NGT-21-002-080
NGT-80001

PROPOSAL FOR A

LUNAR TUNNEL-BORING MACHINE

by

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presented to

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May 5, 1988

(NASA-CR-184746) PROPOSAL FOR A LUNAR TUNNEL-BORING MACHINE Final Report (Texas A&M Univ.) 67 p CSCL 13B
N89-17753
Unclas
H1/31 0189653

NASA/USRA GRANT

ABSTRACT

A need exists for obtaining a safe and habitable Lunar Base that is free from the hazards of radiation, temperature gradient, and micrometeorites. A device for excavating lunar material and simultaneously generating living space in the subselenian environment has been researched and developed at the conceptual level. Preliminary investigations indicate that a device using a mechanical head to shear its way through the lunar material while creating a rigid ceramic-like lining meets design constraints using existing technology. The Lunar Tunneler is totally automated and guided by a laser communication system. There exists the potential for the excavated lunar material to be used in conjunction with a surface mining process for the purpose of the extraction of oxygen and other elements. Experiments into lunar material excavation and further research into the concept of a mechanical Lunar Tunneler are suggested.

ACKNOWLEDGMENTS

The authors would like to thank the following people for the assistance they provided in making this report possible. Professor Stan Lowy and Dr. Tibor Rozgonyi provided invaluable guidance. Special thanks also to Dr. Thomas C. Pollock, Dr. T. Schobeiri, and Dr. Erian Baskharone.

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INTRODUCTION

A Lunar Base is being considered by NASA because of the numerous advantages it would offer. These advantages include use as a vacuum testing ground for conducting experiments, mining of certain elements, and a threshold for further space exploration. Problems such as high radiation, solar flare danger, large temperature changes, and micrometeorite damage arise when locating a base on the surface of the Moon. A method must be obtained to shield the Lunar Base from these environmental hazards while minimizing transport weight and cost.

An underground Lunar Base is preferred over a surface base for various reasons. Two methods, trenching and back-covering, could be used in the design of a protected Lunar Base. However, neither of these techniques is able to provide total environmental protection, and both require extensive ground-moving equipment. A base located 10 to 30 meters (about 30 to 100 feet) beneath the lunar surface will be effectively shielded from all environmental hazards. Normal radiation dosage on the lunar surface is approximately 30 rem per year, increasing to approximately 70 rem per hour during an intense solar flare. (See Figure 1.) Long-term exposure to these radiation levels has been proven to be fatal. Establishment of a lunar base at the suggested depth will ensure that the radiation levels do not affect the inhabitants. A second argument in favor of the underground base is the large temperature change. The Moon, having a temperature difference of approximately 250°K between lunar day and night, creates heating and cooling difficulties, associated structural deformities, and health hazards. For a subsurface Lunar Base the temperature change is reduced to a negligible amount. In addition, micrometeorites call for design considerations to account for structural damage, limiting travel on the lunar surface as well as requiring a larger quantity and weight of structural elements to be brought from Earth. (See Figure 2.) With all of the above design considerations in mind, it was proposed that large living spaces might be created beneath the lunar surface instead of locating the base on the surface itself. These living spaces could be created be placing habitation modules inside the tunneled-out areas and then sealing the tunnels through an air-locking technique. A tunnel-boring machine, a *Lunar Tunneler,* was considered to be the most efficient method of creating large amounts of living space.

Radiation Dose for a Person Exposed on the Lunar Surface

GCR	~30 REM/yr
Avg. Solar Bckgrd.	negligible
Large Solar Flare	up to 70 REM/hr

FIGURE 1: RADIATION DOSAGE ON LUNAR SURFACE (FROM REPORT BY LOS ALAMOS)

Crater Diameter (μm)	Impacts/m^2/yr
.1	30,000
1	1,200
10	300
100	.6
1000	.001

FIGURE 2: MICROMETEORITE FLUX ON LUNAR SURFACE (FROM REPORT BY LOS ALAMOS)

There were several preliminary general design considerations for the Lunar Tunneler. These included total automation, lack of débris removal, absence of utility lines, and the ability to handle lunar material of different sizes and hardness values. For reasons outlined below neither of the methods reviewed, melting or mechanical, could meet the constraint of no débris removal.

In considering a Lunar Tunneler, the trade-offs and advantages of different methods had to be examined. The lack of an atmosphere reduced the considerations to two methods, thermal melting and mechanical excavation. Choices for power generation were between solar and nuclear because of the constraints for a totally automated tunneler and elimination of the need for fuel. Using a small nuclear power plant was preferred over solar power generation because the latter could not produce sufficiently high amounts of energy due to low efficiency and the problem of energy storage during lunar night.

Purely mechanical tunnelers and tunnelers that rely only on melting both offer several advantages and disadvantages that were evaluated in coming up with a Lunar Tunneler design. Initially, thermal melting was assumed to be the best method because of the small number of moving parts and less down-time expected. It was also considered that melting would have allowed the lunar material to be packed into a much smaller space through density changes, obviating the need to dispose of any excavated waste material. Because of the lack of mechanical débris removal equipment this method was believed to be comparatively fast. As a consequence, this kind of tunneler was assumed to have greater potential for total automation. However, a nuclear power source would not meet the heat requirements of such a design. For this reason the mechanical tunneler was examined in greater detail. Initially, this type of tunneler was thought to be relatively labor- and equipment-intensive. Consequently, it was thought to be a slower method than melting as well. However, further research revealed that both techniques yield approximately the same tunneling rate. In addition, with the mechanical technique, producing sufficient energy to meet the high temperature requirements is no longer a factor. Extensive data from tunnel-boring machines on Earth indicate that down time due to breakage of moving parts is not as great as initially thought. Also, automation can be easily achieved.

An underlying design objective was to use as much existing technology as possible in the design in order to lower cost and minimize down-time. Most Earthly tunneling devices use mechanical means; melting tunneling devices are almost nonexistent. Digging through lunar material would be executed by using a rotating mechanical head with disc cutters. This head design was derived from methods used in sizing existing Earth tunneling devices. Propelling the Tunneler through the lunar material would be performed by adapting a system produced by Lovat[1] of Ontario, Canada. To control and guide the Lunar Tunneler, a laser communication and computer system was adapted from existing technology produced by ZED Instruments, Ltd.[2] in the U.K. Transporting the excavated lunar material would be accomplished by a conveyor belt design manufactured by Flexowall, Inc.[3] By using these existing systems in conjunction with the new technologies developed for lining and supporting the tunnel, a viable Lunar Tunneler has been conceived.

The Lunar Tunneler design is illustrated in Figure 3. The device essentially consists of a rotating mechanical head which shears its way through the lunar material while simultaneously creating a rigid glass-like ceramic lining to support the tunnel walls. In order to propel the tunneler forward a hydraulic gripper propulsion system is used. The excavated lunar material travels to the material holding tank in the rear of the tunneler using the conveyor system. Periodically, the lunar material contained in the holding tank is transferred to the dump truck which then dumps the excavated material outside the tunnel.

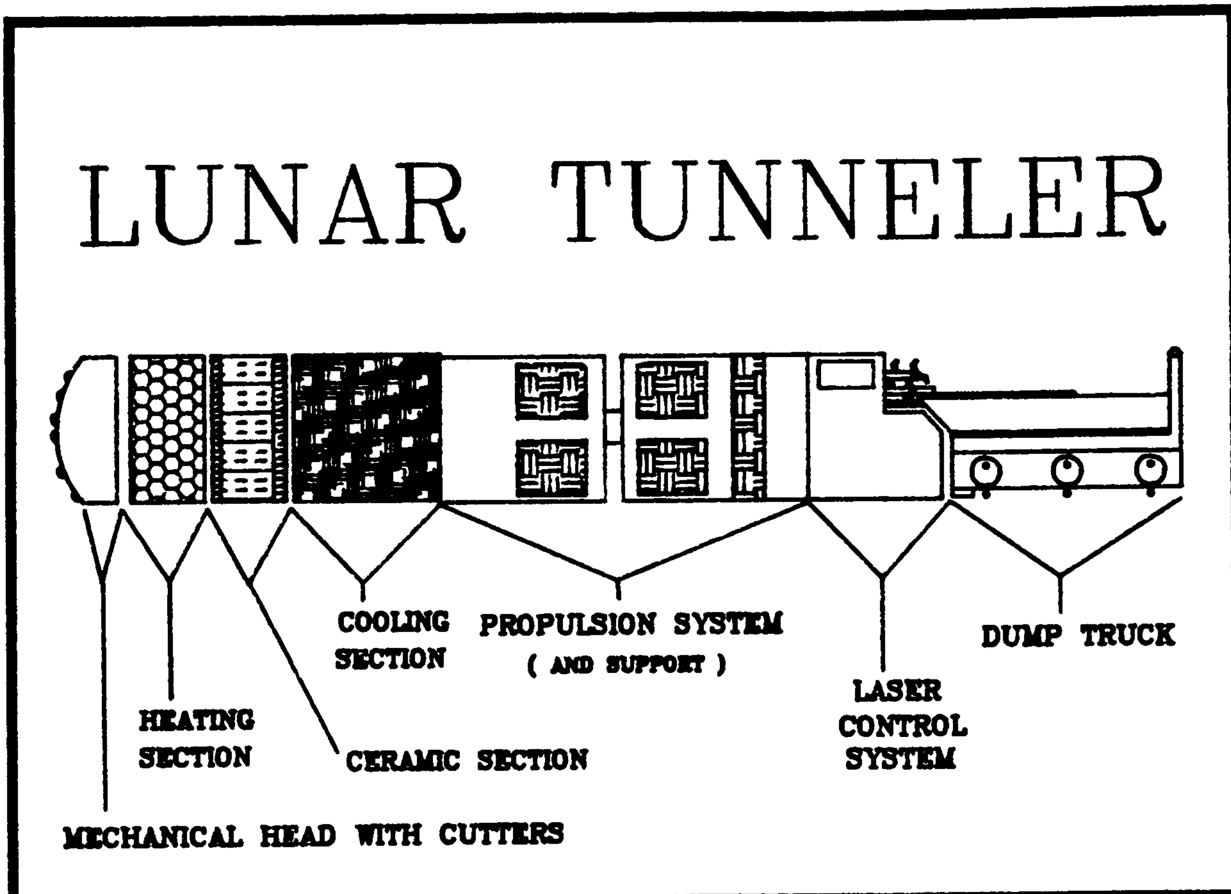

FIGURE 2: LUNAR TUNNELER

Above, in Figure 3, is the general design concept for a Lunar Tunneler. A more detailed explanation of each section is discussed in the remainder of this report.

CUTTERHEAD

The rock-cutting technique is the primary means by which the Lunar Tunneler creates space beneath the lunar surface. Rock cutting involves impressing the rock surface with a cutting tool while simultaneously pushing forward. The groove that is created by the cutter then fractures, and the crushed rock is left behind as it progresses forward. In order to indent the rock effectively, a normal force, or *thrust,* must be imparted to the rock surface. Also, a forward rolling force is required to propel the tunnel-boring machine. The rolling force, combined with a torque to rotate the cutterhead, drives the machine forward through the rock. A tunnel-boring machine is designed to supply these forces. The machine acts to generate thrust to push the cutterhead forward while simultaneously producing a torque to turn the cutter and oppose the tangential resistive forces.

The face of the cutter, shown in Figure 4, rotates using motors located behind the back panel of the cutterhead. The torque reaction acts through the main beam, which is connected to the cradle assembly and gripper pads. It is then transmitted to the cutterhead by way of pinion gears connected to a fairly large diameter bull gear which enables the cutterhead to rotate around the main bearing.

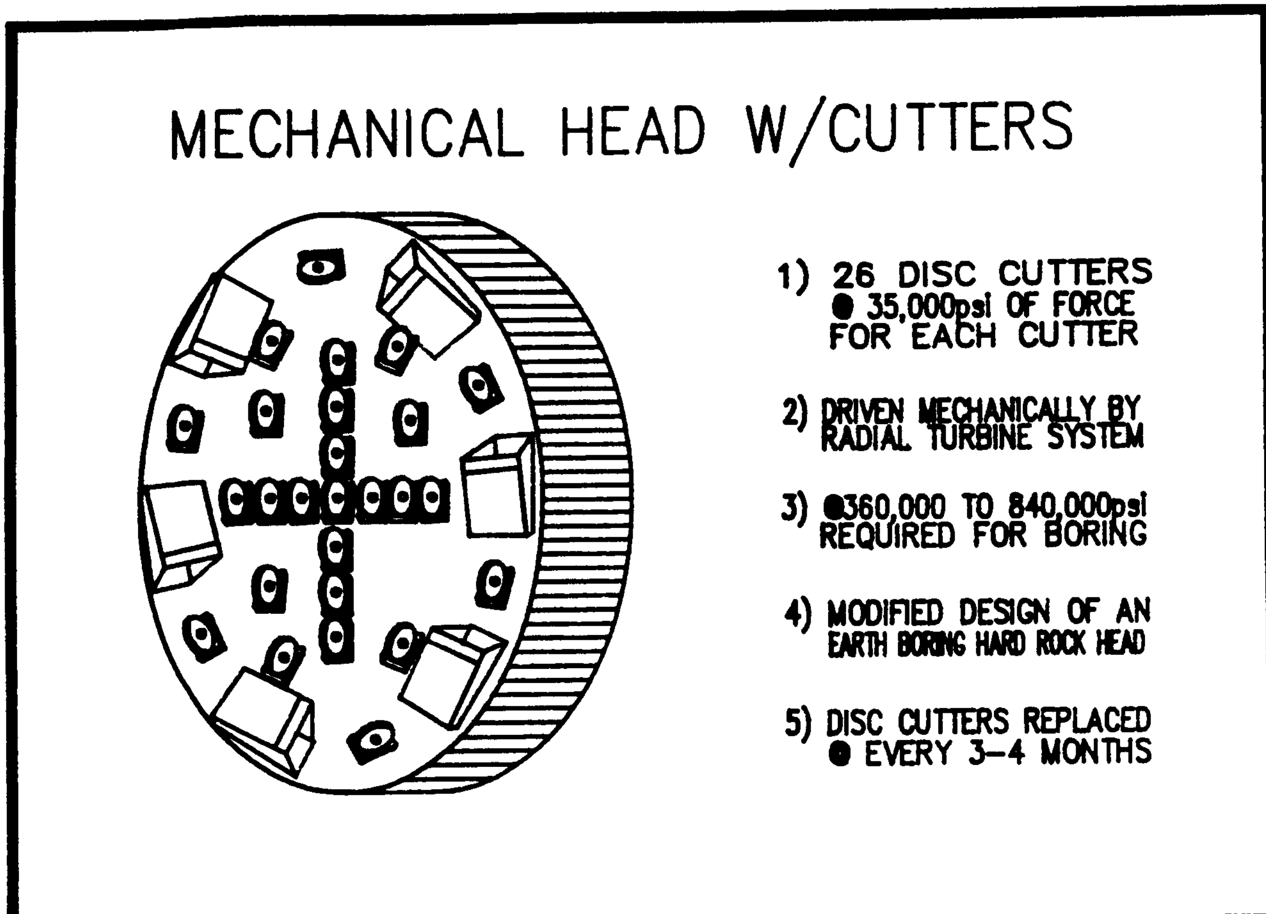

FIGURE 4: ROTATING MECHANICAL HEAD WITH DISC CUTTERS

The determining factor in the operation of the torque system is the quantity of power used by the motors, expressed in terms of *amperage:* if the motors draw too much electric current, they could overheat and cause internal damage. Motors are usually designed to provide 149kW (200 horsepower) at a maximum amperage of 216A. On Earthly tunnel-boring machines, ammeters on each motor allow the human operator to make adjustments in the thrust, thereby keeping the amperage close to the maximum operating rating.

The equation for determining the amount of torque transmitted to the face is expressed as

$$T_o = \frac{N_m P e}{2\pi S}$$

where T_o is the torque, N_m is the number of motors, P is the power consumed by each motor, e is the motor efficiency, and S is the rotational speed of the cutterhead in revolutions per unit time. Motor efficiency can be estimated from the operator records of average amperage consumed in a given work shift. The combined efficiency of the motor and drive train is usually about 85%.

The average rolling force per cutter blade, t, can be estimated by calculating the product of the torque, T_o, and the inverse of the weighted average cutter distance from the center of the face, R. It is expressed as

$$t = \frac{N_m P \epsilon}{n^2 \pi S R}$$

.

Whole face tunnel-boring machines commonly use a single disc cutter as the cutting tool, and this type is employed in the Lunar Tunneler. (See Figure 5.) This class of cutter is composed of a disc on a hub connected to a central shaft protruding from either side of the unit. The cutter is mounted on a steel saddle so that it can freely rotate about its longitudinal axis. This steel saddle, in turn, is bolted to the face of the cutterhead. The typical single disc cutter is 39.4cm (15.5in) in diameter and can transmit up to 45,000 pounds of force to the rock face.

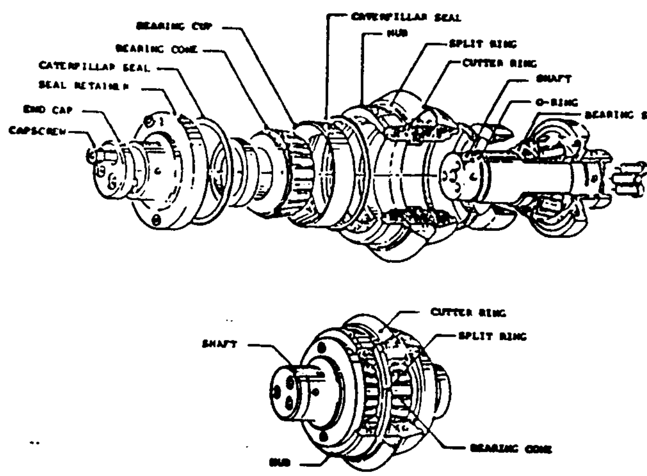

FIGURE 5: DISC CUTTER SCHEMATIC (FROM THESIS BY PRISCILLA NELSON)

The cutter ring, shown in Figure 6, is composed of a highly alloyed heat-treated steel. The cutter ring is attached to the hub by first heat-shrinking it and then locking it in place with a welded split ring. The hub rotates on tapered roller bearings that are isolated within the hub behind metal-to-metal face seals. The inside of the hub is filled with oil to protect and lubricate all moving parts.

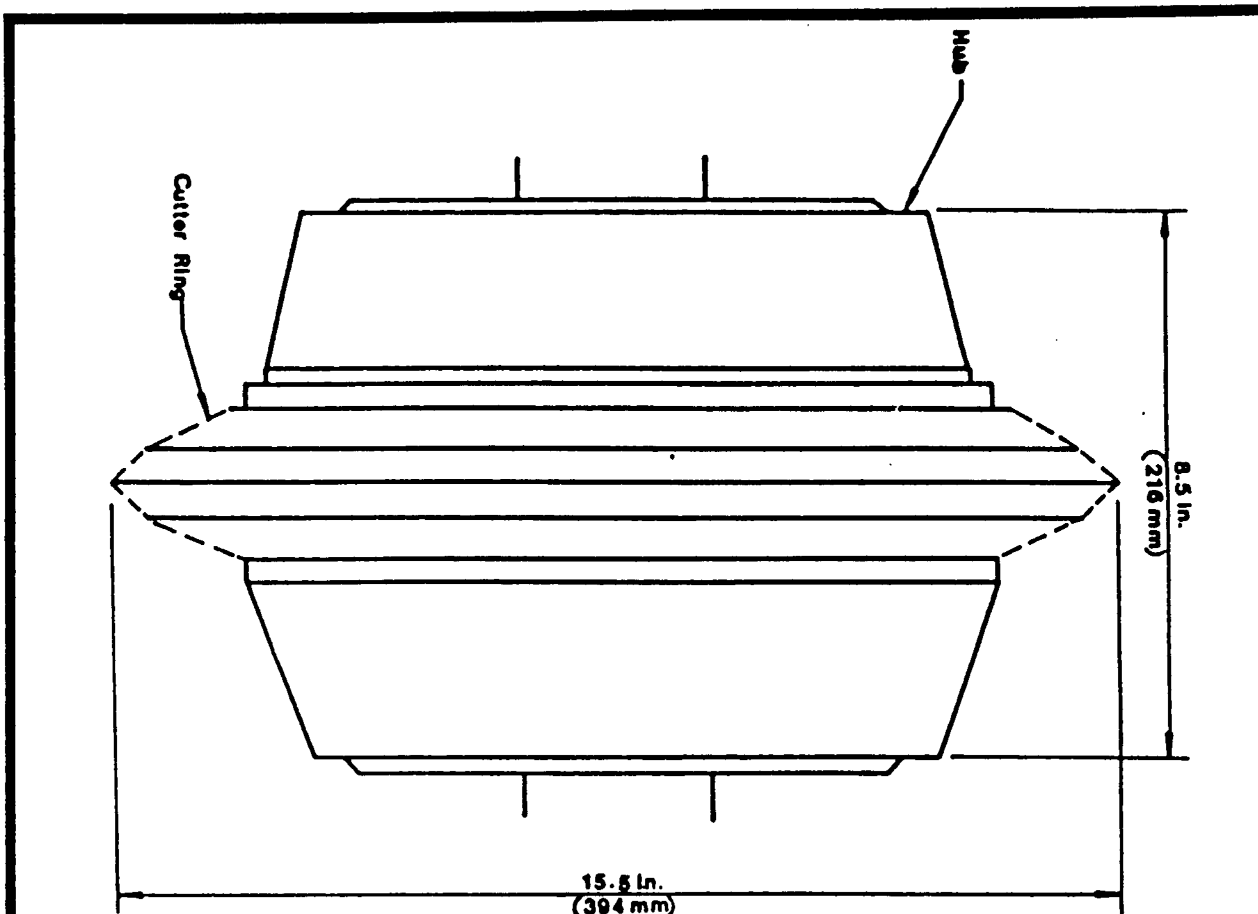

FIGURE 6: CUTTER RING SCHEMATIC (THESIS BY R.D. BENNETT)

Cutters are differentiated according to their locations on the face of the cutterhead. The four *central cutters* are usually about 30.5cm (12in) in diameter and are mounted on two twin-disc assemblies. These middle-most cutters rotate within the central 30.5cm (12in) radius of the cutterhead; consequently, they must withstand significant scuffing. The next set of cutters are the *face cutters*. They are generally 39.4cm (15.5in) in diameter and are located between the center cutters and the outer edge of the cutterhead face. The face cutters tend to be positioned across the face profile on a line with a constant radius of curvature. The outermost cutters are the *gage cutters*. These cutters are generally 39.4cm (15.5in) in diameter and are positioned on the outer extremes of the cutterhead where it curves to form the edge of the three-dimensional tunneler.

In order to determine the number of cutters required for a cutterhead of a certain diameter, the total diameter of the cutterhead is divided by the ideal diameter stroke for each cutter. The ideal diamter stroke is taken as 15.2cm (6in) for the Lunar Tunneler, since this size would be just sufficient to loosen the lunar material while minimizing abrasion and friction. Accordingly, the centrifugal force would cause the lunar material to spread out to the perimeter of the tunnel, after which it would be collected by the hoppers. For a 4m (13ft) diameter cutterhead on the Lunar Tunneler, twenty-six cutters would be required. Cutterhead specifications are given in Appendix A.

The gage cutter derives its name from a term used by the drilling industry to describe drilling tools that determine the diameter of the bore hole. The gage cutter functions to excavate rock only along the diameter of the tunnel. Several gage cutters are positioned at increasingly greater angles to the direction of thrust as the transition from face to side excavation occurs. Consequently, the gage cutters are subjected to substantial tangential forces that act perpendicular to the rolling direction. Abrasion of the disc ring and damage to the roller bearings result from these forces. As the radial distance from the center of the cutterhead increases, the distance between the gage cutter paths decreases rapidly. By contrast, the paths of the face cutters are typically 7.5cm (3in) apart and constant.

The performance of tunnel-boring machines is generally measured in terms of progress or *advance rate*. The two main factors determining the advance rate are the rate of excavation or *penetration rate* of the tunnel-boring machine and the amount of time allowed for the excavation process. The advance rate is defined as the product of the penetration rate and machine utilization. *Machine utilization* is the percentage of available work shift time during which excavation or rock penetration takes place.

Several factors affect the performance of the tunnel-boring machine. The overall machine configuration is the major element. This includes thrust, torque, gripper reactions, gripper configurations, capacities, steering mechanism, and overall machine stiffness. A second factor is cutterhead design, which includes the cutterhead profile, spatial array of the cutters, spacing of the cutters, and muck-removal components. In addition, the design of the cutters themselves plays a major part in the performance of the tunnel-boring machine. Included in this category are the type of cutter, composition, geometry, and roller bearing capacities. Also, it should be noted that the disc, hub, and steel saddle of a gage cutter may be subjected to more abrasion than those of a central cutter.

Operation of a tunnel-boring machine necessitates careful record-keeping and examination of wear-prone parts. Operating shifts should be numbered sequentially and include the day, date, shift times, and shift duration. A shift is defined as the total distance traveled by the cutterhead due to the thrust in one maneuver. The tunnel stations should be recorded at the beginning and end of each shift. In order to determine the operating hydraulic pressure, the thrust cylinder pressure and gripper cylinder pressure should be recorded for each thrust cylinder restroke. Cutterhead motor status can be determined by recording the number of functioning motors and operating amperage for each thrust cylinder restroke. The hydraulic fluid and lubricating oil temperature should be checked at least once during each shift. In order to maintain an adequate cutter wear record, several items should be checked at each cutter change. These include recording the cutter position number, cutter hub identification, type of disc on the cutter, a full description of reason for replacement, and time of replacement. Finally, front and rear laser target readings should be recorded at least for the beginning and end of each operating shift.

Down-time for the mechanical cutterhead assembly occurs in the areas of electrical systems, hydraulics, cutter replacement, stroke recycle, cutterhead motors, and the excavation conveyor. Electrical system down time is due to loose or broken wires in the control panel or defective arc welding; it is estimated at 1.6% of work time. Hydraulics down-time is due to leaks in gripper cylinders and replacement of hydraulic hoses and pressure valves; it is estimated at 8.2%. Cutter replacement can take place while the system is already down. A 0.3% down-time is estimated for motor overheating, and a 1.5% downtime is estimated for repair and splicing of the belt conveyor. Stroke recycle down-time amounts to an estimates 3.9%.

Several areas of further research into the mechanical cutterhead are suggested. Linear cutter tests chould be performed on a wide variety of rocks of diverse strength, stiffness, and porosity. Replacement rates for bearing deterioration and defective wear should be analyzed. Also, muck gradation analysis can aid in determining comparative machine efficiencies in different rocks. Finally, the hopper between the cutterhead and main beam should be arranged to provide the greatest access to remove muck blockages and to reduce the chance of recurring blockages.

GLASS-FORMING SECTIONS

Just behind the cutterhead would lie the heating section of the Lunar Tunneler. The heating section would serve to melt a layer of lunar material within the excavated tunnel to a depth of only a few inches. This molten material could then be cooled to form a rigid ceramic material suitable for lining the interior of the tunnel.

The ceramic lunar material would provide designers with a virtually inexhaustible supply of strong, rigid structural material. Unlike ceramic on Earth, lunar ceramic can withstand much greater forces and support larger loads. The anhydrous hard vacuum conditions on the Moon cause the silicate materials to have different mechanical properties compared to what they would have on Earth.

On Earth, the damage state of the surface and the corrosion process, due to the presence of water in microcracks, are used in determining the fracture strength of brittle amorphous and crystalline materials. Crystalline silicates are greatly affected by dislocation motion caused by the presence of small amounts of water at high temperatures and pressures. Polar water molecules will cause fragile hydrogen bonds to substitute for the SiO bond. This hydrolyzation is the weakening mechanism in the SiO bonds since the network-forming action of the SiO bond produces the inherent strength of the silicates.

Dislocations and highly stressed microcrack edges are the primary sites where the hydrolyzation occurs. At these locations the water causes increased movement of the dislocations, so that the cracks can be propagated with a lower applied stress; the net result is a general weakening of the structure. Since hydrolyzation is a thermally activated progression, it affects all temperature-dependent mechanical properties of silicates, including brittle and plastic creep, fatigue, and crack growth.

Experimentally obtained data attest to the fact that anhydrous conditions allow for greater strength in lunar materials. When samples of simulated rock from lunar maria were degassed and subjected to strength tests in a moderate vacuum, compressive strength was found to be twice as great as that under conditions of one hundred percent humidity. In addition, it has been found that a decrease in the partial pressure of water vapor directly reduces the subcritical crack velocities in simulated lunar glass by several orders of magnitude. From this it can be deduced that, in the presence of a strong vacuum environment, static fatigue processes will be severely restricted or completely absent. The dissipation of vibratory energy in lunar rocks has also been found to be affected by minute quantities of water. Hydrolysis of crack surfaces and the resulting loss of surface energy is a probable cause for this diffusion. Finally, lunar soil samples that were subjected to atmospheric moisture contamination under moderate to strong vacuum conditions were found to have sharply different mechanical properties from those that were not.

The hydrolytic weakening process is inescapable on Earth due to the presence of water during the fabrication of manmade and natural materials into useful products. Its effects are felt in such diverse areas as solid earth mechanics, drilling and mining, glass and ceramic technology, fiber optic communications, and laser optics.

The small amounts of water present in lunar soil samples are probably due to contamination of some sort. This contamination could have been oxidation of hydrogen deposited by the solar wind, or it could have occurred after the specimens were brought to Earth. Consequently, contamination of all kinds must be avoided in order to protect lunar materials from water-induced weakening.

With the above soil considerations in mind, the heating section was designed to use electrical resistance heating elements in conjunction with a thermally conductive, chemically nonreactive shield. (See Figure 7.) Carbon-carbon composite is proposed for the heating element, and a molybdenum-tungsten alloy, Mo–30W, is proposed for the shield. The heating section would be two meters (six and a half feet) long.

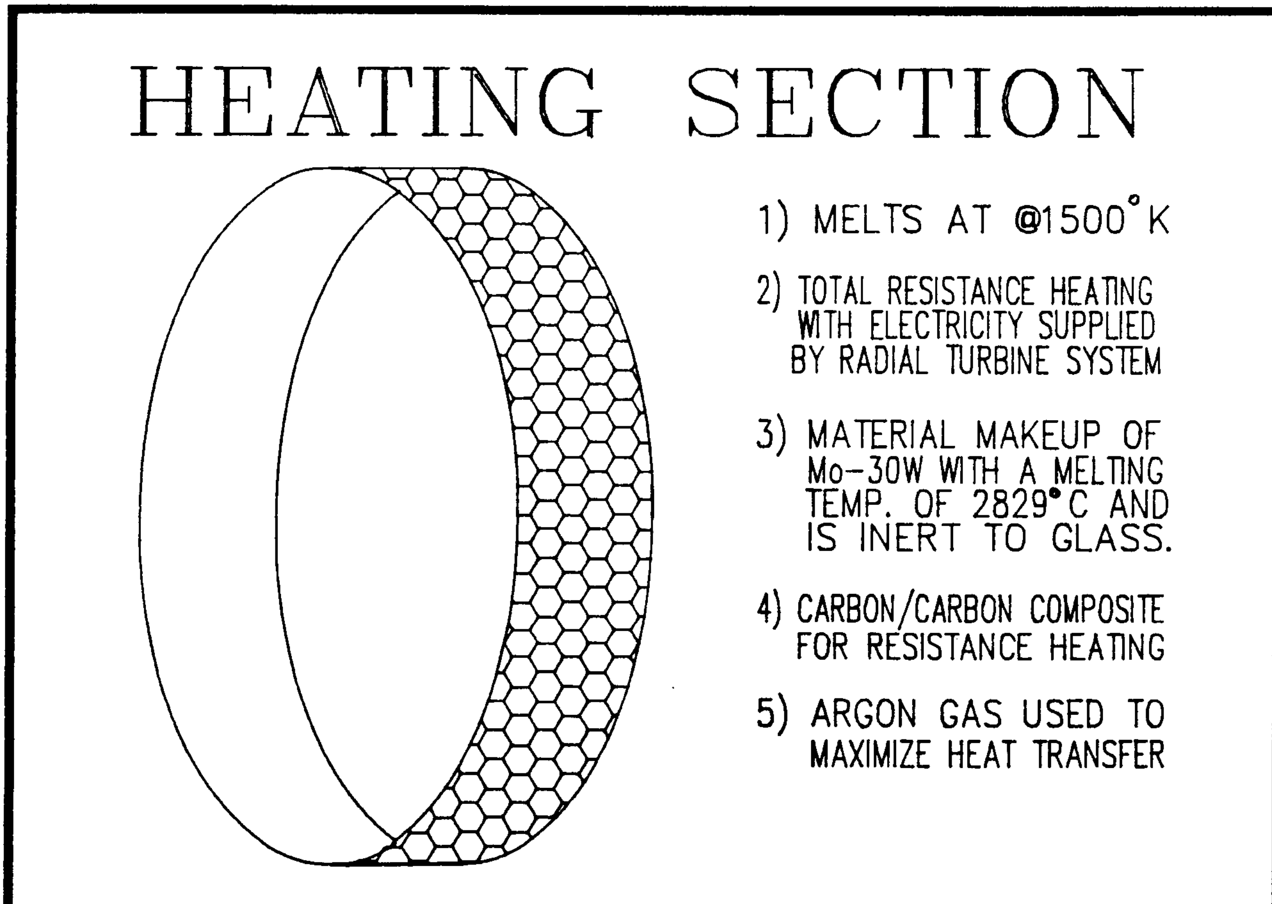

FIGURE 7: HEATING SECTION

Fireproofed carbon-carbon composite is suggested for the resistance heating element because of its light weight and very high melting point of 3,550°C. Carbon-carbon composites also have strengths that are among the highest for fiber-reinforced composites. Although nichrome and carbon are both viable resistant elements and less expensive than carbon-carbon composite, they were ruled out for this application because they both have lower strengths and lower melting points.

A shield composed of Mo–30W is proposed to uniformly distribute the heat to all of the lunar material to which it comes into contact. Alloy Mo–30W is one of the most readily available and least expensive of refractory alloys and has a high melting temperature of 2,829°C. Its excellent thermal conductivity makes it ideal for this application. In fact, only silver, gold, copper, and aluminum have better thermal conductivities than molybdenum and tungsten, and all have drawbacks that preclude their use in this application. Other important properties of Mo–30W are its ease of fabrication and cleaning and chemical nonreactivity to most molten glasses.

Argon gas would be used to fill any gaps between the heating element and outer shield. Argon would be used in order to maximize heat transfer from the heating elements to the shield without the losses associated with air. Because argon is a noble gas, it would not decompose or react with the Mo–30W shield or the carbon-carbon composites.

The ceramic section of the Lunar Tunneler would serve to separate the heating section from the cooling section, thereby minimizing heat transfer between them. (See Figure 8.)

This section would be four meters (thirteen feet) long. Glass-ceramics provide a wide choice of materials for fulfilling the primary requirements as well as the requirements of resisting liquid permeation and nonreactivity to the molten glass.

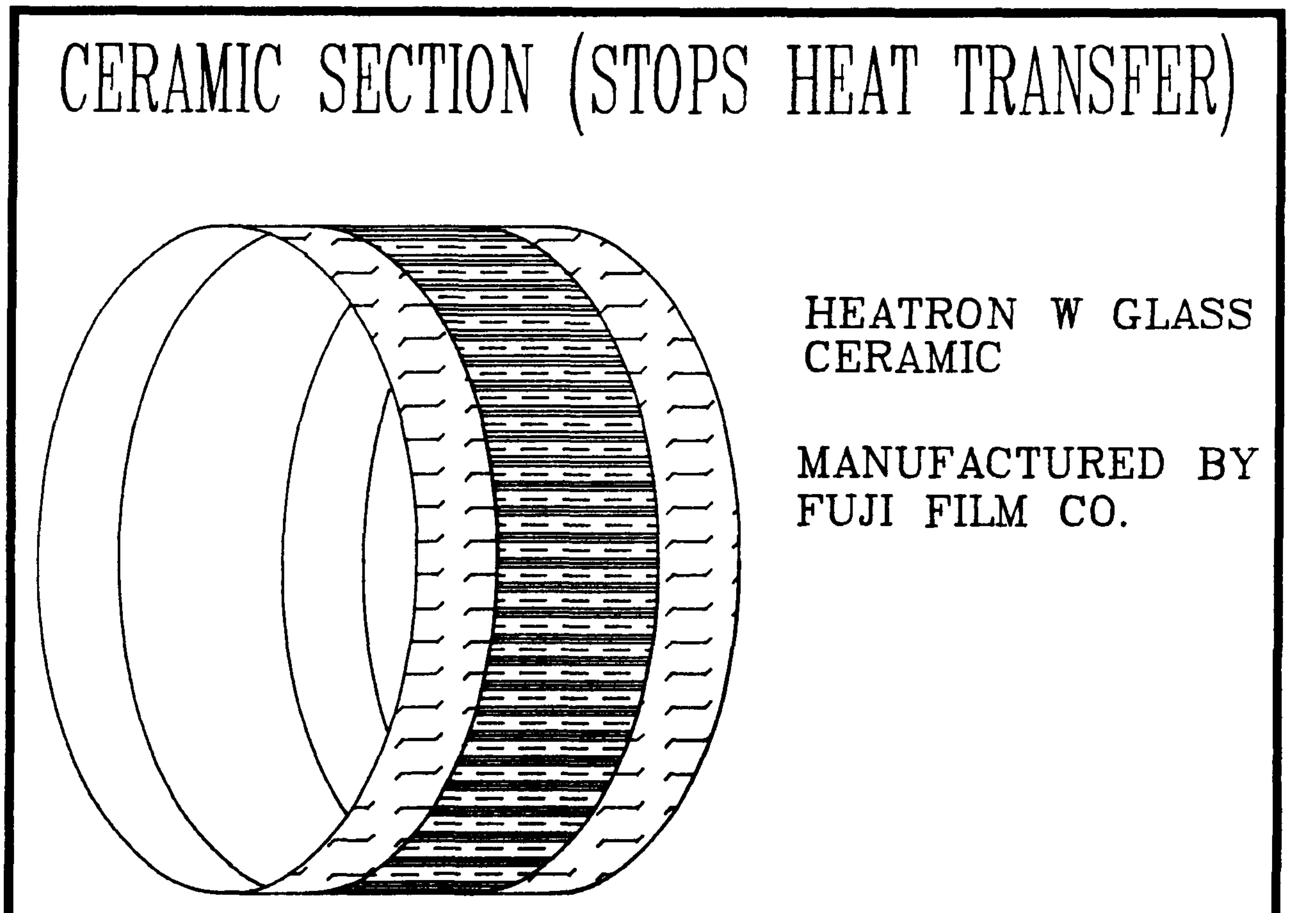

FIGURE 8: CERAMIC SECTION

Glass-ceramic materials are defined as polycrystalline solids containing a minimal glass phase. They are manufactured by melting glass and controlling the crystallization, number of crystals, crystal growth rate, and crystal size by the appropriate heat treatment.

For the purpose of evaluating mechanical properties, glass-ceramics can be regarded as composite non-porous materials consisting of minute crystals evenly distributed through the glass phase. Glass-ceramics in general have improved mechanical properties over glass while retaining the characteristic features of glass, such as transparency. They have greater bending strengths and greater elastic moduli than do glass and ceramics separately. Through modifications of the surface of the glass-ceramic, even higher strengths can be achieved. Thermal properties can be altered by controlling the size of the glass phase. For optimum chemical resistance to be achieved, the residual glass phase must be free of high concentrations of alkali metals.

Heatron W, a glass-ceramic product manufactured by the Fuji Photo Film Company, is proposed for the ceramic section of the Lunar Tunneler. This glass-ceramic is highly resistant to thermal shocks, exhibits low thermal conductivity, and has a maximum working temperature of approximately 1,500°K. The maximum working temperature can be raised even higher if the amount of glass is limited upon formation of the glass-ceramic. Chemical resistance and lack of reacttivity were also factors influencing this choice, and Heatron W has superior properties in both cases.

The cooling section would act to lower the temperature of the molten lunar material so that the material would crystallize and form the rigid ceramic needed to support the tunnel walls. (See Figure 9.) The cooling section is not intended to cool the molten glass to the temperature of the surrounding undisturbed lunar material but rather to cool it sufficiently so that a crystallization phase change can take place. Once this ceramic lining has hardened, it can be further reinforced by sealing with rubber or another liner such as sputter-coated metal. This second reinforcement may be required to protect the tunnel wall from weakening due to hydrogen and any other gases that may remain trapped in the tunnel.

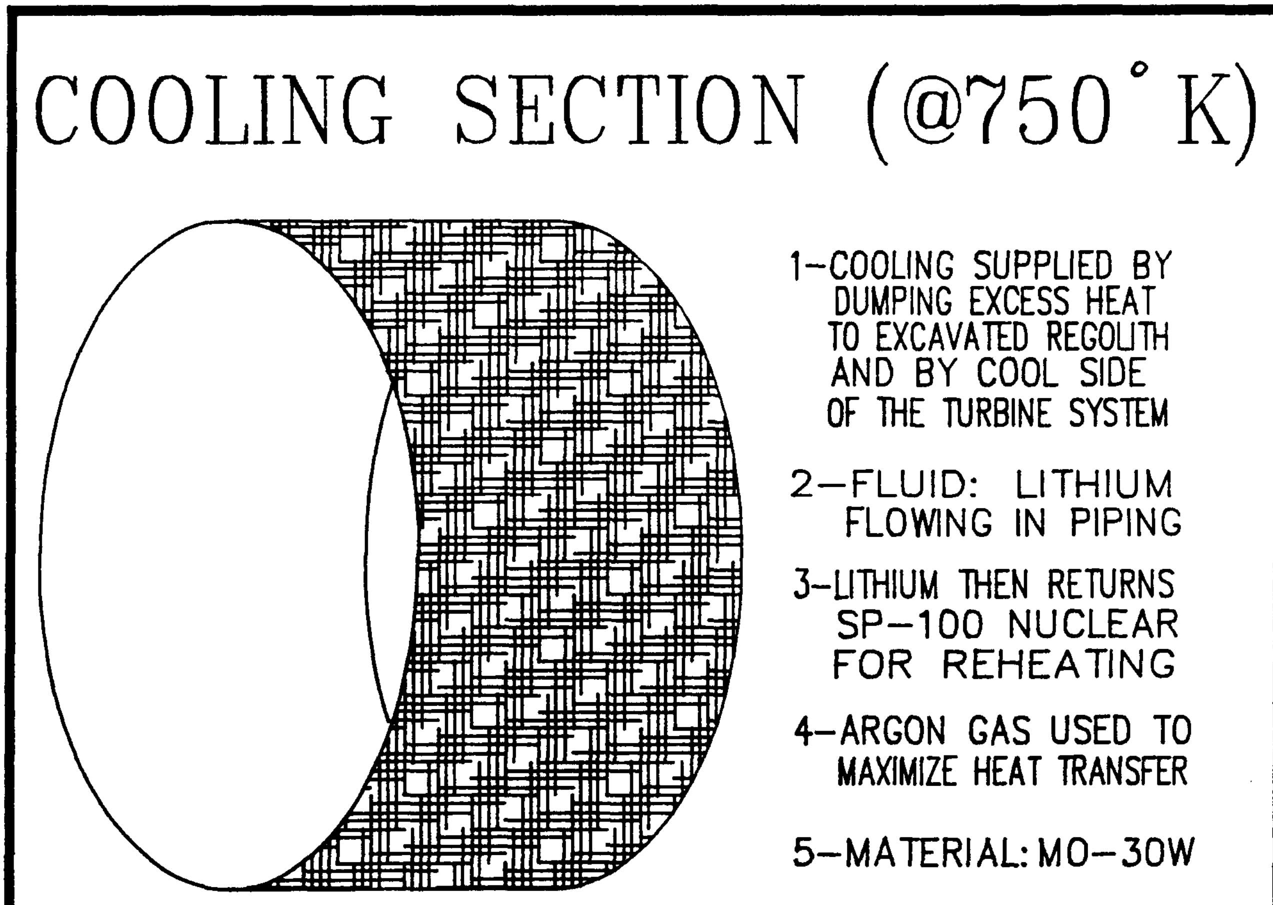

FIGURE 9: COOLING SECTION

Perhaps the most economical tunnel liner would be a form of lunar concrete. A lunar concrete or cementitious product could be used to line the tunnel wall and protect against solar wind, cosmic rays and other types of radiation, and micrometeorites. On Earth cement is primarily composed of limestone, clay, and iron ore. Lunar materials have been found to contain sufficient quantities of silicates, alumina, and calcium oxide to make it possible for a cementitious material to be produced. However, the quantity of calcium oxide on the Moon is rather low compared to that of the silicates and alumina. Also, quenched shock-melted lunar glass has been found to be amorphous and has the potential for use as a cementitious material if crushed to a very fine particle size. This quenched shock-melted glass is found in abundance in the crater rims.

The cementitious elements present on the lunar surface have been determined to have condensation temperatures around 1,400°K. This condensation temperature is estimated to be at least 200°K above those of the non-cementitious materials. Consequently, the separation of cementitious and non-cementitious is not a problem and can easily be achieved through a melting process. In such a process, a high temperature of 3,000°K would be required for elemental evaporation.

There is an abundant supply of aggregates for use in a lunar cement. Lunar concrete, like Terrestrial concrete, would be composed would be composed of a cement paste and aggregates. Lunar rocks generally have specific gravities close to 2.6 and are believed to be suitable for use as aggregates.

The effects of temperature changes on the lunar concrete should be minimal. While the surface temperature on the Moon varies from $-150°C$ at night to $120°C$ during daylight, the strength of concrete is virtually unaffected by the extreme temperatures. Also, in the presence of zero percent humidity, concrete neither gains nor loses strength as the temperature drops. Consequently, with only minimal hydrogen in the lunar soils, a lunar councrete should retain its strength well. Because concrete exhibits low thermal conductivity, high specific heats, and thermal stability up to $600°C$, lunar concrete should prove to be an excellent heat-resistant structural material.

Several other properties make lunar concrete worth considering for lining and structural applications. It exhibits satisfactory gamma-ray absorption and resists abrasion well. In addition, a loss of free moisture under hard vacuum conditions would have no effect on the strength of concrete.

The cooling section operates by using a Mo–30W outer shield and liguid lithium contained in thermal pipes. The pipes would bring refrigerated lithium coolant from the SP–100 atomic reactor (see "Internal Power Cycle") and circulate it directly behind the Mo–30W shield. The shield would help to uniformly transfer the cooling action of the lithium to the molten lunar material while simultaneously removing the heat from the lunar material. The liquid lithium then carries the heat through the Lunar Tunneler and uses it to partially heat the excavated lunar material in the holding tank (see "Material Excavation System"). Since more of the lunar material is excavated than heated, the excavated lunar material will only be gradually heated rather than melted because the heat will be transferred to a large quantity of material. Also, the heat losses experienced in the lithium pipes as the lithium travels from the glass-forming section to the holding tank would lower the temperature such that melting of the excavated lunar material could not occur even if it were a design objective. The space between the lithium thermal pipes and the Mo–30W shield is backfilled with argon gas to maximize heat transfer between the pipes and the shield. Lithium is suggested as the coolant because it would achieve minimal heat loss while circulating through the Lunar Tunneler after leaving the nuclear reactor. Based on heat transfer calculations, twelve meters (thirty-nine feet) is the ideal length for this section.

PROPULSION, MANEUVERING, AND CONTROL

The Lunar Tunneler would be provided thrust and torque by hydraulic systems similar to those used in tunnel-boring machines on Earth by Lovat Tunnel Equipment, Inc. of Toronto and Atlas Copco Jarva, Inc. of Solon, Ohio.[1,4] A system of hydraulic cylinders provides for the generation of thrust and torque for the rotary cutterhead and for maneuvers.[4] Maneuvering is automated in conjunction with a laser/inclinometer guidance system. Information given by Nelson[4] concerning thrust and torque systems is outlined below.

Hydraulic cylinders are located around the drive shaft as shown in Figure 10. Eight gripper pads in an "X" configuration anchor the Lunar Tunneler to the tunnel wall (see Figure 11), and the thrust is transferred to the cutterhead through the torque reaction tube shown in Figure 10. Thrust would be applied in cycles, and each cycle should advance the Lunar Tunneler by 1.2 to 1.5m (3.9 to 4.9ft). The maximum pressure in the cylinders on Terrestrial machines is around 25MPa (3,600psi), providing a maximum forward thrust of around 9,000kN (2,000kip), and loads of the same order are expected on the Lunar Tunneler. Simply moving the cuttinghead forward without touching the rock face would require about 3.5MPa (510psi). Typically, the thrust cylinders in tunnel-boring machines are about 330mm (13in) in diameter and have a stroke length of about 1.5m (4.9ft).

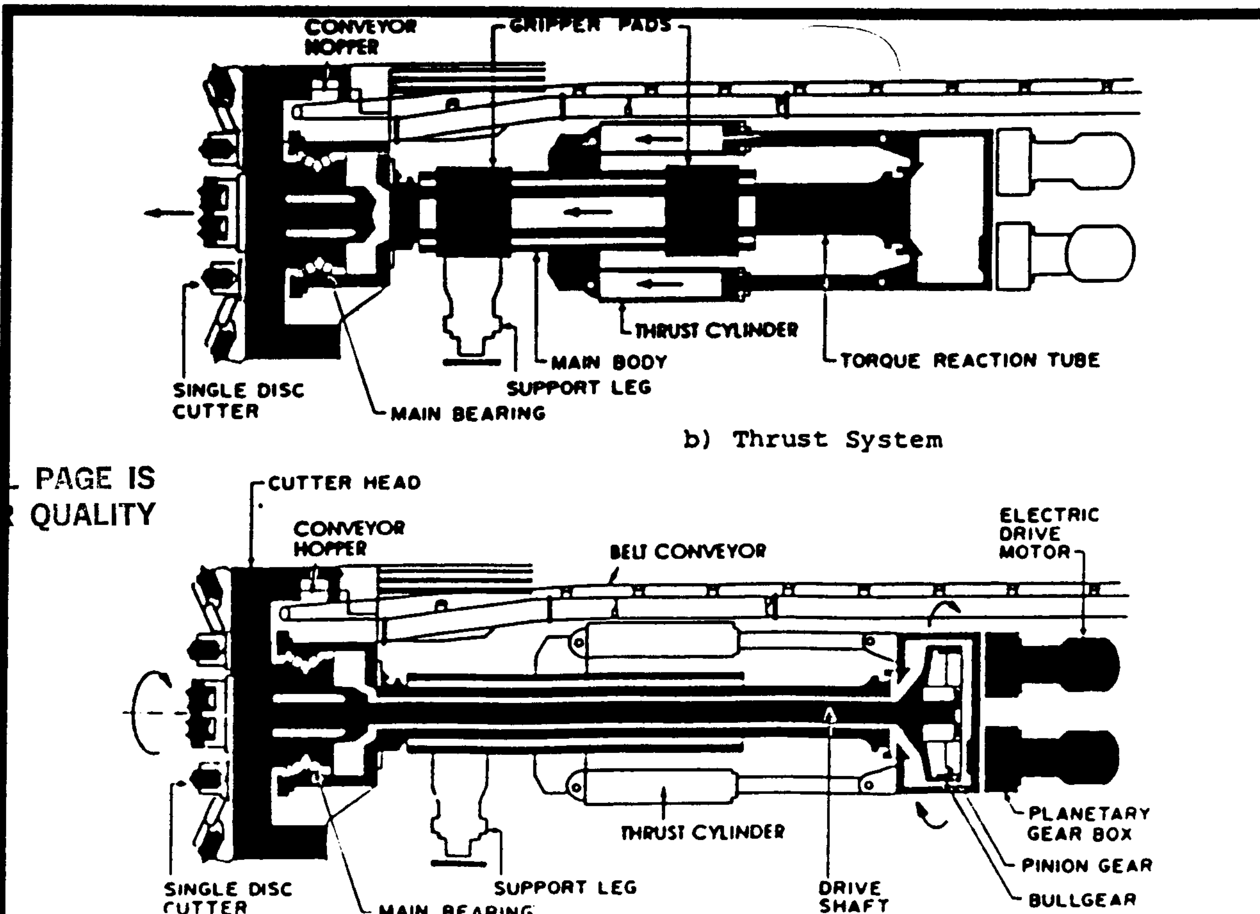

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FIGURE 10: THRUST CYLINDER (THESIS BY PRICILLA WELSON)

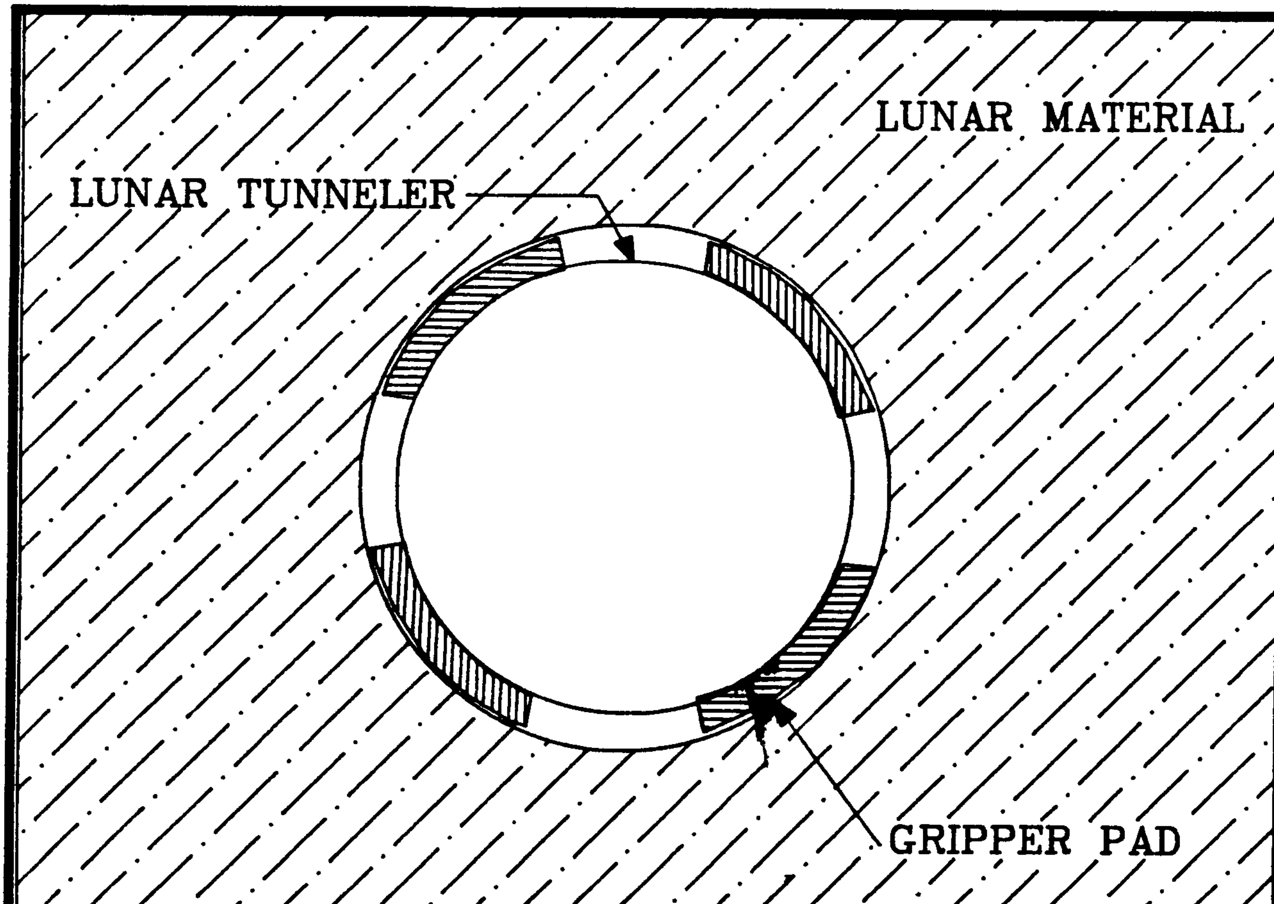


FIGURE 11: END VIEW SHOWING "X" CONFIGURATION OF GRIPPER PADS

Figure 12 illustrates the four-step thrust cycle for an Atlas Copco Java machine. First, the gripper pads are extended to anchor the main body. Second, the drive shaft is driven forward until the hydraulic cylinders have been extended the entire stroke length. Third, a support leg is lowered and the gripper pads retracted. Finally, the main body is pushed forward into position, the gripper pads are extended and the support leg retracted, and the cycle begins anew. In practice, the thrust actually transmitted to the cutterhead is the force produced by the hydraulic cylinders less the sliding resistances of the machine.

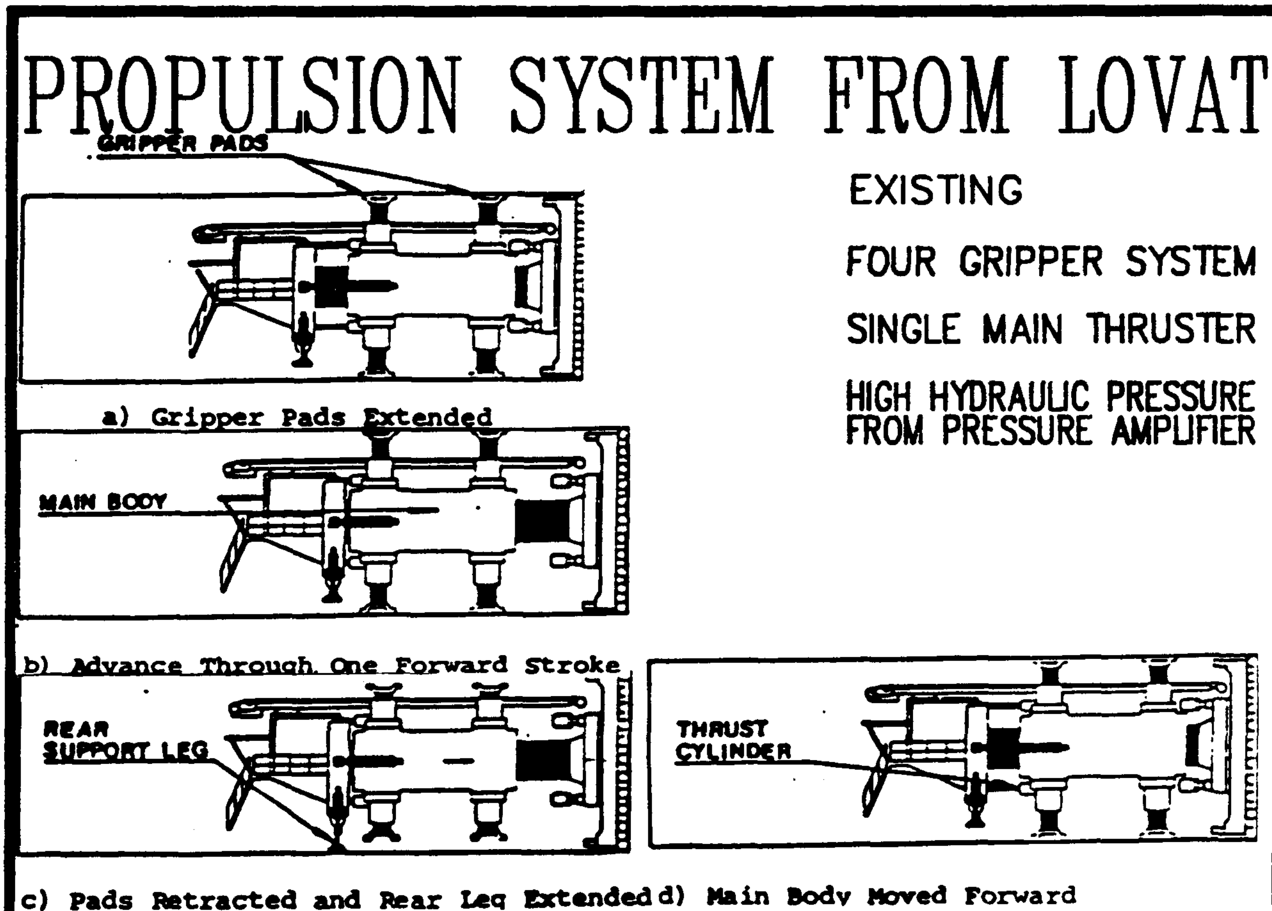


FIGURE 12: PROPULSION SYSTEM BY LOVAT(THESIS BY PRICILLA NELSON)

For generation of torque for the cutterhead, motors are anchored to a frame at the rear of the drive shaft as shown in Figure 10. The gripper cylinders connecting the main body to the gripper pads provide reaction for torque, and torque is transfered through pinion gears and bull gear located at the rear of the drive shaft. Thrust and torque are transmitted to the cutterhead by way of a system of tapered roller bearings. The combined weight of the hydraulic thrust and torque system and cutterhead is around 2,600kN (580kip). The motors used to produce torque are described under "Cuttinghead."

The hydraulic cylinders can also be used to maneuver the machine. The cylinders are connected to a rear segment of the tunnel-boring machine, and different pressures can be applied by the hydraulic cylinders to the face of this segment. The resulting angle between the segment and the rest of the machine can be controlled for steering left, right, up, or down. (See Figure 13.)

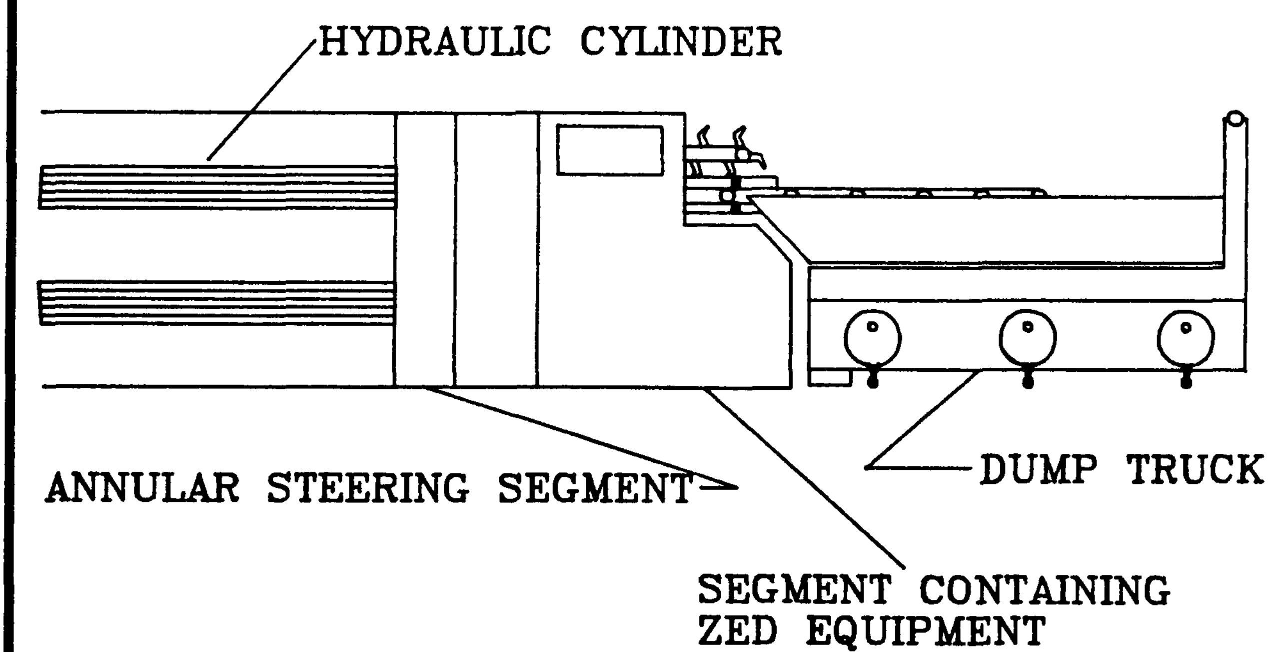


FIGURE 13: HYDRAULIC ANNULAR STEERING SEGMENT

While tunnel-boring machines on Earth are usually manned by an operator, this would not be feasible for the Lunar Tunneler due to heat and radiation. (See "Glass-Forming Sections" and "Internal Power Cycle.") The Lunar Tunneler would have a computer in the rear portion of the machine to serve as the operator. Desired tunnel axis, maneuvers, and other inputs would be programmed into the computer as needed before operation, as well as commands to shut off power after a specified time or in the event of a fault condition. This "automated operator," coupled with the automated guidance system described hereafter, would be a powerful tool for accurate maneuvering. Although there is at present little experience with automated steering systems in tunnel-boring machines on Earth, the capability exists, and it is expected that they will be used more frequently in the 1990s.

A TG-260 Tunnel Guidance System, manufactured by ZED Instruments, Ltd.[2] in the U.K., is proposed for guidance of the Lunar Tunneler. This system, which represents the state of the art in automated guidance systems, uses a laser beam and inclinometer to provide precise position and attitude information. Such a system would obviate the need for surveying and measurement; this would save not only time but also the maintenance and material costs that could ensue from deviations by the Tunneler from the desired tunnel axis. These Tunnel Guidance Systems have been in use on Earth for several years, and they have proven to be reliable tools for precise tunneling about any of the three orthogonal axes of motion. They have also been useful for rendering even the most cumbersome tunnel-boring machines easy to steer. Information provided by ZED Instruments[2] is outlined below.

On the proposed Lunar Tunneler, steering is guided by a computer located in the rear portion. The computer reads all position and attitude data provided by the TG-260 and makes any needed course corrections. ZED Instruments could provide hardware and software that would be compatible with the guidance system.

The components of the TG–260 system are shown in Figure 14. From some distance behind, a collimated helium-neon laser beam would be aimed at a target unit located in the rear of the Lunar Tunneler but in front of the Dump Truck (see "Material Excavation System") as shown in Figure 15. (The Dump Truck would be designed to not obstruct the beam.) The laser would require less than 2mW (2.682×10^{-6} hp) of power and would have a spot size of 12mm to 25mm (0.47in to 0.98in). The inclinometer would also be located in the rear of the Tunneler, along with linear distance measuring equipment located on the Tunneler. An engineer's unit that receives all survey data is located near the laser, and a remote computer with a terminal and printer is located above ground, possibly several kilometers away. On a Terrestrial tunnel-boring machine, an operator's monitor usually would be located on the machine; the unmanned Lunar Tunneler would not require this.

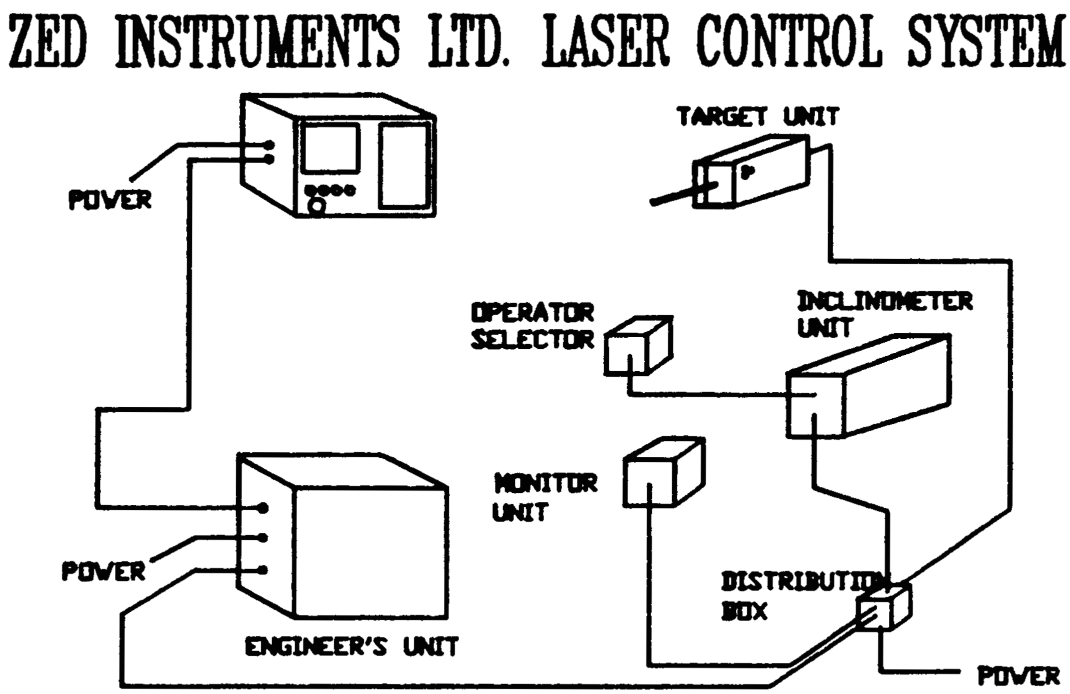


FIGURE 14: ZED INSRTUMENTS CONTROL SYSTEM

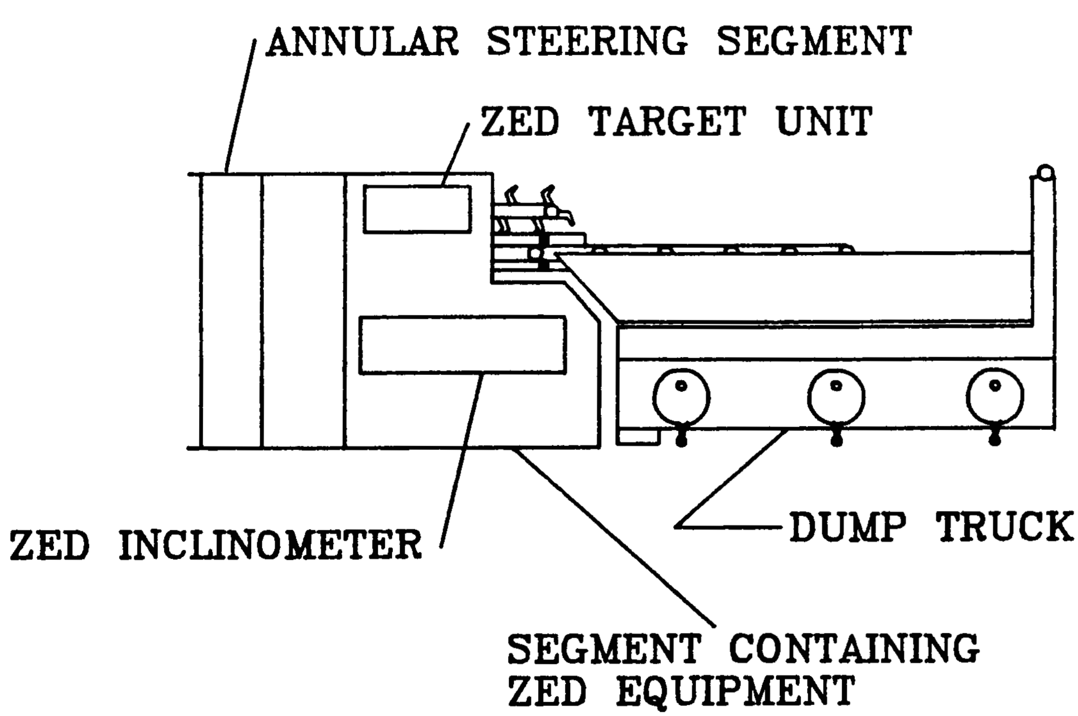


FIGURE 15: LOCATION OF ZED TARGET UNIT AND INCLINOMETER

The TG–260 system determines five coordinates from the laser beam and inclinometer. Coordinates x, y, and lead are determined relative to the laser beam; coordinates roll and look-up are determined relative to the vertical. Moreover, the linear distance measuring equipment provides a z coordinate, the distance along the tunnel. (See Figure 16.)

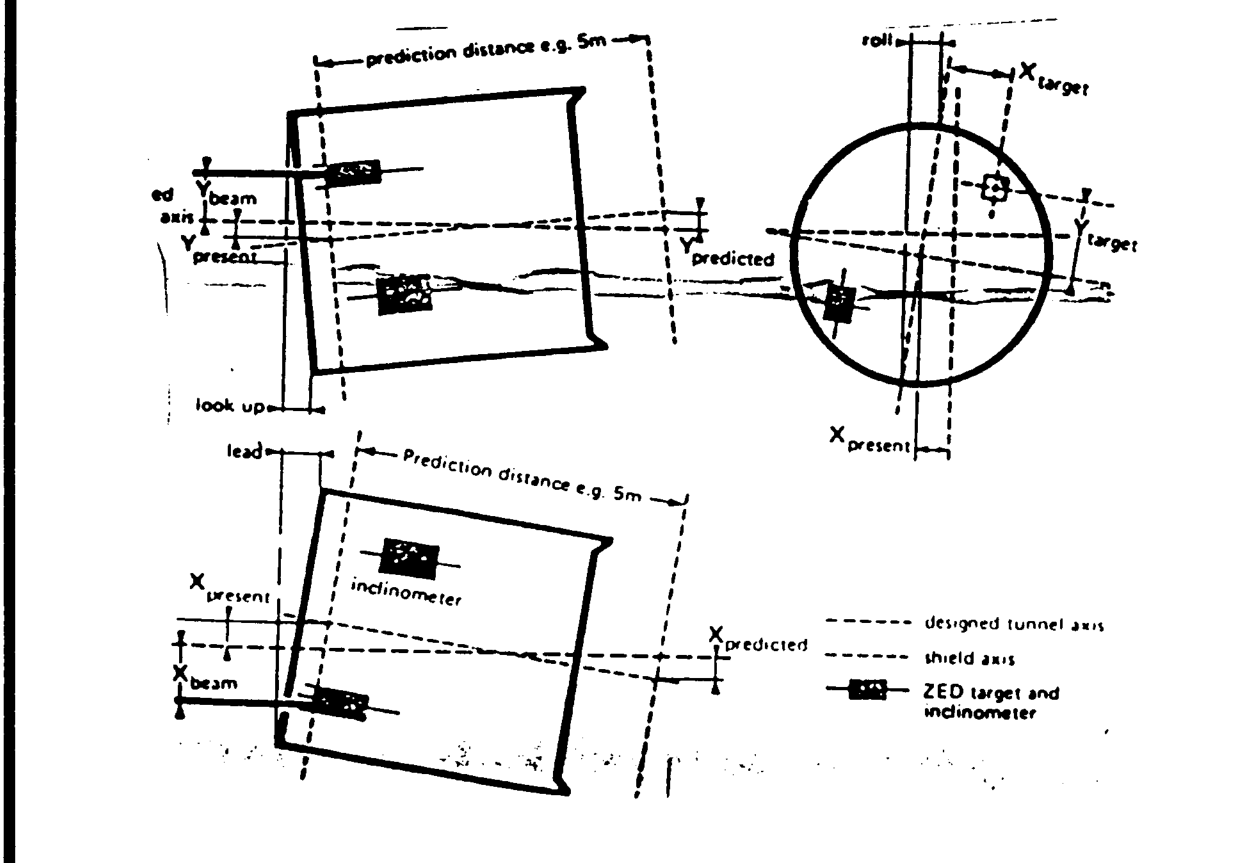


FIGURE 16: ZED INSTRUMENTS AXIS

The data are provided continuously in digital form to the steering computer; they are also made available at the engineer's unit at some distance behind the Tunneler and at the above-ground terminal. Using the data, the computer would steer the machine to minimize deviations. The data can also be used to provide predicted position and attitude data. For example, angular deviations can be shown before the Tunneler leaves the desired axis. These would not only eliminate the need for large course corrections but also allow for better understanding of the Tunneler maneuverablity. A complete record of the survey data with corresponding dates and times can be printed at a remote terminal automatically at regular intervals or at any time on command. Moreover, the data can remain in storage for thirty days after the power is shut off. Thus, a power failure or shutdown for maintenance does not destroy the survey data.

The laser target of a TG–260 system has a range of reception of ±58mm (±2.3in), a resolution of 1mm (0.04in), and a precision of ±2mm (±0.08in) for the x and y coordinates. For the lead coordinate, the reception range, resolution, and precision are ±100, ±1. and ±2 milliradians (±5.7°, ±0.057°, and ±0.11°), respectively. For the roll and look-up coordinates. the inclinometer has a reception range, resolution, and precision of ±100, 0.1. and ±1 milliradian (±5.7°, 0.0057°, and ±0.057°), respectively.

The linear distance measuring equipment provides absolute measurements of distance along the tunnel length. The correct distance is registered and maintained, even in the event of movement after the power is shut off. Distance is measured from an arbitrary reference point with a reception range of –199.99m to +999.99m (–656.13ft to +3280.8ft), resolution of 1cm (0.4in), and precision of ±1cm (±0.4in).

The engineer's unit reads as input zero offsets (±999 milliradians/±57.2°) for roll, lead, and look-up. Target coordinates with an allowed range of ±9999mm (393.7in) are also read. For output the engineer's unit displays present and predicted x and y coordinates in millimeters and lead, look-up, and roll in milliradians. An analog monitor could also be provided to display the plan section and elevation graphically.

The above-ground computer reads as input designed tunnel axis points, wherein x and z have a possible range of ±999.999m (±3280.83ft) and y has an possible range of ±99.999m (±328.08ft) in intervals of 0.5m or 1m (1.6ft or 3.3ft). Laser position is read as one point and bearing and zenith angles. The computer also reads other information, including date and time. The outputs on the monitor are the designed tunnel axis points as given, interpolated tunnel axis points, design data, survey and control data, and other information. A printer displays survey data as described before as well as any other output requested.

A few problems are foreseen regarding placement of the laser. In the earliest stages of tunneling, the laser and engineer's unit can be placed at the tunnel entrance. If a curved tunnel is made, however, obstruction of the target view could necessitate repositioning of the laser inside the tunnel, thus changing the required x, y, and lead offsets. (See Figure 17.) However, this problem has been confronted in small-bore tunneling on Earth and should not be insuperable. Another unresolved source of concern is that the laser and engineer's unit behind the Lunar Tunneler could prevent the Dump Truck from traveling to the tunnel entrance when necessary. Also, settling of dust in the tunnel sometimes affects the integrity of the laser beam. If the TG–260 system is used for the Tunneler, ZED Instruments can provide advice on these matters.

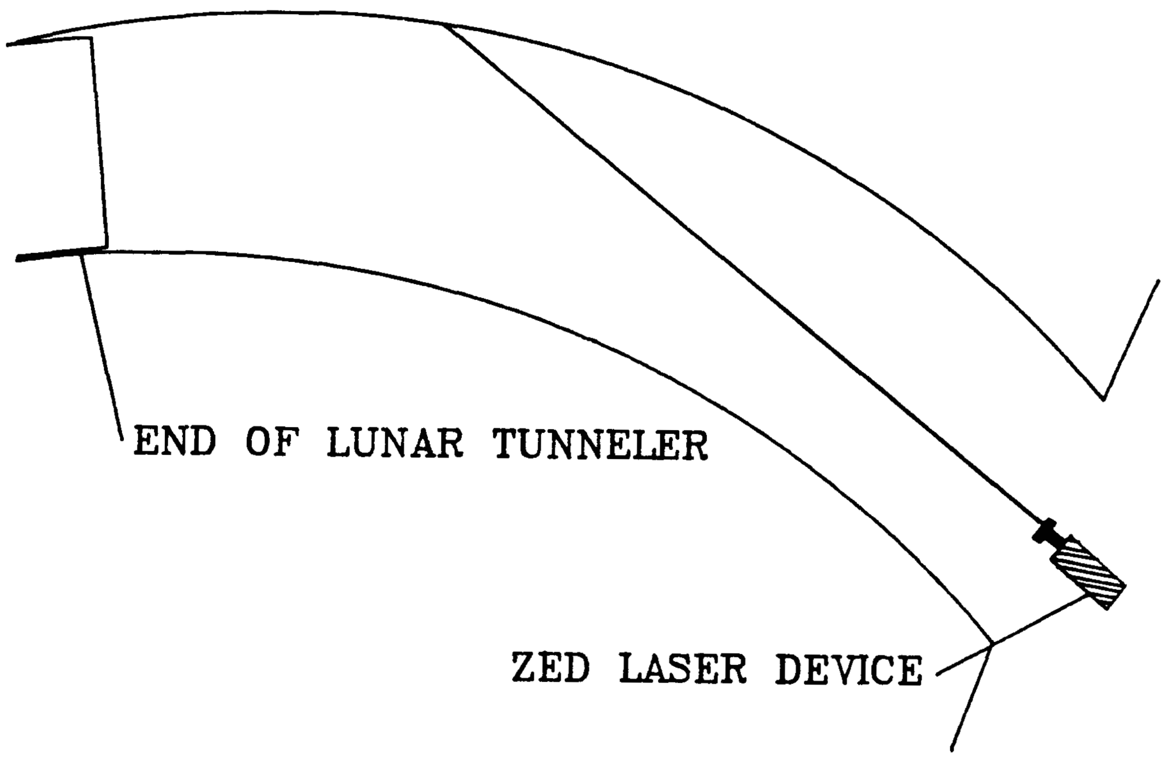


FIGURE 17: POSSIBLE OBSTRUCTION OF LASER BEAM BY CURVATURE OF TUNNEL

MATERIAL EXCAVATION SYSTEM

The problem of tunnel excavation is age-old, and to this day the rate of excavation is the limiting factor on how fast tunnels can be dug on Earth. In fact, the excavation rate of Earthly tunnels has not been increased significantly since the advent of tunnel digging. The excavation rate of the Lunar Tunneler, however, will not be the limiting factor. Because of the slow pace of the glass-forming process, the rate of lunar excavation must be adequate but not record-breaking.

After the lunar material is cleaved off by the rotating cutterhead, it is necessary to immediately move the material through the Tunneler and out to the rear so the progress of the Tunneler will not be impaired. It is then necessary to completely remove the material from the tunnel in order to leave behind space for radiation-free habitation. Finally, the excavated material should be placed so it may be easily recovered for future oxygen, water, or fuel production.

The first problem is to move the excavated material to the rear of the Tunneler. The easiest way to accomplish this task is to use a belt conveyor. Several belt conveyors were looked at, beginning with designs that were already existing on Earthly tunnel-boring machines.

The first and second designs that were looked at each use a bucket elevator. (See Figure 18.) This bucket elevator is located immediately after the cutterhead in the first design and at the rear of the Tunneler in the second.

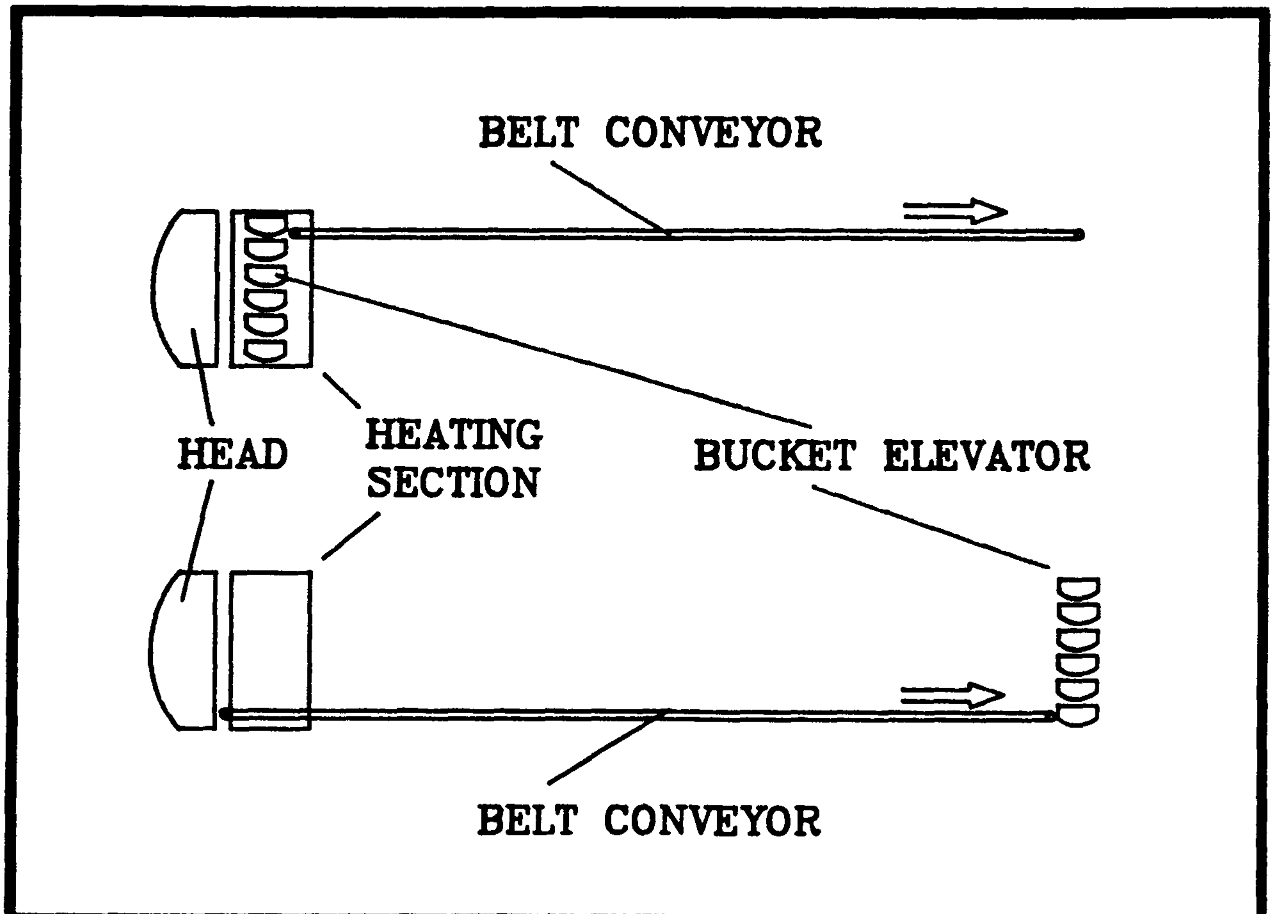


FIGURE 18: BUCKET TYPE CONVEYORS

These designs create problems in feasibility because of the systems' proximity to the heating section. Also introduced is a large amount of down-time and retardation of the excavation rate, due to the complex structure and precision-tuned nature of the bucket elevator.

The problem was solved by taking into account the abundance of empty space in the center of the glass-forming section. The belt conveyor moves the loose material from directly behind the cutterhead up an incline over the heating section to the top of the Tunneler. The comparatively simple conveyor then levels off; it continues to process the material along the top of the Tunneler and over the propulsion section to the rear of the machine. (See Figure 19.)

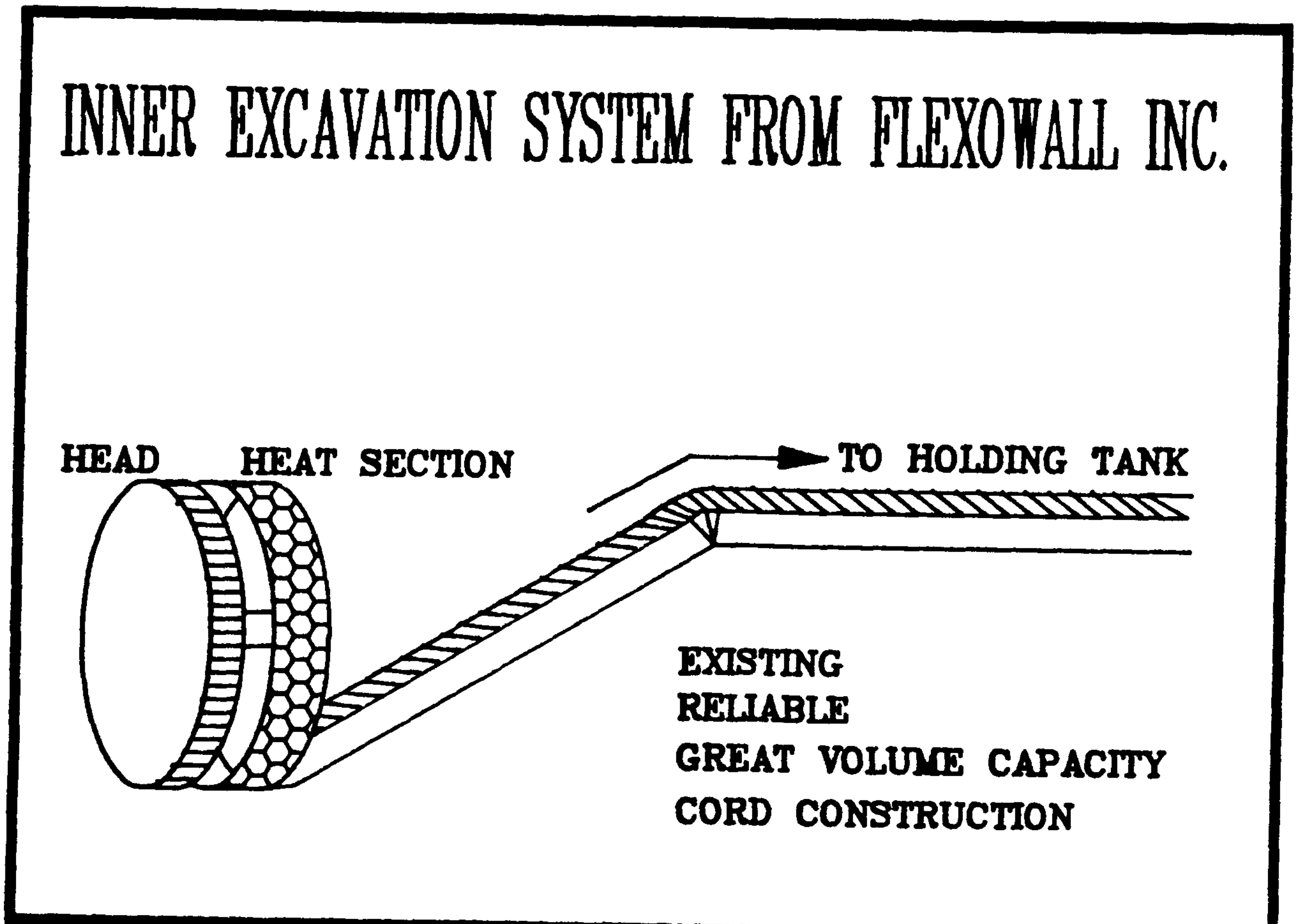


FIGURE 19: EXCAVATION SYSTEM FROM FLEXOWALL INC.

Several designs were examined to excavate the material entirely from the Tunnel. Two of these included methods of vertically transferring the material from the inside of the tunnel directly to the surface of the Moon. (See Figure 20.)

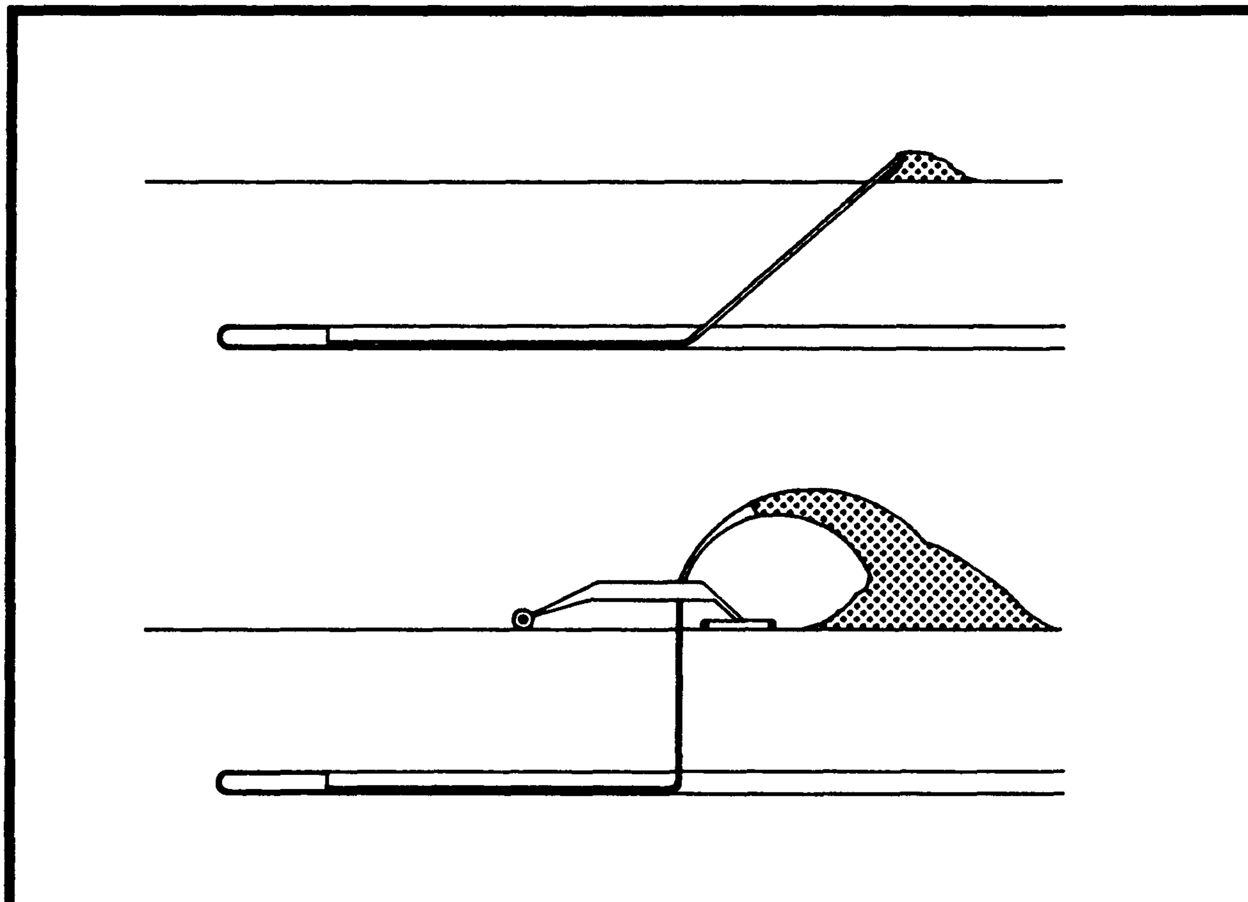


FIGURE 20: EXCAVATION SYSTEMS

The first of these methods has two problems: first, the amount of power required; second, the awkwardness of drilling upward through the glass lining and lunar soil while physically pushing the loose lunar material up to the surface. The disadvantage of the second method is that in would require a separate system on the surface of the Moon to drill downward and pump the material to the surface. The system should be as autonomous as possible.

An alternative to drilling more holes in the Moon is to take the material out through the mouth of the tunnel. The circular shape and relatively smooth walls of the tunnel could be used to act as a track for a modified *Dump Truck* that could be maneuvered with a computer, similar to that used to guide the Tunneler, to dump the material at a specific location. This concept was adopted for the Lunar Tunneler.

Other considerations in the design of the excavation system include the need to dissipate excess heat created by the tunneling system and the desire to tunnel as continuously as possible without having to stop and wait for the Dump Truck. These added requirements led to the concept of a holding tank. This tank would not only store the excavated lunar material; it would also heat the material so the excess heat and lunar material can be excavated simultaneously. Putting the pieces together, the total concept for the Lunar Tunneler excavation system would be as shown in Figure 21.

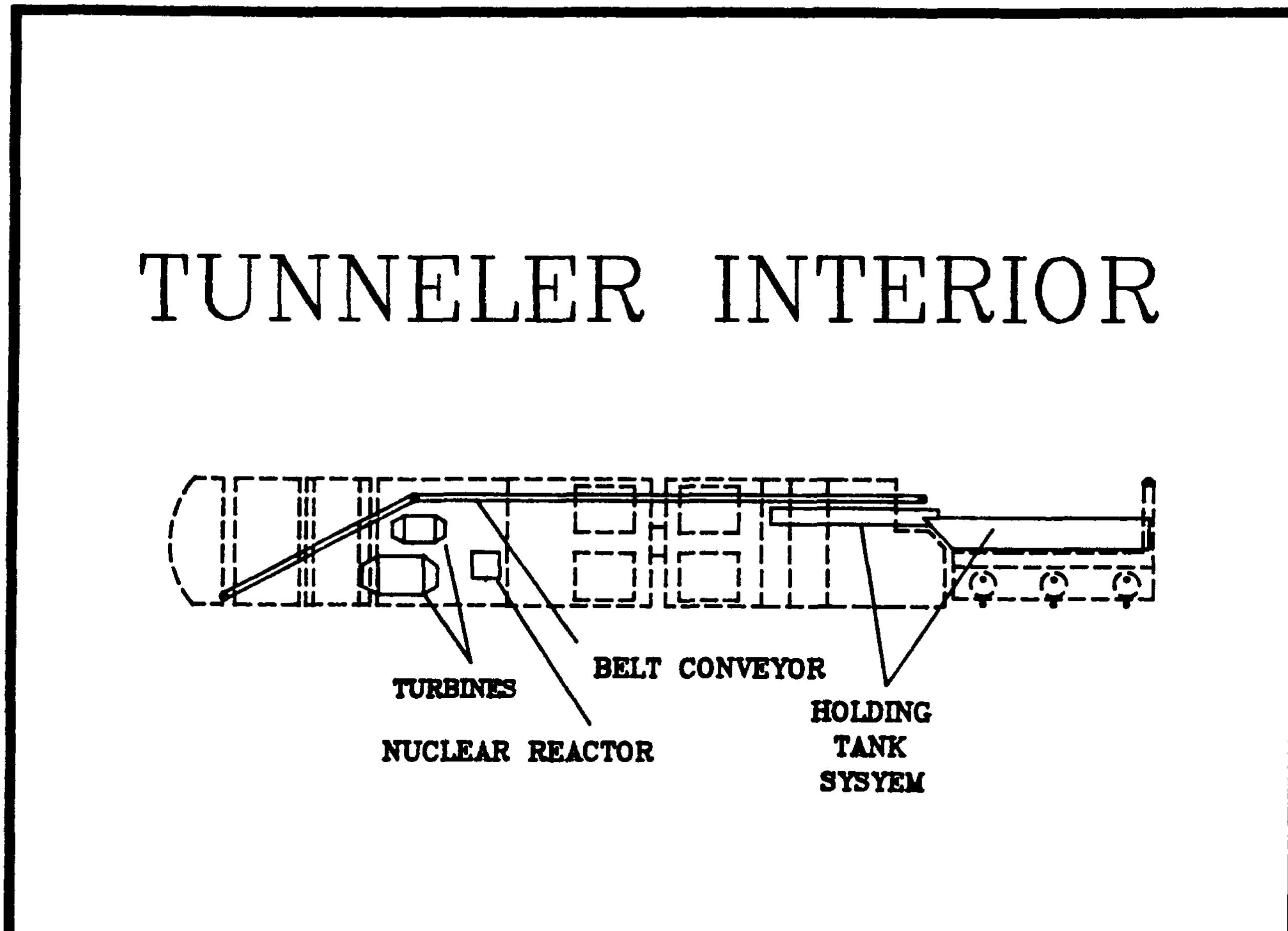


FIGURE 21: EXCAVATION CONCEPT

The belt conveyor adopted for the Tunneler is an existing design by Flexowall.[3] This conveyor system has high reliability, low down-time, high strength, and good flexibility. With large capabilities and high belt speeds, the belt conveyor capacity is much greater than necessary. Flexowall can also construct the conveyor with a heat-resistant material so that any heat transfer due to the heating section or friction of the rotating cutterhead will not impair the device.

The holding tank would be a dual pan system as shown in Figure 22. A shallow pan used to maximize the slow process of heat transfer to the loose lunar material would be placed above a larger holding cell that stores the already heated material while the Dump Truck is detached from the Tunneler. The heating system would be comprised of carbon-carbon electrical resistance heating elements, much like in the heating section, powered by a radial turbine that utilizes the heat given off by the molten lunar material in the cooling section. The shallow pan would move further toward the rear as the belt conveyor dumps the material into it. When it is at capacity, a section in the bottom of the shallow pan opens, and the entire pan retracts while a stationary plate pushes the lunar material out of the hole and into a larger holding cell below. Material gathers in the large holding cell until the Dump Truck reattaches to the rear of the Tunneler below the larger cell. The bottom of the cell would then open, like double doors, and the material would be transferred into the Dump Truck. The doors would close and the Dump Truck would detach and dump. (See Figure 23.)

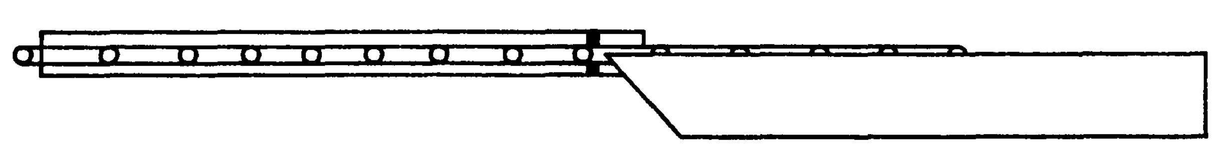


FIGURE 22: HOLDING TANK

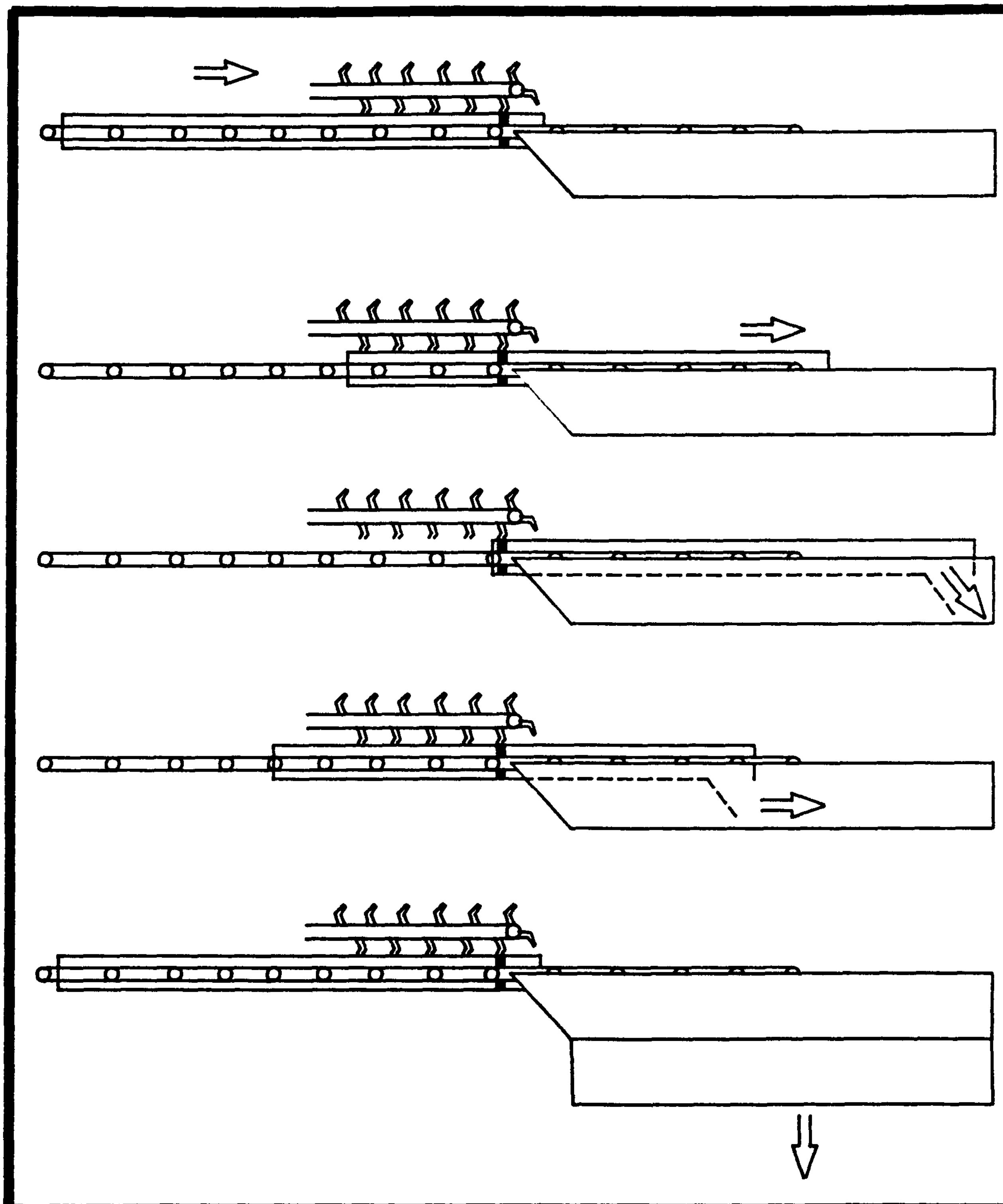
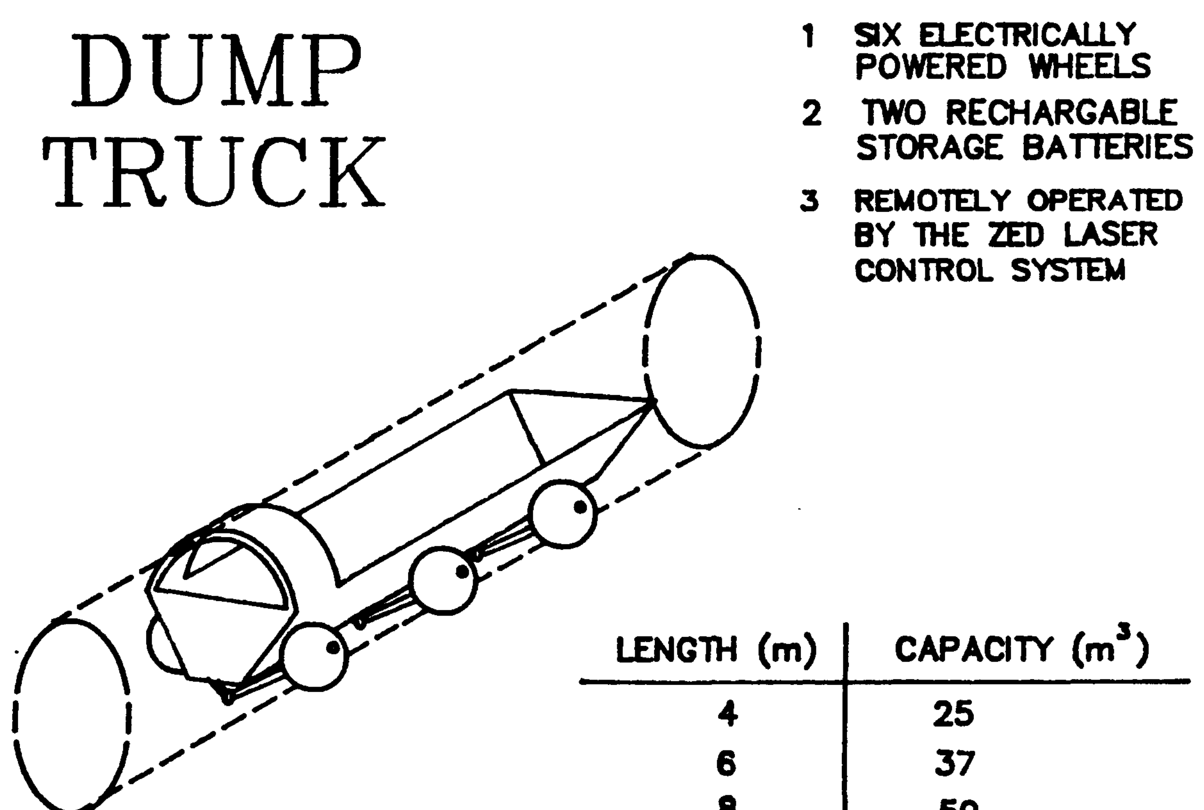


FIGURE 23: HOLDING TANK OPERATION

The Dump Truck is the most complex and important component of the proposed excavation system. It should use the tunnel as a track but also be able to propel itself on the lunar surface. Moreover, the Dump Truck must dump the lunar material in a spot that will not impede its own movements.

It was decided to make the Dump Truck cylindrical, with small wheels around its perimeter in conjunction with large drive wheels to keep the Dump Truck on track. (See Figure 24.) Hydraulic systems would be used to extend and retract the drive wheels for surface or tunnel drive and to move the bed of the Dump Truck to dump the material. (See Figure 25.) The material would be unloaded off to the side, so that once out of the tunnel the vehicle can drive in a relatively straight line without blocking the tunnel entrance.



LENGTH (m)	CAPACITY (m^3)
4	25
6	37
8	50

FIGURE 24: EXCAVATION DUMP TURCK

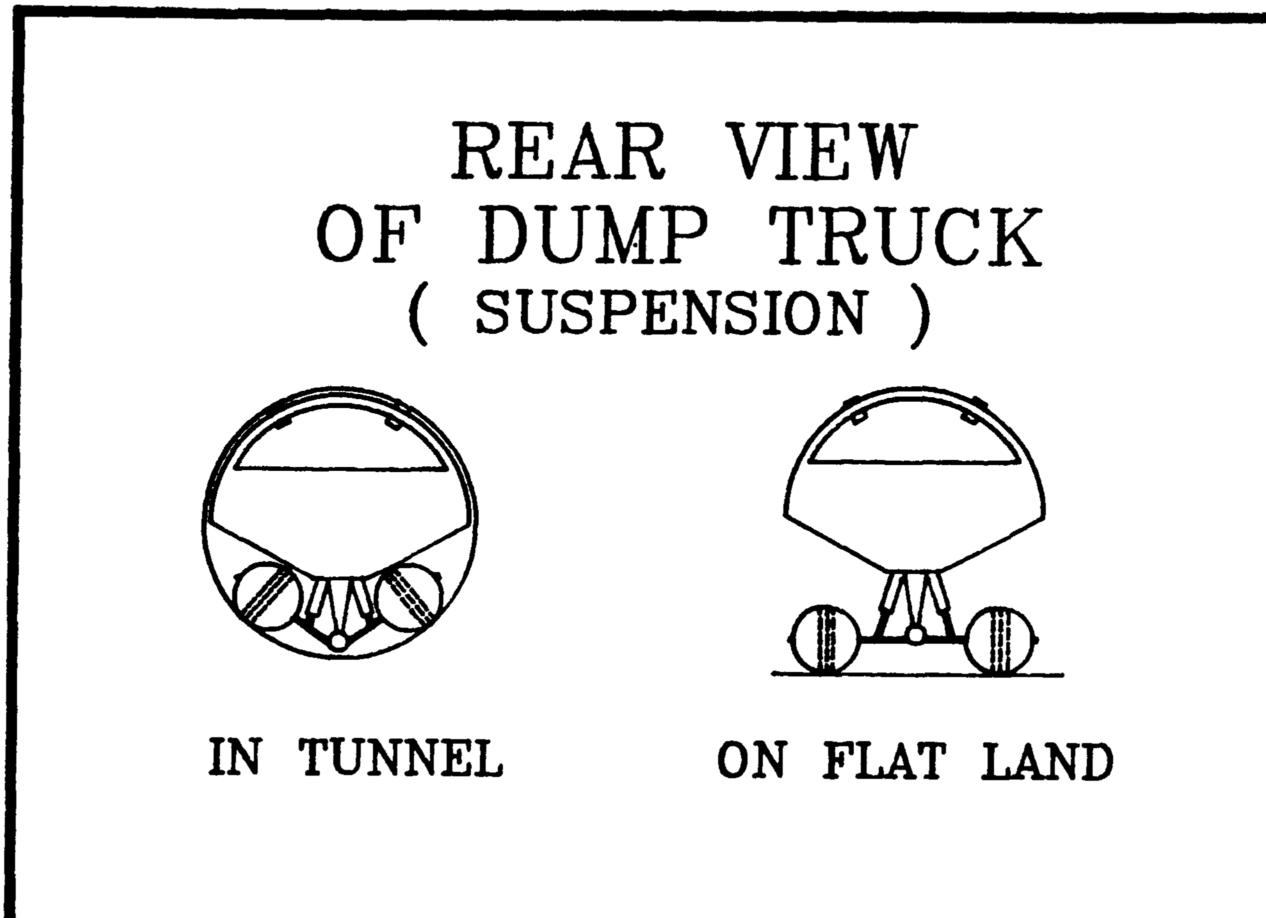


FIGURE 25: DUMP TRUCK SUSPENSION

The Dump Truck would be powered by a rechargeable battery system. These batteries are charged initially and plugged into the Tunneler power system to be charged each time the Dump Truck returns from a dump. The batteries would power six sealed electrical motors that would turn six 1m (3.3ft) diameter spherical wheels.

Guidance of the Dump Truck would be performed by a computer using components manufactured by ZED Instruments. The computer would be preprogrammed to control vehicle motion and monitor vital signs such as hydraulic pressure.

All support systems and driving would be mounted on a framelike structure located below the bed as shown in Figure 26. This structure is intended to maximize the space available for transportation of lunar material and to act as a stable base for relative movement of the rest of the vehicle. Left in a row of mounds, the lunar material would be readily accessible for strip-mining for chemical processing.

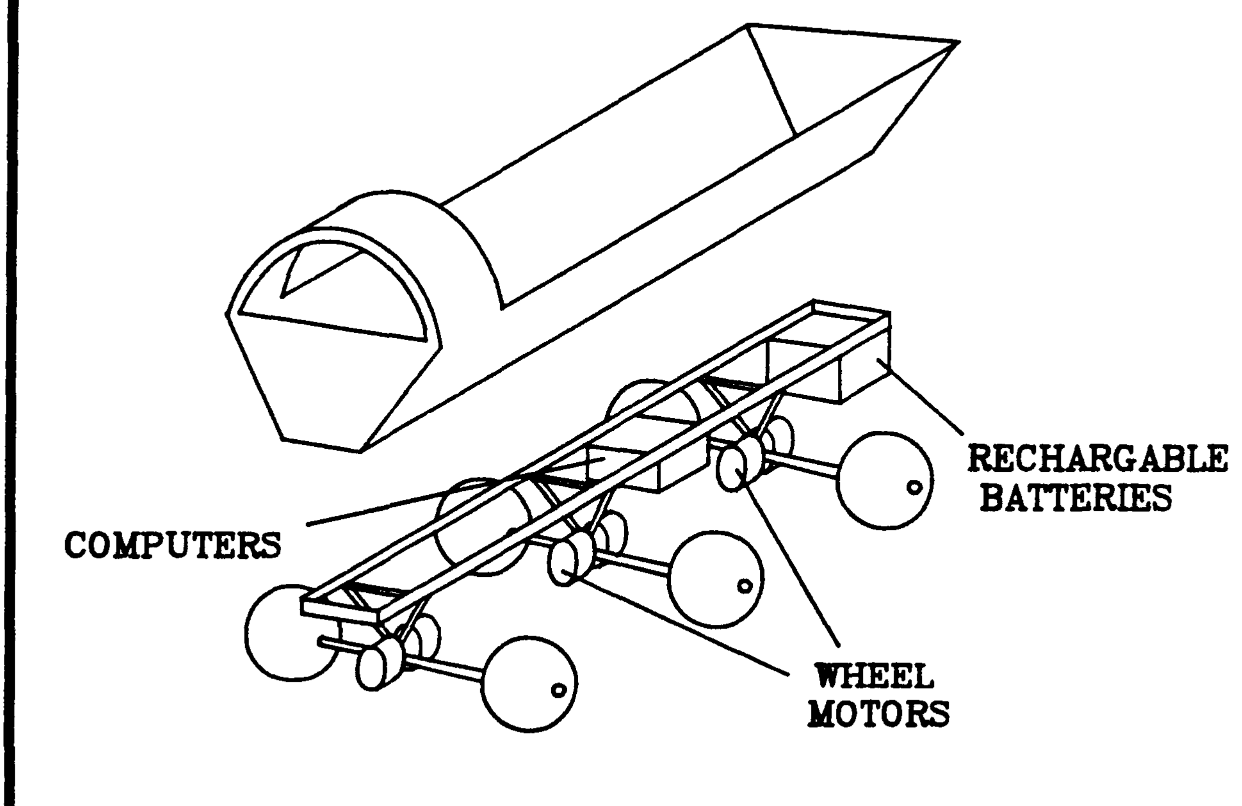


FIGURE 26: DUMP TRUCK FRAME

With a diameter of 4 meters (13 feet) and length of 4, 6, or 8 meters (13, 20, or 26 feet), the capacity of the Dump Truck would be 25, 37, or 50 cubic meters (880, 1,300, or 1,800 cubic feet), respectively. Since the Tunneler is projected to create approximately nine meters of tunnel per Terrestrial day, the 4, 6, or 8 meter Dump Truck would need to make 4.5, 3.0, or 2.2 dumping trips per Terrestrial day. Thus, even the shortest vehicle would meet the dump rate requirement.

This concept of the Lunar Tunneler excavation system was designed optimizing simplicity to reduce the cost and down-time of each of the components in the system. Many components utilize existing designs to further lower the cost of design and production.

INTERNAL POWER CYCLE

Problems exist within the hazardous environment of the Moon. With a vacuum present, the problem of heat dissipation from the tunnel, molten lunar material, and all mechanical devices becomes the greatest constraint in developing a mechanical tunneling device that uses the glass-forming sections with their required high temperatures. Heat generated inside the tunnel cannot escape through normal conduction means; therefore, an internal cycle must be developed which not only dissipates heat from the tunnel but cools the molten lunar material to its relatively cool glass-ceramic form. This raises the problems of how to cool the working fluid while keeping the Tunneler totally automated.

The internal power cycle of the Lunar Tunneler, shown in Figure 27, begins with a nuclear reactor which uses liquid lithium as the working medium for cooling. Lithium was chosen for its ability to remain liquid at very high temperatures and for its proven ability in heat transfer uses. The reactor feeds heated liquid lithium to a radial turbine which drives a generator to electrically power all components of the Tunneler. After the lithium leaves the turbine, the relatively cool fluid is circulated through the cooling section to cool the molten lunar material to its ceramic form. This operation raises the lithium temperature again, and the fluid is circulated through another radial turbine to lower the fluid temperature and further generate electricity. After the relatively cool liquid lithium leaves the second radial turbine, it is pumped back to the nuclear reactor for cooling purposes and to be reheated, thereby completing the cycle.

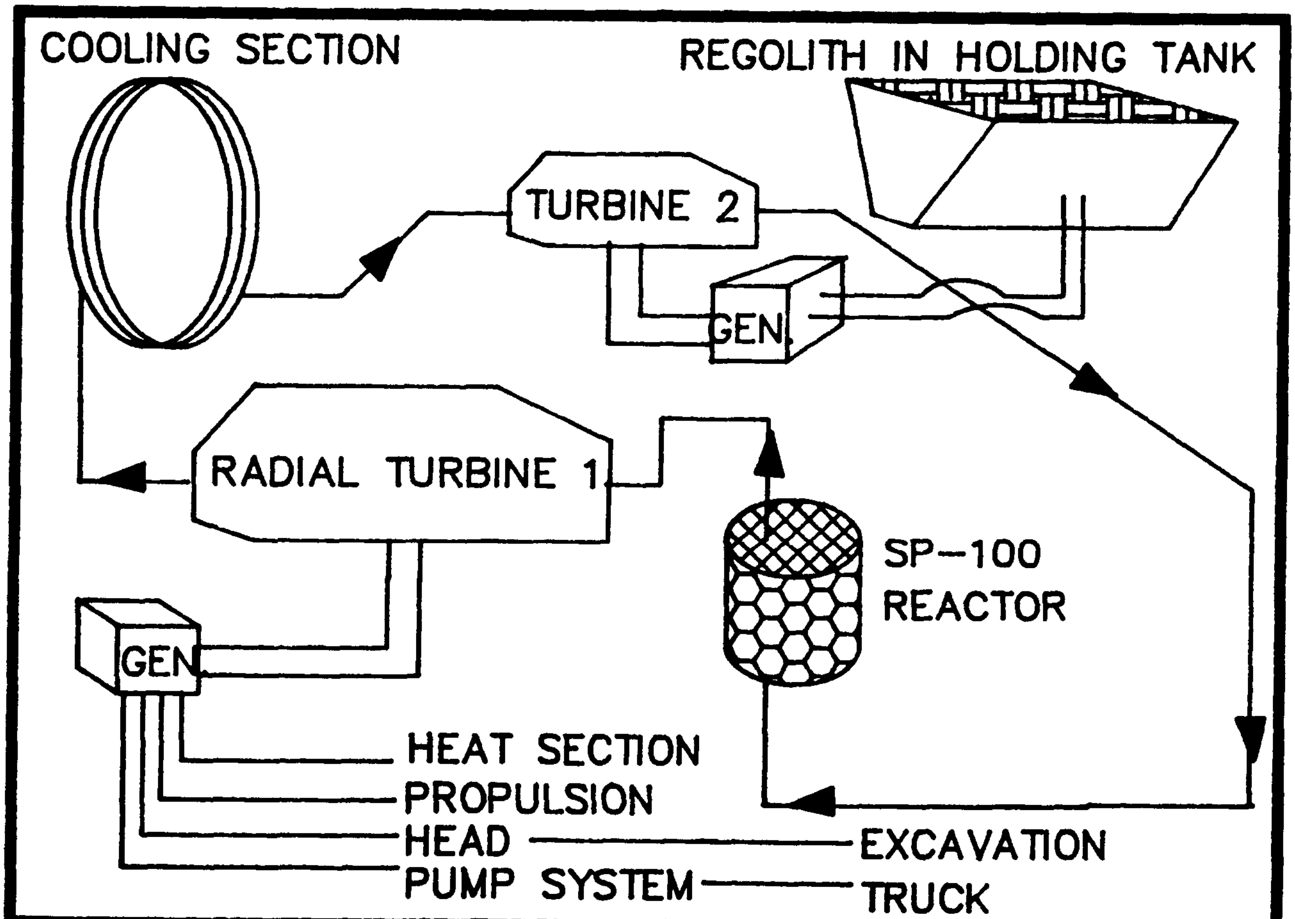


FIGURE 27: INTERNAL POWER CYCLE FOR LUNAR TUNNELER

The nuclear reactor, shown in Figure 28, is a high speed SP–100 fission device which uses the standard control rods to regulate the reactor output. These control rods can be inserted or extracted in varying amounts to increase or decrease the reaction rate and thus vary the reactor temperature. Heat pipes carrying liquid lithium are contained throughout the interior of the nuclear reactor. The basic components of the heat pipes proposed for the Lunar Tunneler are of the type developed by Los Alamos.[5] The heat pipe, shown in Figure 29, is a gas-tight tube containing lithium liquid and vapor; one end of the tube is an evaporator, the other a condenser. For nuclear applications the evaporator end is placed directly at the inlet to the first radial turbine. The interior of the heat pipe is lined with multiple layers of woven wire screen called a *wick*. The liquid lithium within this wire matrix is heated and thus evaporated inside the nuclear reactor. The continuously forming vapor fills the interior of the heat pipe and flows toward the cooler condenser end. At the condenser end the vaporized lithium rejects its latent heat and returns to the evaporator end by means of capillary movement through the wick. The process begins again to keep the cycle continuous. The advantage of the heat pipe with evaporator and condenser ends is its ability to maintain very high heat fluxes with very small temperature differences between the ends. This happens because the thermal exchange involves the latent heat of vaporization instead of the temperature difference of only one phase.

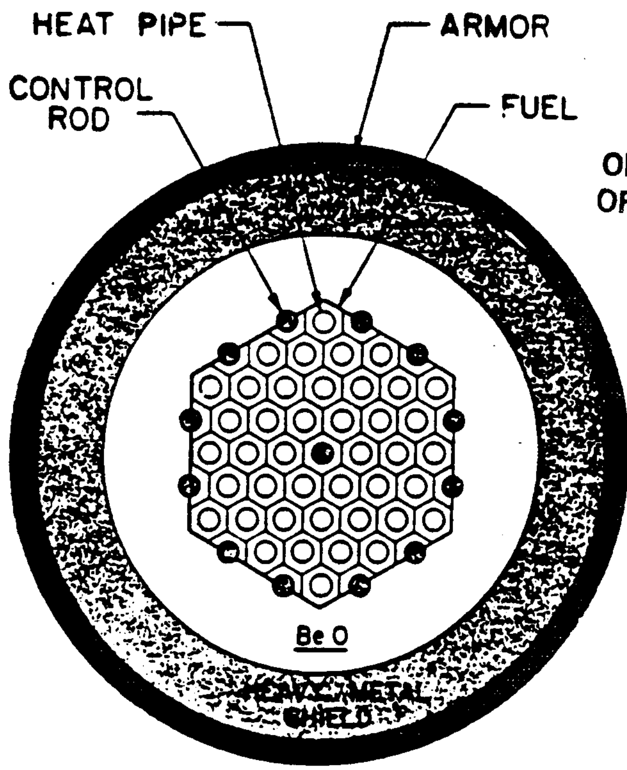


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FIGURE 28: SCHEMATIC OF SP-100 REACTOR(REPORT BY LOS ALAMOS)

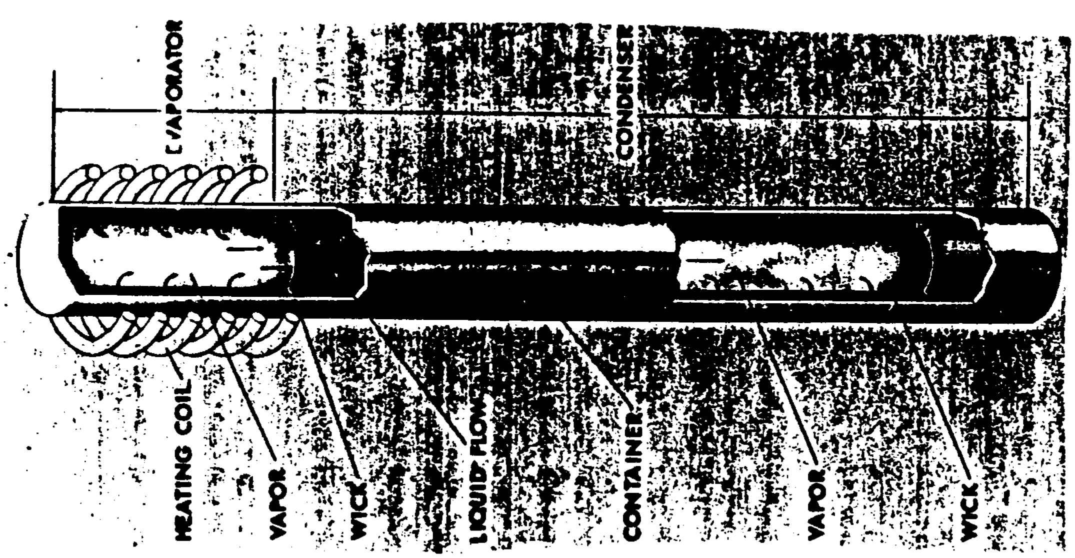

FIGURE 29: LOS ALAMOS HEAT PIPE(REPORT BY LOS ALAMOS)

Because of the problems of heat pipe breakage inside the reactor, exhaustion of fuel, and other factors, it is necessary to be able to replace the nuclear core. This would allow the exchange of fuel elements and broken components within the core. By having a section within the core where the heat pipes can be disconnected from the core, robotic maintenance devices can replace the core without any extensive disconnecting of hardware. (See Figure 30.)

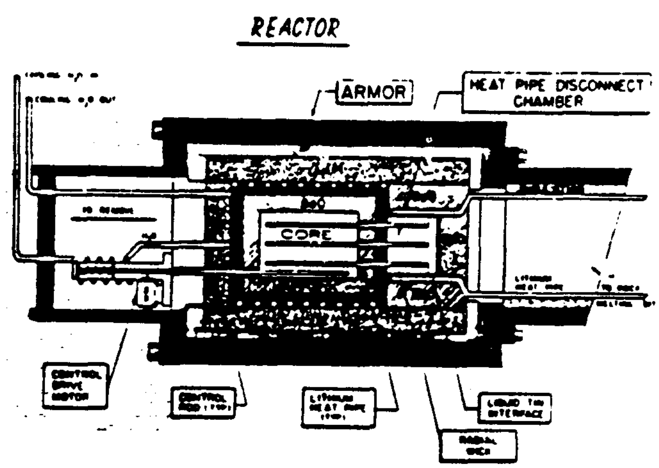

FIGURE 30: DISCONNECTING REACTOR (REPORT BY LOS ALAMOS)

After the nuclear reactor heats the lithium, the liquid is circulated to the first radial turbine. (See Figure 31.) The turbine, using the liquid lithium as the working medium, is about one meter (three feet) in diameter with inlet and exit temperatures of 1,200°K (2,160°R) and 750°K (1,350°R), respectively. With an assumed efficiency of 75%, the characteristics of lithium and the power requirements dictate a mass flow energy of $1.6861 kg \cdot s^{-1}$ ($0.115 slug \cdot s^{-1}$) (See Appendix B for mass flow calculations.) The design power output of the first turbine is approximately 2,500kW (3,400hp). To maximize the inlet temperature, and hence the power output of the turbine, the distance between the reactor and turbine should be minimized. (A small distance is needed to maximize heat transfer between the turbine and reactor.) The first turbine has two purposes, lithium temperature decrease and power generation. The turbine would produce shaft work while lowering the temperature of the liquid lithium by approximately 450°K (810°R). This temperature decrease across the turbine would allow the relatively cool lithium to circulate through the cooling section, thereby allowing formation of the glass-ceramic from the molten lunar material. Power generation is created by converting the turbine shaft work through a gear box, which in turn drives an electrical generator, which produces approximately 2,500kW (3,400hp) of power. This power would be available for driving the mechanical cutterhead, operating the hydraulic propulsion system, supplying heat to the heating section, operating all pumping and instrument systems, driving the belt conveyor, and recharging the Dump Truck.

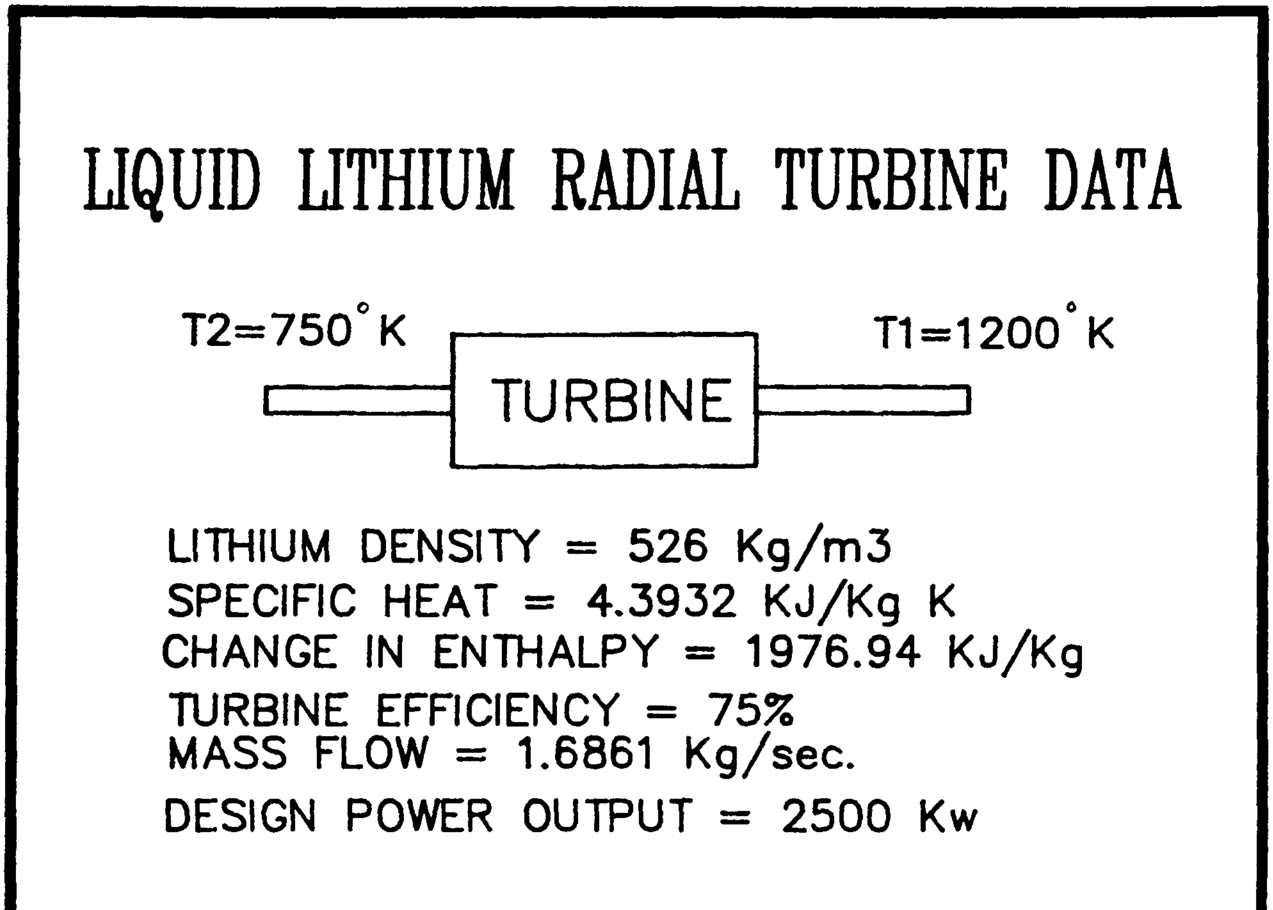

FIGURE 31: RADIAL TURBINE DATA

The cooling system accepts the 750°K (1,350°R) liquid lithium and, in turn, circulates it through the exterior Mo–30W alloy shell. (See "Glass-Forming Sections.") The lithium, by means of heat transfer, accepts approximately 500°K (900°R) of the heat from the molten lunar material to transform the material to glass-ceramic form. At this point the lithium is at a temperature of 1,250°K (2,250°R) and is too hot to return to the reactor. In order to dump as much excess heat from the lithium as possible, the fluid is directed to another radial turbine. The second turbine has three purposes: to provide additional power for the Lunar Tunneler, to generate resistance heating inside the non-heated lunar material holding tank (see "Material Excavation System"), and to lower the temperature of the liquid lithium. By generating the resistive heat inside the holding tank, excess heat can be transferred to the non-heated lunar material and dumped outside the tunnel whenever the Dump Truck dumps its load. By directing the lithium fluid through the turbine the temperature is lowered to approximately 800°K (1,440°R). Lithium at this temperature can return to the nuclear reactor for cooling purposes and reheating to continue the cycle. With this cycle in place, the Lunar Tunneler can be operated for as long as the fuel in the nuclear reactor is sufficient to heat the lithium fluid to 1,200°K (2,160°R).

Power requirements for all systems and components (except the heating section and Dump Truck) were obtained by extensive research on six Robbins earth rock tunneling devices. This research obtained a power requirement of 700kW (938hp) for the propulsion system. all other hydraulic systems, cutterhead, and belt conveyor. The heating section power requirement was estimated at 500kW (670hp), considered to be a conservative amount. The rechargeable system for the Dump Truck had a power requirement estimated to be 30kW (40hp). This gives a total power requirement for the Lunar Tunneler of 1,230kW (1,650hp), which is less than half of the design power output of the first turbine. (See Figure 32.) Excess power is included in the design of the Lunar Tunneler for reasons of safety and convenience.

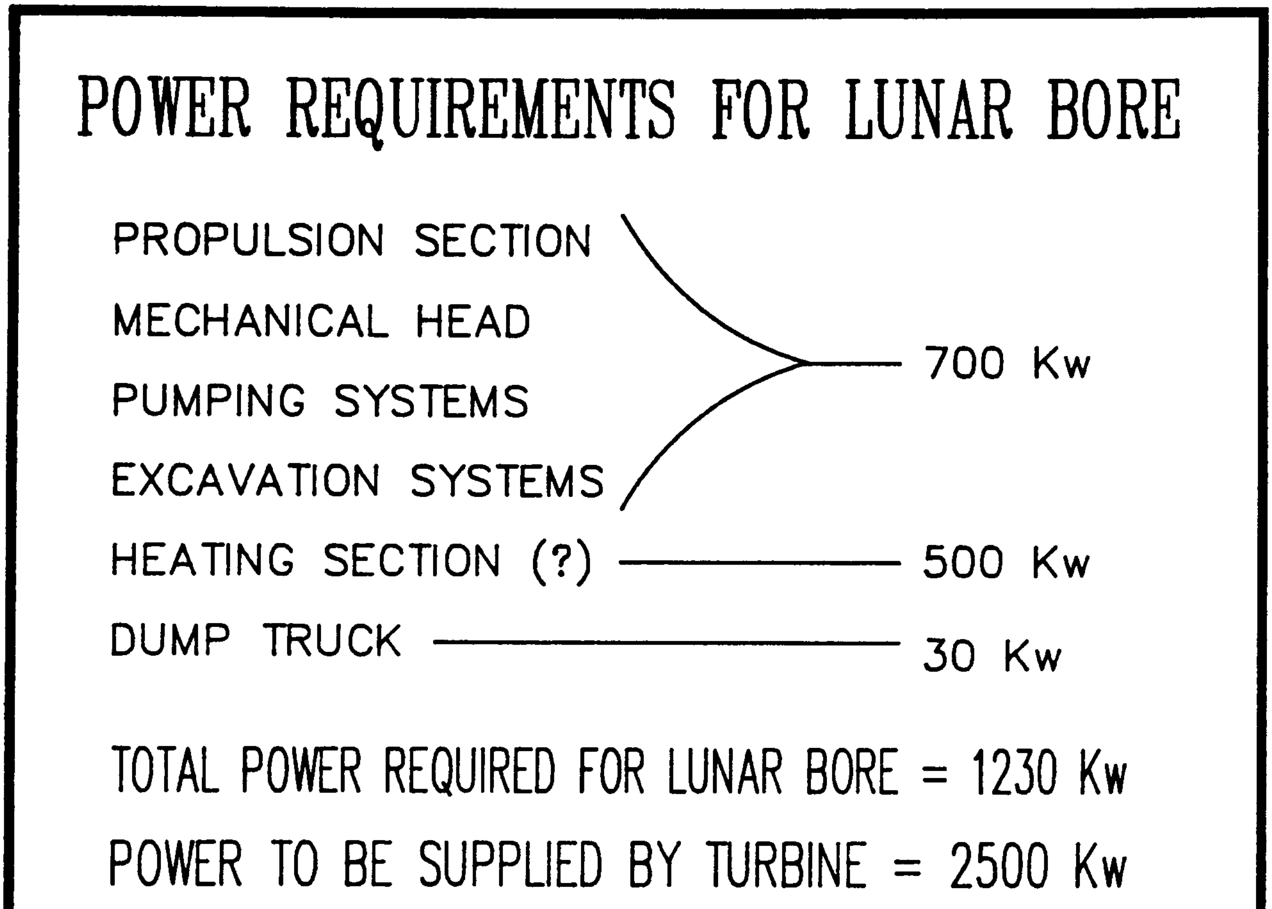

FIGURE 32: POWER REQUIREMENTS FOR LUNAR TUNNELER

Percent down-time of six Robbins earth-tunneling devices were studied to give average numbers as estimates for the Lunar Tunneler. (See Figure 33.) Neglecting factors that pertain only to the Earth's atmosphere and taking into account technological progress in hydraulic sealings, an estimate of 25.3% down-time was reached. Even with this relatively high down-time percentage, the generation of many cubic feet of safe living space can be obtained before any maintenance is required. With further research in the areas of hydraulic seals, materials, disc cutter wear, and stroke recycle time, this down-time percentage can be brought to a lower value.

PERCENT DOWNTIME FOR LUNAR TUNNELER

CUTTER CHANGE	2.6%
GEN. MAIN. & INS.	4.2%
LUBE OIL	0.9%
HYDRAULICS	5.0%
MOTORS	0.3%
CONVEYOR	1.5%
ELECTRICAL	1.6%
POWER SUPPLY	0.3%
SURVEY	0.1%
GRIPPER DIFF.	0.2%
STROKE RECYCLE	3.9%
OTHER	4.7%

TOTAL DOWNTIME=25.3%

FIGURE 33: PERCENT DOWNTIME FOR LUNAR TUNNELER

CONCLUSION

From the findings presented in this report, it is concluded that a mechanical Lunar Tunneler is a viable and efficient technique for creating large amounts of underground living space. An SP–100 high speed atomic reactor is the best choice for supplying the power requirements in this application because of its compactness, longevity under adverse conditions, and ability to provide ample power for lunar tunneling. The completely mechanical cutterhead, with twenty-six disc cutters, would be able to shear its way through the lunar material without using the large amounts of power required by a melting tunneler. The mechanical head is based on a proven design and should be very reliable with minimal down-time. In addition, using a mechanical head would eliminate the problem of transporting the molten lunar material through the interior of the tunnel-boring machine. Using the existing lunar materials to form a rigid ceramic structure was found to be totally viable and more efficient than transporting structural lining materials from Earth. Propulsion of the Lunar Tunneler would be performed by a proven existing design built by Lovat and other companies. Features of the propulsion system include low power requirements, a hydraulically activated gripper system, and the ability to maneuver in all directions. Navigation of the Lunar Tunneler is accomplished by using an existing laser system developed by ZED Instruments. The Lunar Tunneler can be guided with a computer operating in conjunction with the laser guidance system. Removal of the unheated lunar material to the rear of the Tunneler would be accomplished by an existing conveyor system developed by Flexowall. This conveyor system is very reliable with adjustable speed control and has the advantage of a large capacity for transporting excavated material. The conveyor system would move the excavated lunar material into a holding tank, where excess heat would be transferred to the material. Once the holding tank is filled, it transfers its load to the Dump Truck for removal from the tunnel. This would eliminate the accumulation of heat within the tunnel while not requiring the addition of further cooling elements. For the above reasons the Lunar Tunneler should prove to be a straightforward and reliable design.

REFERENCES

1. Lovat Tunnel Equipment, Inc., 441 Carlington Dr., Toronto, Ontario M9W5G7, Canada.

2. ZED Instruments, Ltd., Molesey Ave., West Molesey, Surrey 14T8 0RY, England.

3. Flexowall, Inc., 2336 Merced Street, San Leandro, Calif. 94577.

4. Pricilla Nelson, "Tunnel-Boring Machine Performance in Sedimentary Rock," Ph.D. thesis, Cornell University, May 1983.

5. E. S. Robinson *et al.*, "A Preliminary Study of the Nuclear Subterrene," Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico, April 1971.

6. R. D. Bennett, "State-of-the-Art Construction Technology for Deep Tunnels and Shafts in Rock," Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

7. Kenneth Budinski, *Engineering Materials: Properties and Selection,* Reston Publishing, 1985.

8. I. I. Cherkasov, *Lunar Soil Science,* Israeli Program for Science, Jerusalem, 1975, pp. 146-168.

9. Brian H. Mason, *The Lunar Rocks,* Wiley-Interscience, New York, 1970, pp. 62-79.

10. W. W. Mendel, *Lunar Bases and Space Activities of the 21st Century,* Lunar and Planetary Institute, Houston, 1985, pp. 381-401, 465-476, 487-494, 571-580.

11. Tony V. Nero, *Guidebook to Nuclear Reactors,* U.C. Berkeley Press, 1979, pp. 9-11.

12. Eric N. Simons, *Guide to Uncommon Metals,* Hart, New York, 1967, pp. 115-121, 211-216.

13. R. F. Smallwood, *Refractory Metals and Their Industrial Applications,* ASTM Special Publications, Philadelphia, 1984, pp. 3-17, 82-105.

14. Zdenek Strnad, *Glass-Ceramic Materials,* Elsevier Publishing, New York, 1986. pp. 166-184, 207-209.

15. A. N. Zelikman, *Metallurgy of Rare Metals,* Israeli Program for Science, Jerusalem, 1966, pp. 1-7, 60-62, 439-445.

APPENDIX A

Mechanical Cutterhead Specifications

Diameter	4.0m (13ft)
Length	1m (3.3ft)
Weight	2.8MN (630kip)
No. of drive motors	6
Drive motor rating	149kW (200hp) at amperage 216A
Rotation speed	2.93 RPM
Average thrust power per cutter	93.6kW (126hp)
No. of thrust cylinders	4
Cylinder diameter	330mm (13.0in)
Stroke length	1.5m (4.9ft)
Maximum cylinder pressure	24.1MPa (3,500psi)
Average operating pressure	18.3MPa (2,650psi)
Cylinder pressure to move	4.1MPa (590psi)
No. of cutters	26
Cutter type	single disc

Cutter Specifications

	Center	Face	Gage
Rolling distance			
($m \times 10^6$)	0.05	0.78	0.77
($ft \times 10^6$)	0.16	2.56	2.53
No. of changes per 1,000ft of tunnel per cutter position	0.78	0.74	1.55
Cutter clock life (hours)	189	281	141

APPENDIX B

Equations for Internal Power Cycle

Specific heat of liquid lithium $c_p = 4.3932\text{kJ}\cdot\text{kg}^{-1}$ ($47{,}300\text{ft}\cdot\text{lb}\cdot\text{slug}^{-1}$)

Turbine power output $P = 2{,}500\text{kJ}\cdot\text{s}^{-1}$ ($1{,}840{,}000\text{ft}\cdot\text{lb}\cdot\text{s}^{-1}$)

Turbine efficiency $\eta = 0.75$

For temperature T and enthalpy h of the fluid,

$$c_p \Delta T = \Delta h$$

For $\Delta T = 450°\text{K}$ ($810°\text{R}$),

$$\Delta h = 1{,}976.94\text{kJ}\cdot\text{kg}^{-1}\ (38{,}313{,}000\text{ft}\cdot\text{lb}\cdot\text{slug}^{-1})$$

For mass flow rate $\dot{m}$,

$$\dot{m} = \frac{P}{\eta \Delta h}$$

Thus,

$$\dot{m} = 1.6861\text{kg}\cdot\text{s}^{-1}\ (0.115\text{slug}\cdot\text{s}^{-1})$$