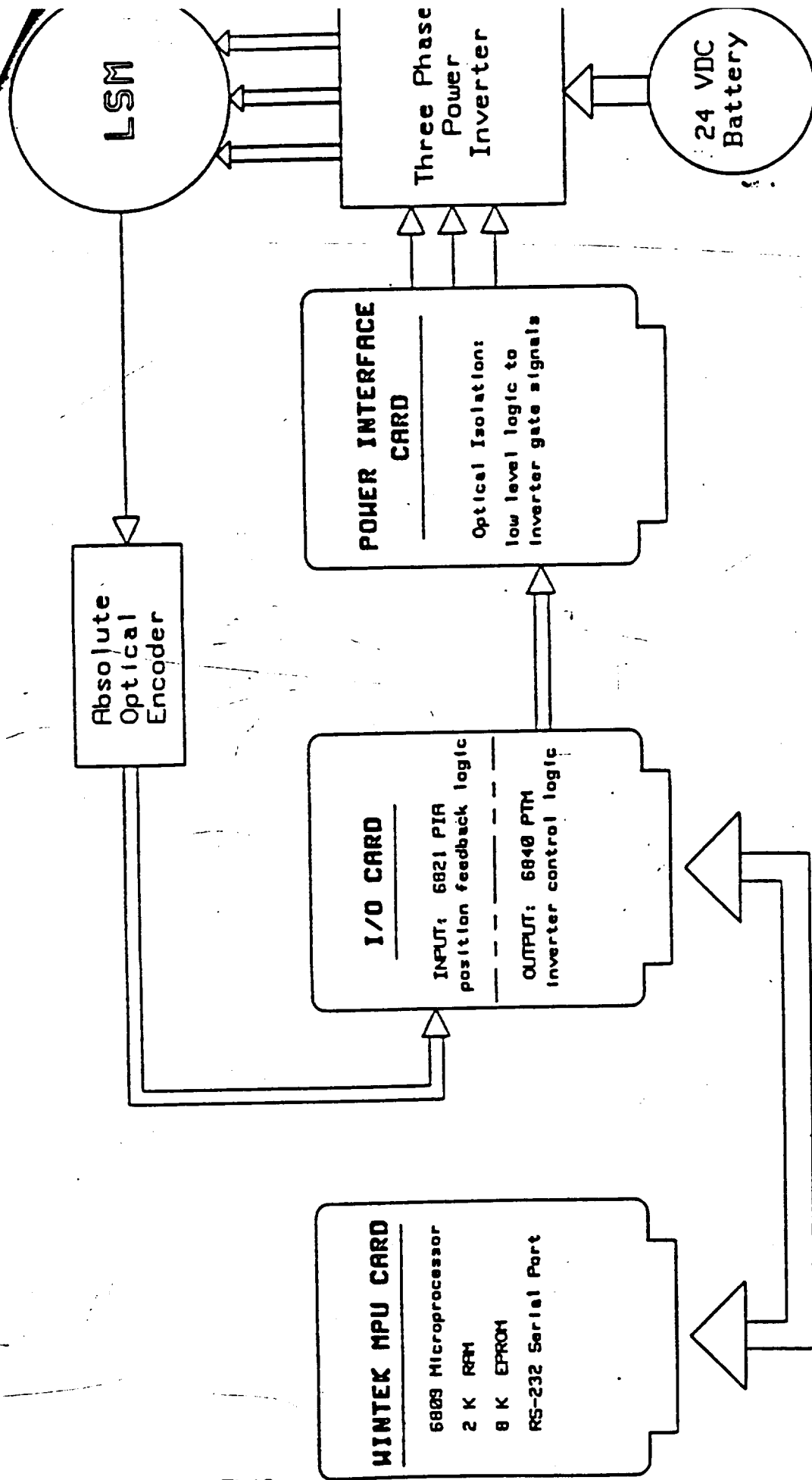
LSM

Three Phase Power Inverter

24 VDC Battery

POWER INTERFACE CARD

Optical Isolation;
low level logic to
Inverter gate signals

Absolute Optical Encoder

I/O CARD

INPUT: 6821 PIA
position feedback logic

OUTPUT: 6840 PTM
Inverter control logic

WINTEK MPU CARD

6809 Microprocessor

2 K RAM

8 K EPROM

RS-232 Serial Port

Fig. 10 LSM Control System

FINAL PROGRESS REPORT
M.E.4182
TWO-WHEELED LUNAR DUMP TRUCK
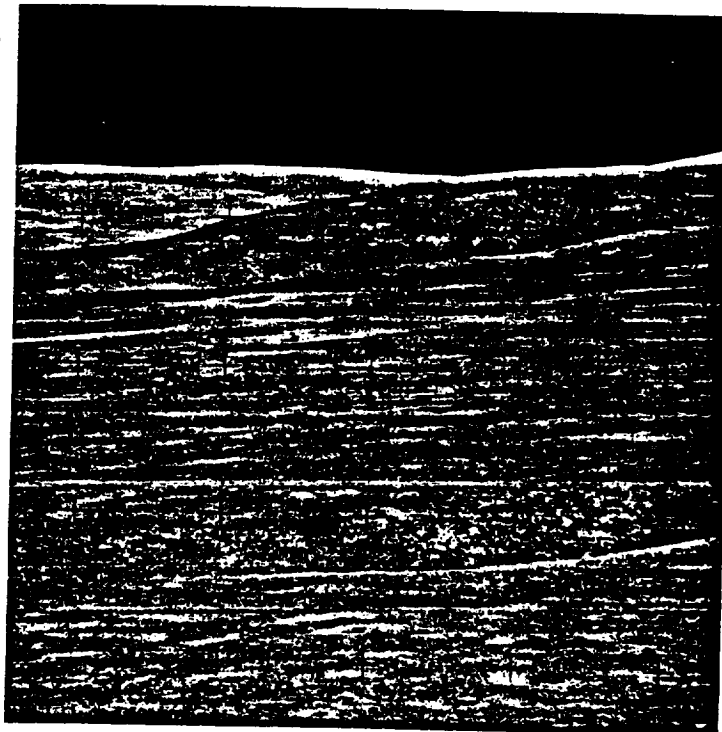PREPARED BY: Michael Brus
November 22, 1988

During the course of the past week our group has made
substantial progress leading to the completion of this
project. Some of this progress included completion of the
model, obtaining data concerning the surface of the moon that
the truck will most likely be utilized, and beginning to
compile information for our final report and presentation.

Although the scale model has been constructed for
approximately two weeks, we have faced various difficulties
in the past when trying to obtain experimental data. We have
since corrected all of the problems that we faced and have
obtained limited but very reasonable data (as compared to our
analytical models). A short list of some of the information
we have collected from testing our model that we feel will
transfer almost directly to the lunar version is as follows:
1) The model has successfully climbed hills with an
approximate grade of 35 degrees, 2) it has also traveled down
the same slope with no difficulties. 3) The model has
traversed a hill of approximately 45 degrees which
corresponds directly with our original analytical estimate.
Other experiments have been performed and more are planned to
take place in the near future (scheduled for Wednesday) to
obtain more data.

Information obtained from reports of various Apollo
missions concerning the surface of the moon where the
majority of the excavation might take place has proven to be
very helpful. From the photographs taken by both Apollo
astronauts and satellites we feel that the lunar version of
the dump truck will have little difficulty performing the
tasks it was designed to accomplish. Some of the more
interesting of these photographs have been included with this
report.

Information for the final report and presentation is
currently being compiled as well as the final touches of the
design itself. We feel that we are approximately 60-70%
complete with our final report and we have all areas to be
discussed identified and certain group members assigned to
ensure that portion of the project is completed.

On the side of Hadley Delta ... the CDR took a series of ... with the 500-mm telephoto ... crater in the foreground, ... approximately 2 km, is ... series of white dots to the ... LM (approximately 5 km ... deployed ALSEP. The ... that forms the background ... is Pluton at a distance of 8 ... approximately 800 m in ... the largest boulder in the ... approximately 20 m in diameter ... 1324). ...

the flag depl...
Delta forms ...
...ted in a crater ...
...ver is parked ...
...ermal constra...
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...s just above ...
...-92-12446).
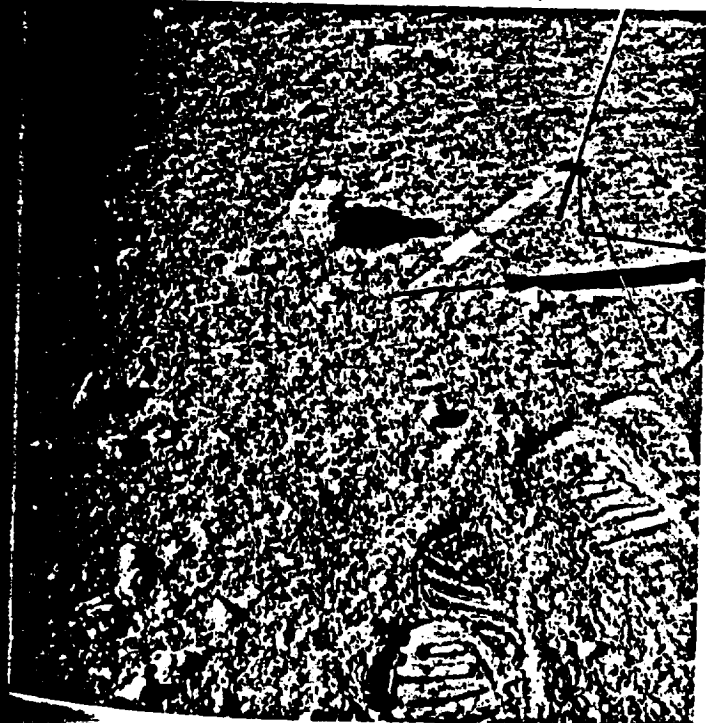
FIGURE 3-20.—The small white clast on top of the larger gray fragment located to the upper left of the gnomon is the "genesis" rock as the Apollo 15 crew found it on the lunar surface. It should be noted that this anorthositic fragment is not in situ but occurs as a clast within a breccia. This sample was collected at station 7, Spur Crater, on EVA-2 (AS15-86-11670).
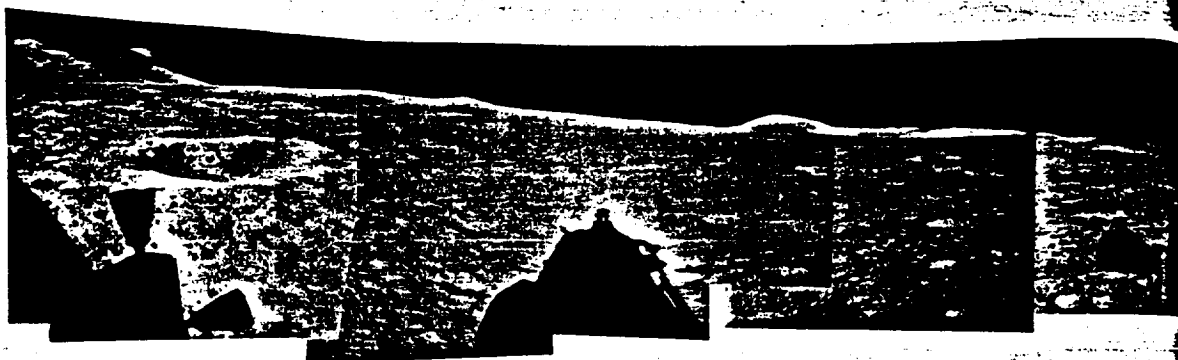
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FIGURE 3-12.—Seven of the 14 photographs taken from the left- and right-hand LM windows have been used in this composite photograph. The view covers approximately 180° from Hadley Delta in the south to the base of Mt. Hadley in the north (S-71-47078).
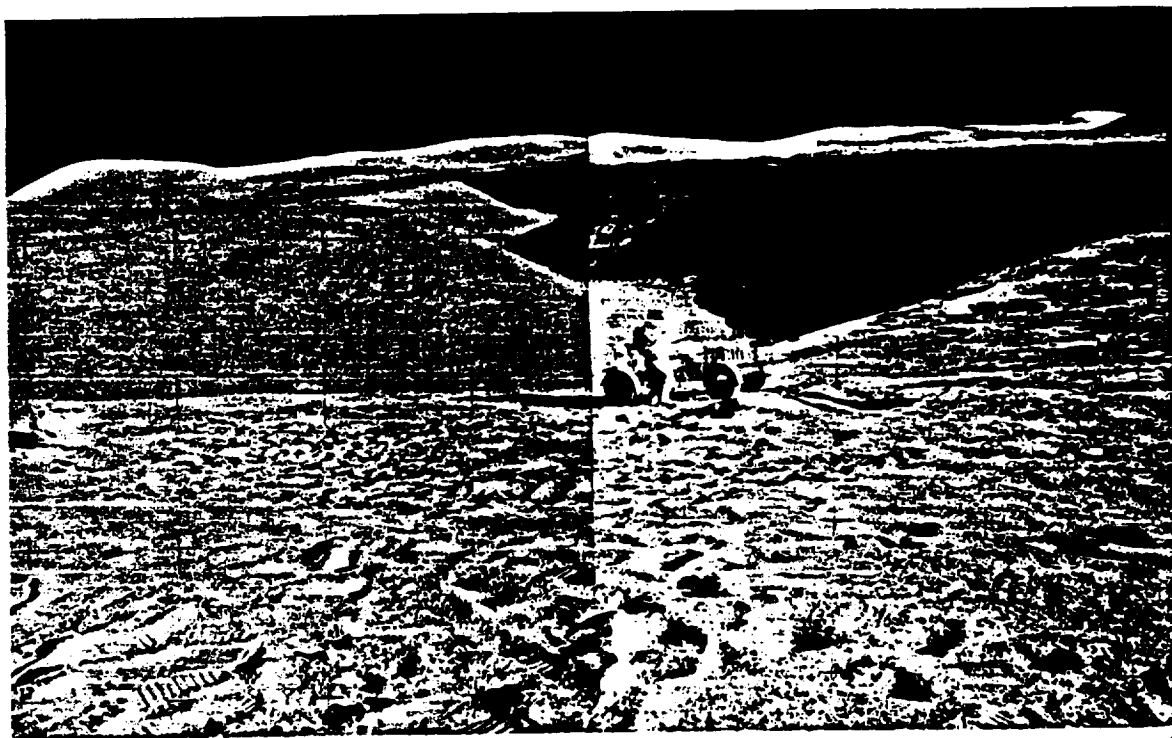

FIGURE 3-13.—Composite photograph forms a view to the north along Hadley Rille. Some horizontal tonal and textural differences, which can be detected in the east wall, may correlate with the horizontal bedding in the west wall of the rille. The boulder to the right center was the location of the major sampling and documentation activity at station 2, where the CDR is unloading equipment from the Rover. Fragments from the boulder and fine material from around and from under the boulder were collected (S-71-51735).
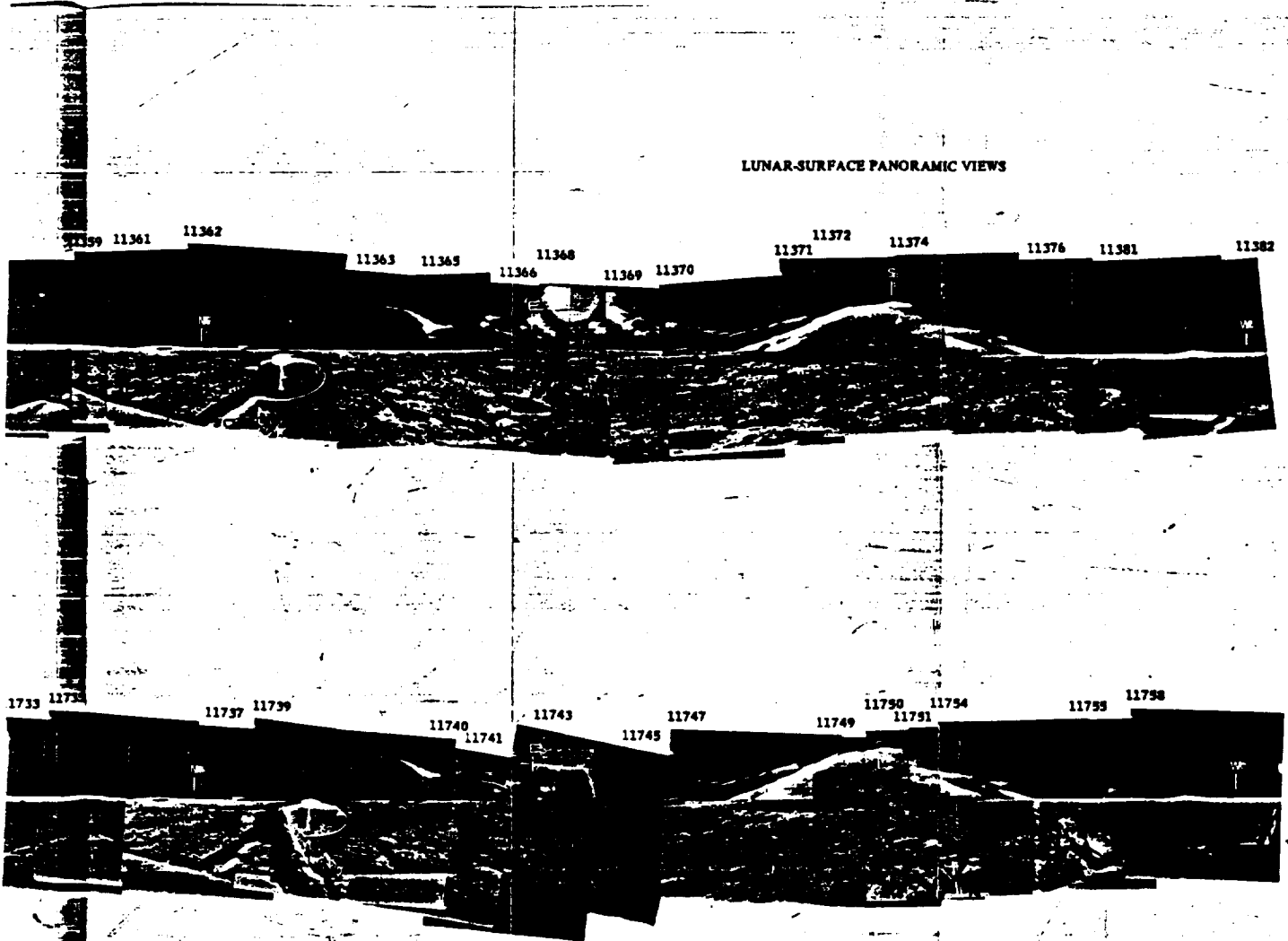
Figure D-1.—Vertical stereophotographs taken during standup EVA. (a) Upper portion (AS15-85-11354 to 11382). (b) Lower portion (AS15-87-11730 to 11758).