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FEASIBILITY OF MINING LUNAR RESOURCES FOR EARTH USE: CIRCA 2000 A. D.

VOLUME II: TECHNICAL DISCUSSION

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FOREWORD

This is Volume II, "Technical Discussions", of a two volume report on lunar mining. Reported in this volume are the technologies and systems required to establish the mining base, mine, refine, and return the lunar resources to earth for use. Gross equipment requirements, their weights and costs are estimated and documented. Unfortunately, the quantitative results such as weights determined in these types of studies dealing with operations in the future have a high probability of uncertainty and should thus be observed cautiously.

Volume I, the "Summary", presents a general overview of the study and deals primarily with the broad technical and cost results along with the conclusions of the study.

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ABSTRACT

The feasibility of commercially mining the moon for minerals destined for Earth use in the early 21st Century is reported here. The study was undertaken to determine whether it might be appropriate for NASA to include in its planning, development of space technology that would be pertinent to such an undertaking. Also, the question of depleting commercially exploitable Earth mineral resources in the 21st Century is becoming of national concern, and this concept appeared as though it could be a possible solution to this problem. The results show that, within the technological constraints of this study, it would not be commercially feasible to mine, refine, and bring back to Earth lunar minerals. Their costs are approximately two orders of magnitude higher than similar Earth mineral costs for the year 2000 A.D.

A broad systems approach was used to analyze and evaluate the problem. In the performance of the study, assumptions pertaining to the available transportation systems, equipment and science technologies were made to keep them consistent with that time period. This was necessary to obtain a realistic, representative cost for the lunar minerals. All major elements associated with the establishment of the mine and refinery facilities, the mining and refining operations, and the transport system for getting the mineral back to Earth have been included in the study.

INTRODUCTION

This is Volume II of a two volume report entitled "Feasibility of Mining Lunar Resources for Earth Use: Circa 2000 A.D." and contains the analytical details. Summary information such as cost comparison of lunar materials (delivered to earth) and earth minerals are contained in Volume I. Also the general assumptions made in conducting this study are contained in Volume I.

The format used in reporting the detailed analysis here, resulting when preliminary analysis indicated the logical division of the study into five general areas. They are transportation, base construction, power generation, mineral mining and mineral refining. The analyses of these areas have included the interrelationships between the areas and the results obtained are therefore consistent for the overall study.

System of Units

The primary system of units used in this report is the metric system; although, in specific instances, the engineering systems of units are used for the sake of clarity. These instances are the cases where, through long and accepted usage, the units have become part of the industrial vocabulary, e.g., if the performance rating of material processing equipment given in "tons per horsepower-hour" were to be given in its metric equivalent as "Newton kilograms per joules" or "Newton kilograms per kilogram meters", its descriptive meaning would be lost. Therefore, the authors feel that the use of both systems of units for this report is a necessity.

TRANSPORTATION SYSTEM

So far studies of space transportation systems have concentrated on the problem of transporting a large quantity of mass away from earth orbit while returning only a small fraction of the outward bound mass back to earth. When the transportation requirements for an operation such as lunar mining are considered, it is quickly seen that, on an overall basis, much more material mass is handled within the earth return phase than within the earth-to-moon portion, even including mass requirements for base construction materials, equipment, etc. Therefore, the main concern of this transportation system analysis is to investigate the lunar surface to earth surface operational transport system; of course, the earth surface to lunar surface leg of the transport system is also considered.

Background

The mission of the transportation system is to provide an efficient, flexible and economical means of getting materials, equipment, and men to the moon to establish a lunar mining operation, to sustain the operation, and to bring the mined minerals back to earth.

Basically, for those transport activities dealing with delivering mass from earth to the lunar surface, past studies (e.g., refs. 1-6) allow us to synthesize a reasonable transport system. Examination of the results from these studies indicated that the trip is best divided into three segments: (1) earth surface to earth orbit; (2) earth orbit to lunar orbit; and (3) lunar orbit to lunar surface, with each segment having a distinct transportation vehicle optimized to perform its functional duty with minimum system cost. Therefore, the transportation system used in this study for transport of material, equipment, etc., to the moon was based on these past findings.

Past studies have not addressed the problem of returning large payloads from the moon to the earth, much less in the huge quantities considered in this study. Therefore, this segment of the transportation system required some basic analysis. But based on the relatively high specific cost of delivering material to the lunar surface, it quickly becomes evident that a conventional propulsion transportation system that is dependent on earth-delivered fuel would lead to prohibitive transport costs. Therefore, unconventional, advanced, and imaginative systems that rely on minimal earth fuel support had to be conceived. One such system chosen for detailed evaluation in this study was an electromagnetic accelerator system for imparting the major portion of the velocity requirement for earth return. Another possibly attractive idea, although not investigated in detail in this study, is to use the oxygen from the mineral refining operation in combination with hydrogen delivered from earth to provide the fuel for the lunar lander and the spacecraft carrying the minerals back to earth.

The technology for the vehicles used in the formation of the transportation system is believed to be consistent with the time setting in which a lunar mining operation may occur, circa 2000 A.D. This study has assumed that all the elements of vehicles and components necessary in putting together a transportation system are developed and available for use, with the possible exception of the Electromagnetic Launcher.

This section on Transportation System examines the above problems and the results are discussed in the following subsections. As stated above, the successful return of minerals to earth from the moon is dependent on an innovative transportation concept and thus the electromagnetic accelerator has received a large portion of the analytical emphasis. This area, that of the return transportation, still requires more study before a preferred concept can be advanced.

Velocity Requirements

Velocity requirements to get from the earth to the moon and return have been widely studied. These velocity requirements for earth-moon operations are influenced by the lunar landing site and the earth-moon orbital alinements. Plane change maneuvers to aline the lunar arrival plane and the lunar orbit plane over the landing site are required in general. These plane change maneuvers can be very costly in terms of velocity (refs. 7-11) but fortunately by using a three impulse plane change maneuver at the moon, the velocity penalty need not exceed 300 meters (1,000 feet) per second.*

Use of the three impulse maneuver does have a shortcoming in that an additional day is added to the inter-orbit operational time. This additional day results from the need to establish an elliptical tranfer orbit that will carry the spacecraft out close to the edge of the lunar sphere of influence where the plane change maneuver can be done with small velocity additions. A schematic of the operation showing where the three velocity impulses are supplied is shown in figure 2-1. References 7 and 11 treat this three impulse plane change maneuver in detail and the reader is referred to those documents for further details.

Evaluation of what impact this additional 300 meters per second (600 meters per second round trip) velocity requirement would have on the inter-orbit shuttle weight was done. The results showed that for the baseline solid core nuclear rocket used for this study, there is a 10 percent increase in the fuel requirement or a 5 percent increase in the total system weight (including payload).

The nominal velocity requirements, applicable when the earth departure plane and the lunar arrival plane (or lunar departure plane and earth arrival plane) are properly oriented, are shown in table 2-1. This trip from the earth to the moon is divided logically into three segments, as is the return trip from the moon to the earth. For going to the moon they are: (1) earth surface to earth orbit; (2) earth orbit to lunar orbit;

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* A penalty of 300 meters per second is required each time a plane change is made; e.g., if plane changes are required upon arrival at lunar orbit and at departure from lunar orbit, the total velocity penalty is 600 meters per second.

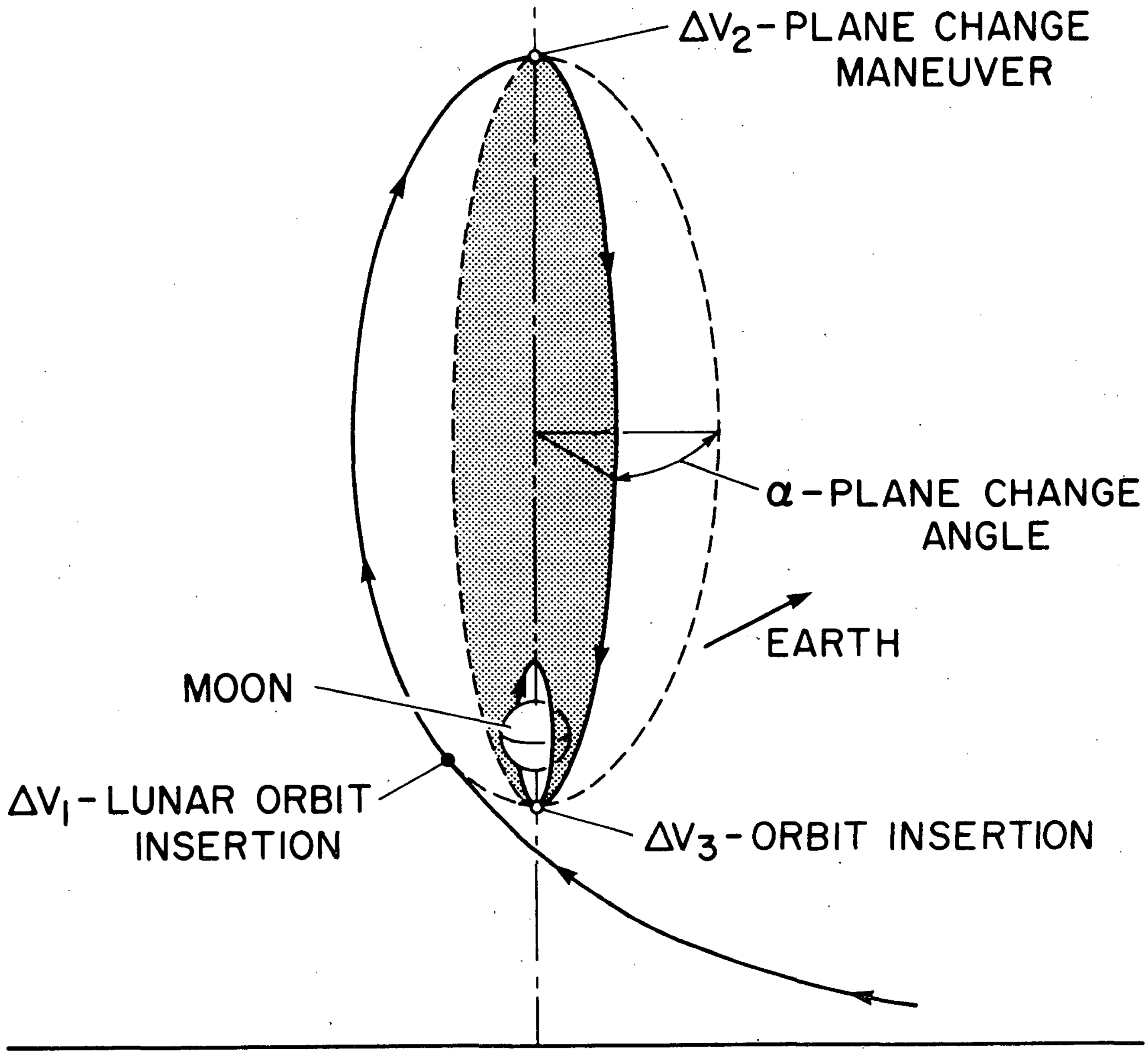

Figure 2-1 Three Impulse Maneuver Schematic.

TABLE 2-1. NOMINAL VELOCITY REQUIREMENTS FOR EARTH-MOON TRIPS

Earth to Moon Operations		Moon to Earth Operations	
Transportation Leg	Total Vel. MPS (a)	Transportation Leg	Total Vel. MPS
Earth Surface to Earth Orbit	9,140 (30,000)[b]	Lunar Surface to Lunar Orbit	2,010 (6,600)
Orbital Velocity	7,740	Ascent	1,740
Gravity Losses	1,340	Gravity Losses	240
Rendezvous & Docking	60	Rendezvous & Docking	30
Earth Orbit to Lunar Orbit	4,240 (13,900)	Lunar Orbit to Earth Orbit	4,270 (14,000)
Translunar	3,260	Transearth	920
Midcourse	30	Midcourse	30
Lunar Orbit Insertion	920	Earth Orbit Insertion	3,260
Rendezvous & Docking	30	Rendezvous & Docking	60
Lunar Orbit to Lunar Surface	2,190 (7,200)	Earth Orbit to Earth Surface	(NA)[c]
Separation & Deorbit	30	Deorbit	180 (System Dependent)
Descent	1,740	Terminal Descent	
Gravity Losses	240	Touchdown	
Touchdown	180		

(a) MPS - meters per second.
(b) Numbers in parenthesis are feet per second.
(c) NA - Not applicable

and (3) lunar orbit to lunar surface and for the return trip from the moon to earth, they are: (1) lunar surface to lunar orbit; (2) lunar orbit to earth orbit; and (3) earth orbit to earth. The velocity requirement for each leg contains the normal delta velocity required for such things as gravity losses (earth to moon), course correction, orbit insertion (at moon or earth), rendezvous, separation and phasing, in addition to the normal earth orbital, trans-lunar, lunar landing, lunar orbital, trans-earth, and earth landing velocities.

Description of Earth to Moon Transportation System

The transportation vehicles described in this section are those used to transport materials, supplies, equipment, men, etc., on the trip from the earth to the moon. The three legs of the trip have been described earlier and each of these three legs will have a different spacecraft as the transport vehicle, and each vehicle has been optimized for providing the transport capability for that particular leg. Some of the considerations leading to the choice of vehicle types are described in the following subsections. The cost of the overall, as well as the individual, legs is summarized in the last subsection.

Earth Launch System. - The Earth Launch System is required to provide a total velocity of 9,140 meters (30,000 feet) per second to raise the payload from the earth's surface into an equatorial orbit of about 500 kilometers (270 nautical miles). Protective requirements from the launch environment for the payload during the launch phase, plus expected improvements to the space shuttle from that currently being developed, lead to a conclusion that a space shuttle type vehicle would be used. Also, safety and environmental considerations restrict the use of noxious or nuclear fuels for the earth launch operations.

The current space shuttle being developed is far from the most economical launch system from operational cost considerations, but is a concept that has been chosen to minimize the developmental cost. As R&D money becomes available, a more economical two-stage fully reusable shuttle system as originally configured would become a reality. In fact, the development of this newer system is expected to be completed well before the time period setting of this study. This new second generation space shuttle is the launch vehicle assumed for this study.

This second generation space shuttle is expected to have performance capabilities that would at least match those of the current shuttle, e.g., payload capability to a 500 kilometer orbit would be about 22,700 kilograms (50,000 pounds). Payload delivery costs should be reduced from the current expected cost of $300-400 per kilogram ($150-200 per pound) to around $20-200 per kilogram ($10-100 per pound), with the actual cost expected to tend towards the lower cost figure.

The Earth Launch System, composed of a fully reusable second generation shuttle, will be used extensively in the base construction phase and to lesser amounts in refurbishing the base and equipment during the operational phase. During the base construction phase, upwards of 5 to 12 million kilograms (10 to 25 million pounds) of cargo will be delivered. The cargo weight covers the equipment and construction requirements for establishing the lunar base and power station as well as the mining and refining operations. In addition, as little as one million and as much as 90 million kilograms of equipment associated with the moon to earth mineral transportation system will have to be delivered to the moon also.

Launch requirements for sustaining the mining operations are expected to be nominal. This is contingent on the assumption that the mineral richness is on the order of 10 percent or better, or that the equipment refurbishment requirement for the mineral dressing process follows the minimum curve in figure 6-3 (Section 6). Based on the foregoing, launch rates of two to three launches per month should suffice--a task that should be easily scheduled with the other shuttle launch tasks.

<u>Earth Orbit to Lunar Orbit Transport System</u>. - For this portion of the transportation leg, the choice of propulsion is broadened to include nuclear as well as noxious chemicals, such as fluorine. Currently, the

operational propulsion technology experience is almost exclusively in the conventional chemical propellants such as LOX-LH_2, LOX-RP, and N_2O_4-UDMH with limited nuclear propulsion experience from component testing in the nerva nuclear engine program. No operational fluorine rocket engine exists but there is a wealth of testing experience from experimental programs, for example, at NASA's Lewis Research Center.

Tradeoffs of these propulsion systems is not the goal here, but rather the goal is to project a likely system that would be developed by the time period in which lunar mining might occur. Examination of the literature related to this subject indicates that the system to be developed will be largely dependent on the space program itself. If a vigorous space program is carried forth, then nuclear propulsion systems would likely be in common usage. The study has assumed that nuclear systems will be used.

There are three classes of nuclear propulsion systems being studied currently; they are the solid core nuclear rocket, gaseous core nuclear rocket, and fusion rocket. Their possible availability in the future also follows that order. The solid core nuclear rocket has been in development for several years and could be made operational in a few years, whereas the gas core and fusion rockets are still only theoretical concepts. Studies such as references 12, 13, and 14 extol the tremendous potential of the gas core and fusion rockets but a comparison of the solid core, gas core, and fusion rockets in reference 12 indicates the fusion rocket is not feasible for lunar operations because of its low thrust levels. That reference also shows that the gas core rocket will require 13-35 percent less initial mass (as the payload increases the percentage increases) in earth orbit than the solid core nuclear rocket. This weight savings results from fuel economy resulting from the high Isp's (1,500-3,000 seconds) for the gas core rockets (versus solid core rockets with Isp's of 825 seconds). But inert weights for the gas core rockets are expected to be 23-36 percent higher than the solid core rocket. This leads to the realization that the advantage of the higher performing gas core rockets diminishes with decreasing fuel cost (delivered cost in Earth orbit) because the cost advantage of using less fuel will decrease and the higher hardware cost of the gas core rocket will override the fuel cost savings. Also, hardware weights tend to increase as a system proceeds from theoretical studies through research and development phases; thus, the gas core rocket weight disadvantage will increase and the slight cost advantage it has over the solid core may erode completely.

Therefore, based on the above, the baseline nuclear system chosen for this portion of the study is the solid core nuclear rocket (Nerva type) with an Isp of 825 seconds.

The payload size for the inter-orbit shuttle was baselined to 136,000 kilograms (300,000 pounds) based on the optimization study result in reference 1 and practical constraints associated with the earth shuttle launch requirements. Associated with the payload of 136,000 kilograms to be delivered to lunar orbit and returning the nuclear rocket to earth orbit is a fuel requirement of 231,000 kilograms (510,000 pounds) for the inter-orbit shuttle. A total of sixteen earth shuttle launches is required to orbit this amount of payload and fuel. At the rate of a shuttle launch per day (current turn-around time anticipated for the earth shuttle is two weeks), the inter-orbit shuttle or the payload will be required to wait in earth orbit for two weeks. As the wait time in orbit increases, other problems such as additional meteoroid protection for the payload and fuel (hydrogen) boil off have to be considered. All these factors were considered in arriving at the payload size of 136,000 kilograms.

The weight breakdowns and costs for an expendable and reusable nuclear orbit to orbit vehicle system are shown in table 2-2. The results shown in this table have been derived from data presented in references 1-5. Note that the total weight for the reusable case is 43 percent heavier. This additional weight reflects the larger tanks and additional fuel required to return the vehicle from lunar orbit to earth orbit, the additional meteroid protection required, and the need of an additional engine to maintain a reasonable initial thrust-to-weight ratio of 0.15.

TABLE 2-2. SOLID CORE NUCLEAR (Isp-825 sec)
INTER-ORBIT SHUTTLE COSTS

	Earth Orbital Cost	
	$22/kg	$220/kg
Expendable		
Total Cost	$61,260,000	$95,100,000
Engine	15,000,000	15,000,000
Subsystems	21,800,000	21,800,000
Airframe	2,700,000	2,700,000
Management (a)	18,000,000	18,000,000
Delivery to Orbit	3,760,000	37,600,000
Payload Delivery Cost From Earth Orbit to Lunar Orbit	$450/kg ($200/lb)	$700/kg ($320/lb)
Reusable		
Unit Cost - Total	$66,610,000	$79,750,000
Engine	30,000,000	30,000,000
Subsystems	31,000,000	31,000,000
Airframe	4,150,000	4,150,000
Delivery to Orbit	1,460,000	14,600,000
Total Cost Per Flight (b)	17,031,000	66,675,000
Propellant (c)	5,370,000	53,700,000
Management (a)	5,000,000	5,000,000
Unit Amortization	6,661,000	7,975,000
Payload Delivery Cost From Earth Orbit to Lunar Orbit	$125/kg ($60/lb)	$490/kg ($220/lb)

(a) Includes program management, system engineering, and vehicle and payload integration.

(b) The total cost assignable to each flight based on 10 reuses per unit.

(c) Includes cost of propellant and propellant delivery cost to earth orbit.

The operational plans are to abandon the vehicle after arrival in lunar orbit for the expendable case and to return just the nuclear stage to earth orbit for reuse in the reusable case. Propellant tanks for the reusable case will be jettisoned as they are emptied on the way to the moon. Those propellant tanks that supply fuel for lunar orbit insertion, lunar orbit departure, and earth orbit insertion maneuvers will be permanent parts of the nuclear vehicle stage. This procedure for the reusable case will help to minimize the total meteoroid protection requirement and thus help to reduce the overall operational cost.

Comparing costs in table 2-2 shows that the cost advantage for the reusable case is overwhelming (3:1) when the earth orbit delivering cost is $22 per kilogram ($10 per pound), but this advantage slips to 4 to 3 when earth orbit delivery cost is $220 per kilogram. Cost advantage for the reusable system shows the direct relation it has with the cost of supplying the fuel necessary for returning the stage from lunar orbit to earth orbit. That is, as fuel cost increases, the cost of retrieving the empty stage increases and the advantage of reusing the stage decreases and in extreme cases it may become more cost-effective not to reuse the stage. It appears that when delivery costs into earth orbit go above $220 per kilogram, reuse for the size stage considered in this study becomes undesirable.

Lunar Landing System. - The requirement here is to land the payload placed in lunar orbit by the inter-orbit transport system (described in the previous subsection) on the lunar surface. The vehicle to be called the lunar tug will have as its primary goal or function the chore of carrying the maximum load down to the lunar surface and flying up to lunar orbit essentially empty. This vehicle will use a LOX-LH_2 propulsion system with proper cryogenic propellant tanks and have a cargo bay equivalent in dimensions to that of the earth orbital shuttle. Also, its payload capability (landing) will match that of the shuttle (nominally 22,700 kilograms). LOX-LH_2 propulsion was assumed for use on this transportation leg to minimize the possibility of contaminating the lunar environment and also because of its high performance.

The lunar tug has the weight breakdown as shown in table 2-3 and its accompanying costs are summarized in table 2-4. The data used in arriving at these weight and cost values were from references 3 and 6. As seen in table 2-5, the delivery cost for this portion of the transportation leg is strongly influenced by the initial earth orbital and the inter-orbit delivery costs. This dependence results primarily from the propellant used in the landing maneuver. Approximately one kilogram of propellant is used for each kilogram of payload landed.

The tug is fueled in lunar orbit with enough fuel to land 22,700 kilograms of cargo on the lunar surface and to fly only itself back into lunar orbit for another landing cycle. Obviously, if the tug is fueled both on the lunar surface and in lunar orbit, the tug will be able to orbit as well as land payloads. If this fueling procedure is used, the payload capability becomes approximately 27,200 kilograms (60,000 pounds) in both directions. The cost for the propellant used in delivering payloads to orbit will cost $550 per kilogram ($250 per pound) because the fuel must first be delivered to the lunar surface, whereas the landing fuel is delivered to lunar orbit at a cost of $150 per kilogram. Use of oxygen obtained from lunar soil could partially alleviate this high fuel cost and this possibility is discussed in the next subsection.

Earth to Lunar Surface Transportation Cost. - The cost of payload delivered on the lunar surface is obtained by summing the cost of the three individual legs discussed individually in the preceding subsections. A summary of these costs is shown in table 2-5.

Earth orbital costs of $220/kilogram are a currently sought after goal. Therefore, with some optimistic projection on traffic and reuse technology, it is not implausible that costs of around $22 per kilogram could be attained in the time frame being discussed in this study; the choice of $22 per kilogram as the earth orbital costs is based on this premise. The inter-orbit and lunar landing costs are not as well defined because the systems used for these transportation legs have not been as extensively studied as the transport system for the earth orbital

TABLE 2-3 LUNAR LANDER TUG - WEIGHTS[a]
($LOX-LH_2$)

	Kilograms	Pounds
Total Weight	46,330	(102,000)
Propellant[b]	33,400	(73,600)
Residuals, Reserve, etc.	910	(2,000)
Crew Module	4,760	(10,500)
ACPS & Astrionics	1,950	(4,300)
Landing Gear	2,360	(5,200)
Propulsion Module (Engines & Propellant Tanks)	2,950	(6,500)

TABLE 2-4 LUNAR LANDER TUG - COSTS[a]
(Lunar Orbit to Lunar Surface)

	Earth Orbital Cost	
	$22/kg	$220/kg
Unit Cost Total	$35,900,000	$42,900,000
Crew Module	11,000,000	11,000,000
ACPS & Astrionics	10,000,000	10,000,000
Landing Gear System	4,000,000	4,000,000
Propulsion Module	9,000,000	9,000,000
Delivery to Lunar Orbit	1,900,000	8,900,000
Total Cost Per Flight[c]	8,520,000	27,390,000
Propellant[d]	4,930,000	23,100,000
Unit Amortization	3,590,000	4,290,000
Payload Delivery Cost From Lunar Orbit to Lunar Surface	$375/kg ($170/lb)	$1200/kg ($550/lb)

(a) Based on payload delivery capability of 22,700 kilograms (50,000 pounds) from lunar orbit to lunar surface.

(b) Propellant is divided into 26,300 kilograms (57,900 pounds) for landing and 7,120 kg (15,700/lb) for orbiting the tug.

(c) Based on 10 reuses.

(d) Initial propellant cost is overwhelmed by delivery cost.

TABLE 2-5 EARTH-MOON TRANSPORTATION COST

Earth to Earth Orbit	\$ 22/kg (\$ 10/lb)	\$220/kg (\$100/lb)
Earth Orbit to Lunar Orbit	126/kg (57/lb)	472/kg (214/lb)
Lunar Orbit to Lunar Surface	375/kg (170/lb)	1208/kg (548/lb)
Total Cost Landed on Moon	~\$550/kg (\$250/lb)	\$1900/kg (\$862/lb)

segment. Therefore, the costs for these systems have a higher degree of uncertainty associated with them.

Note that the cost shown in table 2-5 increases rapidly with each succeeding leg reflecting the cost accumulated from each preceding transport leg in delivering both vehicle and propellant used for that transport leg, which in turn influences the payload delivery cost for that transport leg. For example, the propellant cost for the earth orbital LOX-LH_2 vehicle is about \$.22 per kilogram of fuel oxidizer mixture, but the propellant cost for the second leg, from earth orbit to lunar orbit, increases to \$22 per kilogram (the cost of delivering the fuel into earth orbit) and the propellant cost for the lunar landing leg is \$148 per kilogram (\$67 per pound) (reflecting the cost of delivering the fuel to lunar orbit). The propellant cost is seen to increase almost three orders of magnitude in going from earth surface to lunar orbit. Further, the propellant cost on the lunar surface becomes \$550 per kilogram (\$250 per pound); which means lunar surface to lunar orbit operations will be four times more expensive than the landing operations and therefore the use of chemical propulsion for this operation should be avoided. The mass landed is only a small fraction of the mined mass. This influences the unit cost per kilogram of mineral fractionally whereas the use of this transportation system for orbiting the mined material would add the orbiting cost per kilogram directly to the cost of the mineral.

Lunar Oxygen as Propellant for Lunar Tug: The high propellant cost for the lunar landing tug could be partially reduced by fueling it with native oxygen from the moon. This possibility has not been factored into the economic analysis elsewhere in this study because the oxygen as a by-product of the mineral refining process would not be available in the initial base establishing phase. But this discussion is included to point out a possible method of reducing the sustaining cost for the lunar mining base.

Abundant oxygen will be produced from the mineral refining process during the oxide reduction process, and it would be rather easy to set up a process to take the oxygen from the mineral refining process and purify and liquify it for use both as propellant and in sustaining base operations. The cost of this oxygen will depend primarily and directly on the electrical cost on the moon and to a lesser degree on the cost of the equipment required for this process (delivered on the moon). Cost of electricity generated on the moon is expected to be about three to ten times the cost of electricity generated on earth. If it is assumed that the ratio of cost for oxygen follows that of the electricity, then the cost of the oxygen produced on the moon should not exceed $1.10 per kilogram ($.50 a pound); a trivial cost in comparison to the $550 per kilogram ($250 per pound) it costs to deliver a kilogram of oxygen to the lunar surface. If it is assumed that the preceding is possible, the propellant cost of the lunar landing and lunar orbital operations can be reduced substantially.

If lunar oxygen is to be used, the operational mode for the lunar tug must be modified. The lunar tug is now expected to carry the oxygen it will use in the landing maneuver up into orbit. In order to accomplish this, the tug will use more hydrogen than in the nominal case. Calculations showed that although an increase in landed hydrogen weight is required, this is more than offset by the elimination of the oxygen that was previously landed for use in flying the empty tug to orbit. The result is a net decrease in the landed propellant weight of about 4,550 kilograms (10,000 pounds).

The propellant costs for the landing and orbiting maneuvers can be obtained along with the costs for hydrogen landed on the lunar surface and lunar-manufactured oxygen delivered into lunar orbit, by stepping through the following four equations sequentially until the results converge.

$$C_{pDn} = \frac{K_1\ C_H + K_2\ C_{on}}{K_1 + K_2} \quad \text{(Average cost of landing fuel)}$$

$$C_{Hn} = C_H + K_3\ C_{pDn} \quad \text{(Cost of delivering hydrogen to lunar surface)}$$

$$C_{pun} = \frac{K_1\ C_{Hn} + K_2\ C_o}{K_1 + K_2} \quad \text{(Average cost of orbiting fuel)}$$

$$C_{on} = C_o + K_4\ C_{pun} \quad \text{(Cost of lunar oxygen delivered to lunar orbit)}$$

where

- K_1 = Hydrogen proportionate weight determined by mixture ratio.
- K_2 = Oxygen proportional weight determined by mixture ratio.
- K_3 = Ratio of kilograms of propellant required to land a kilogram of payload (0.881).
- K_4 = Ratio of kilograms of propellant required to orbit a kilogram of oxygen (.928).
- C_H = Constant (initial cost of hydrogen delivered to lunar orbit, $150).
- C_o = Constant (cost of oxygen manufactured on the moon, $1.10/kg).

A value for the cost of oxygen in lunar orbit has to be initially assumed to start the iteration. When converged, the propellant costs for the landing maneuver are, hydrogen $150 per kilogram ($70 per pound) and oxygen $27 per kilogram ($12 per pound) and for the orbiting maneuver they are hydrogen $190 per kilogram ($85 per pound) and oxygen $1.00 per kilogram. Or as weighted values in terms of a kilogram of propellant using a propellant mass mixture ratio of 6 to 1, the landing maneuver propellant cost is $45 per kilogram ($20 per pound) and the orbiting maneuver propellant cost is $17.50 per kilogram ($12.50 per pound).

The weight breakdown using lunar oxygen is shown in table 2-6. All the inert weights and payload are assumed unchanged from table 2-3. The weight for the propulsion module does not change because the weight is predicated on a design propellant capacity of 40,000 kilograms (90,000 pounds). See ref. 13. As seen by comparing the gross weights in tables 2-3 and 2-6 at the point where the tug is in orbit just prior to landing, the use of lunar oxygen is seen to reduce the gross weight by 7,260 kilograms (16,000 pounds).

Comparison of tables 2-4 and 2-7 shows that the propellant costs are substantially reduced. They are reduced from $4,930,000 to $1,535,000, a reduction of 69 percent. Unfortunately the unit (hardware) amortization cost is also on the same order of magnitude as the propellant cost; therefore, the net reduction in the lunar orbit to lunar surface landing cost is 40 percent ($225 versus $375 per kilogram).

These results indicate that the use of lunar oxygen to supply part of the propellant requirements in the operational phase should be a consideration.

Lunar Payload Launch

The logistics problem associated with lunar mineral transportation is significant. Even in a mining operation which continues long enough to amortize the capital investments, the return transportation charges may dominate the entire operation. There are a number of schemes which might be used to launch lunar payloads, including chemical, electromagnetic, and even laser. These are described and compared later.

In the case of a chemical system, the payload would probably be boosted to lunar orbit where it would rendezvous with an inter-orbit tug.

TABLE 2-6 LUNAR TUG WEIGHT BREAKDOWN USING LUNAR OXYGEN

	Kilograms	Pounds
Landing		
Total Weight	61,720	(136,000)
Propellant	23,500	(51,800)
Residuals, Reserve, etc.	910	(2,000)
Crew Module	4,760	(10,500)
ACPS & Astrionics	1,950	(4,300)
Landing Gear System	2,360	(5,200)
Propulsion Module (Eng. & Propellant Tanks)	2,950	(6,500)
Payload	22,700	(50,000)
Hydrogen for Orbiting	2,590	(5,700)
Orbiting		
Total Weight	51,230	(113,000)
Propellant	18,100	(39,900
Residuals, Reserve, etc.	910	(2,000)
Crew Modules	4,760	(10,500)
ACPS & Astrionics	1,950	(4,300)
Landing Gear System	2,360	(5,200)
Propulsion Module (Eng. & Propellant Tanks)	2,950	(6,500)
Oxygen for Landing	20,200	(44,600)

TABLE 2-7 LUNAR TUG COSTS USING LUNAR OXYGEN

Total Cost Per Flight	$5,126,000
Propellant (Landing)	1,035,000
Propellant (Orbiting)	500,000
Unit Hardware Amortization	3,591,000
Payload Delivery Cost – Lunar Orbit to Lunar Surface	$225/kg ($102/lb)

Having arrived at earth, it would be candidate for direct entry or would be retroed to orbit velocity and transferred to earth in a shuttle. A payload accelerated directly to escape velocity from the lunar surface might be targeted for direct entry at the earth, saving the costly retro penalty into earth orbit. Some guidance would almost certainly have to be provided, and some method of synchronizing the entry with the earth's rotation would be necessary. Dropping the payloads into the ocean, say, on the continental shelf, would probably prove feasible, but payload recovery would undoubtedly be easier and cheaper in a remote area such as the desert. Temporarily assuming that the logistics problems can be managed, this section of the report will concentrate only on the methodology for lunar payload escape.

The velocity required to achieve lunar orbit is about 1740 meters per second while the escape velocity is 2900 meters per second (excluding gravity losses). One fundamental question that should, but cannot readily, be answered has to do with the maximum acceleration allowable. If the device is to be capable of transporting men as well as raw material, it should probably be designed for no more than ten g's. A considerable savings can be made in acceleration distance, however, if the acceleration level is higher. Figure 2-2 shows distance requirements versus acceleration level as taken from the relationship:

$$d = \frac{1}{2} at^2$$

where $v = at$
and hence:

$$d = \frac{1}{2} \frac{v^2}{a}$$

The kinetic energy in the projectile, found from $E = \frac{1}{2} MV^2$, is 1.036 kilowatt-hours per kilogram and 0.397 kilowatt-hours per kilogram for the 2,900* meters per second and 1,740* meters per second (9,000 ft/sec and 5,500 ft/sec) velocities respectively.

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* See table 2-1 for gravity losses, rendezvous docking, etc. requirements.

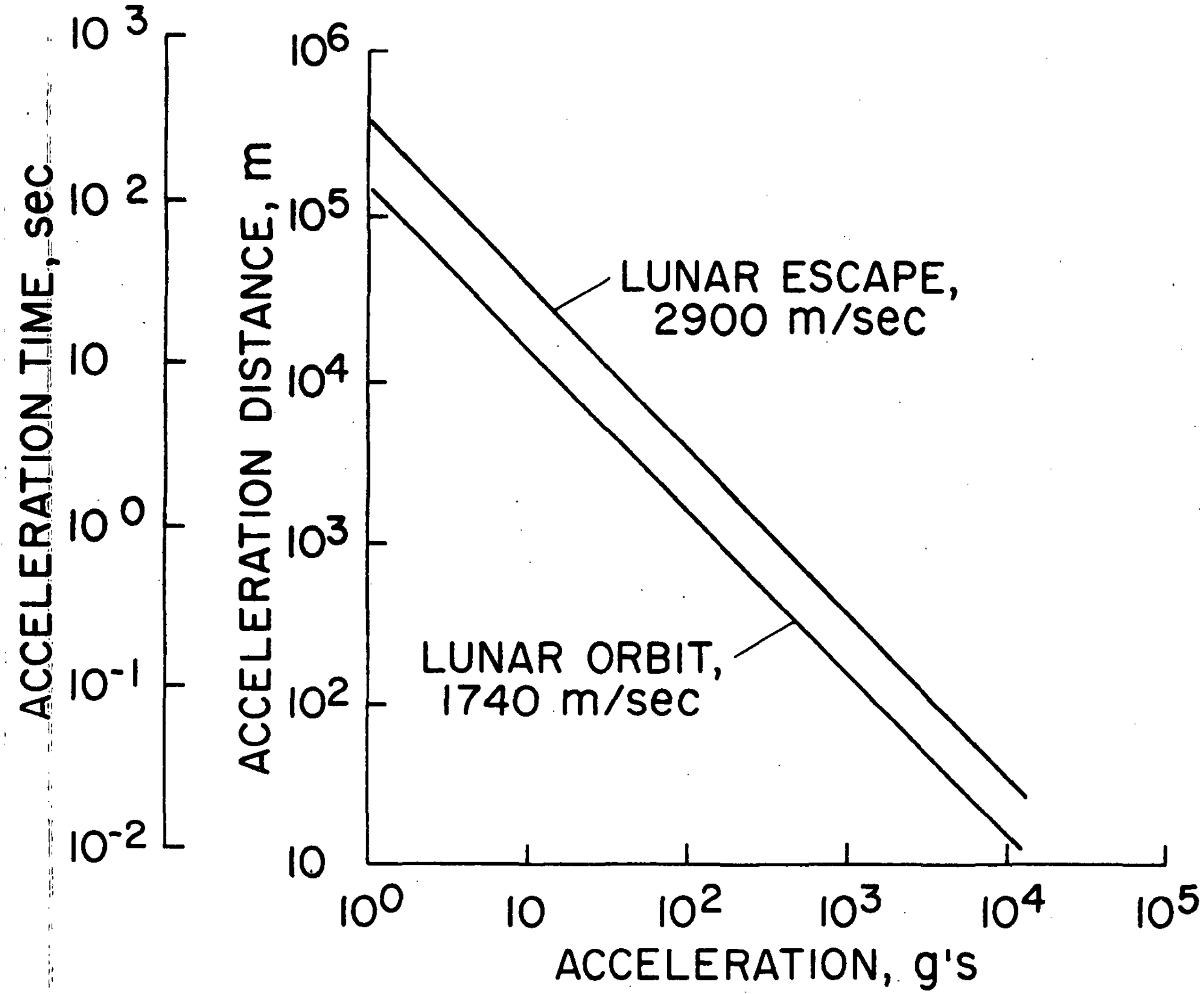

Figure 2-2 Time and Distance Requirements for Lunar Payload Acceleration.

Most of the materials of interest are consumed worldwide at rates between 4.5×10^6 and 4.5×10^{10} kilograms per year (10^7 and 10^{11} pounds/year). This amounts to between 1.36×10^4 and 1.36×10^8 kilograms (3×10^4 and 3×10^8 pounds) per day which would seem to imply that daily launching would be a requirement. This lower number will be used as a baseline, with the assumption that it can be scaled in both directions.

For a given launch energy all launch sites will be along a particular minor circle located on the lunar surface. To achieve minimum energy, the associated minor circle is located on the moon's leading face. It is assumed here that the launch site will be located near this minor circle.

It goes without saying that the criteria for selecting a payload return system is strictly cost. It is just that factor that makes the conventional chemical system unattractive, as shown below. The costs of the other systems are very difficult to obtain since none has been built (or even studied in any detail) on the scale and with the environmental considerations appropriate for a lunar mining operation. It is obvious that some new technology will be required to make large scale lunar payload return economically viable. On the basis of the best kind of assumptions that can be made at this time, the following descriptions and comparisons are offered.

<u>Chemical Rocket Launch</u>. - It is a simple matter to approximate the amount of fuel required for a chemical rocket with the rocket equation:

$$V = I_{sp}\, g \ln \frac{Wo}{W_{bo}} \qquad \text{(ref. 15)}$$

where V is the change in velocity

I_{sp} is the fuel specific impulse

g is the gravitational constant

Wo is the take off weight

W_{bo} is the burn-out weight

If V is to be 2,900 meters (9,000 feet) per second and I_{sp} is 400 sec, Wo/W_{bo} is approximately 2.0; that is, the weight at take-off is about one-half composed of fuel weight. The advantage of a chemical system is, of course, that it is technologically, completely available. There are few uncertainties in the operational procedure. The only difficulty is that each pound of fuel delivered to the moon will cost at least $550 per kilogram ($250 per pound). This means that even if it were possible to ignore structure, heat shield, guidance, and other operational facilities, it would still cost, at minimum, $550 to deliver a kilogram of payload to the earth. Economic viability will require another approach.

Electromagnetic Propulsion. - A number of schemes have been proposed which could accelerate payloads to high velocity electrically, thereby eliminating or reducing the need for expendable fuel. These schemes are especially appropriate in the lunar vacuum, although the advantage of no air resistance is partially cancelled by the lack of a source of gas for air bearings. The approaches that might be used take advantage of reacting magnetic fields and include linear induction motors and direct current devices. These are described below.

Linear Induction Motors: The linear induction motor operates on the same principle as a standard electric motor; a changing magnetic field in the primary winding (or stator) causes motion of the secondary (or rotor) by virtue of an induced magnetic field within it. There is no need, however, for the members to be cylindrical and, in fact, schemes for stretching the device out linearly were suggested before the turn of the century. When the motor is made to act linearly rather than rotationally, it is only reasonable to make one of the two members short while the other extends over the distance of movement. Typically, the moving member is the smaller one, and for the sake of simplicity, it is the smaller one that contains the primary windings. (Some theory and background on linear induction motors can be found in references 16-20 and Appendix A.)

RAE Electric Launcher: The techniques of extracting an accelerating force from magnetic fields are quite varied. One such technique was explored to the prototype stage by the Royal Aircraft Establishment (RAE) in 1954 (ref. 21). The purpose was to accelerate projectiles to high speed for aerodynamic testing. This particular device took advantage of the force experienced by a current carrier in a magnetic field. The equation for the force is:

$$F = \int i \, d\vec{l} \times \vec{B} \text{ (newtons)}$$

where l = conductor length (meters)
B = magnetic field strength (webers/m^2)
and i = current (amps)

The prototype device sent a sliding conductor between two perpendicular current carriers. It is shown diagrammatically in figure 2-3. If the launcher is very long and devoid of friction, the speed of the projectile will be limited as the back emf is equaled by the emf of the armature circuit. The field circuit was designed for 260,000 amps current and the armature circuit for 60,000 amps. Twelve hundred 600 amp-hour batteries were used to supply the energy, with the design point being 12,500 amps per cell for about 0.1 sec at between 1.02 and 1.09 volts.

The argument is made by the authors that permanent magnets, rather than a field current, could be used to provide the required magnetic field, hence, the efficiency is only a function of the armature circuit. The energy balance, on this basis, was given as:

Copper Losses	132,700 joules
Work Against Drag	19,400 joules
Armature Kinetic Energy	27,650 joules
Energy in Arc at Muzzle	7,970 joules
Total Energy	187,720 joules

with the resultant efficiency being 14.5 percent. If, on the other hand, the total energy expended is taken into account, it is necessary to compare

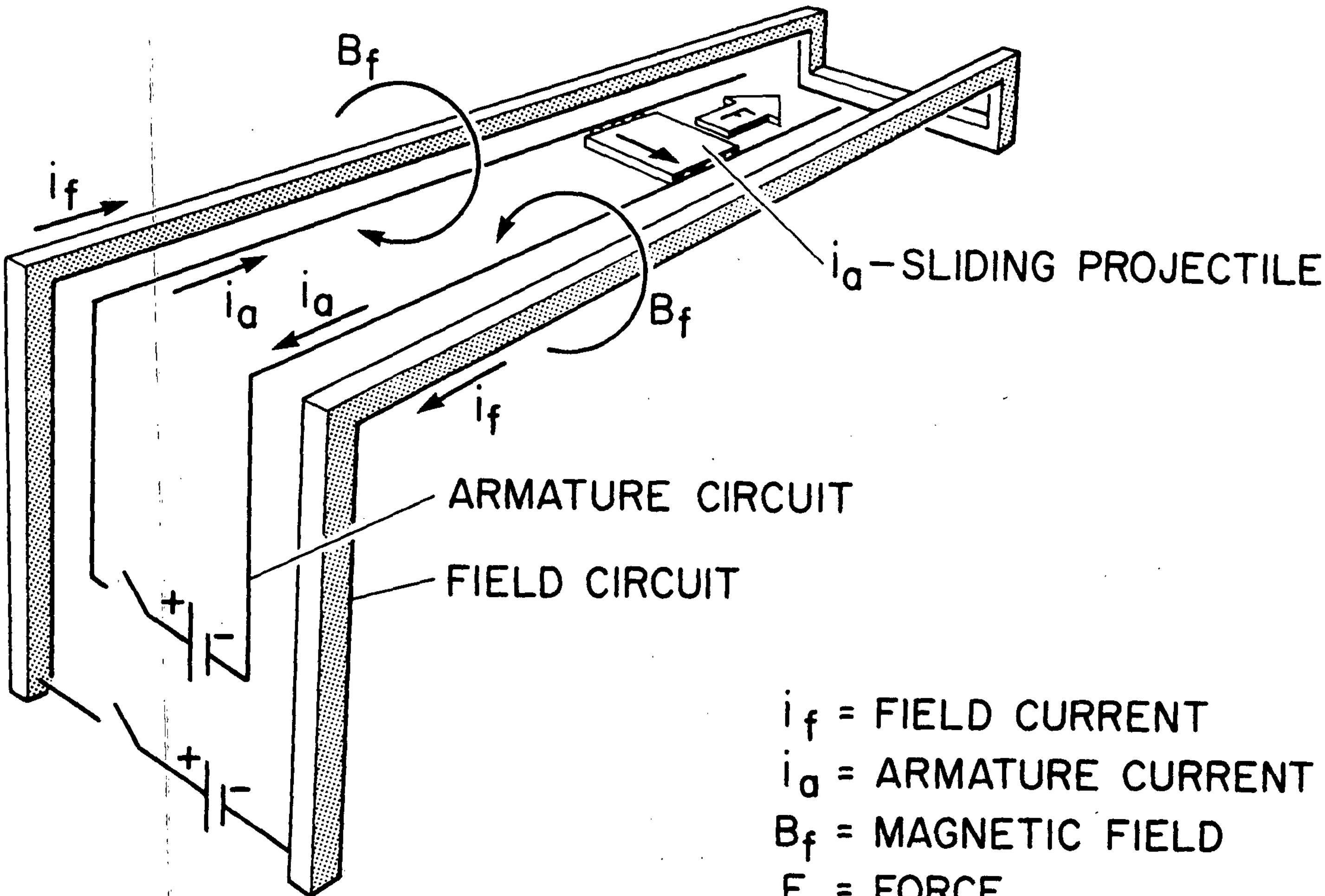

Figure 2-3 RAE Electric Launcher.

the 27,650 joule armature kinetic energy with approximately 1.5×10^6 watt seconds of electrical energy dissipated for an efficiency of only 2 percent.

The system built was composed of a 19 meter (62 foot) long chute maintained to about ±.0127 cm (±.005 in.) accuracy, about 54,400 kg (120,000 lb) of batteries, and perhaps another 22,700 kg (50,000 lb) of switches, controls, cables, bus bars, etc. The projectile, which weighed about 0.738 kg (1 lb, 10 oz), was accelerated to velocities up to about 457 m/sec (1,500 ft/sec).

Sliding Coil Accelerator: For the purpose of simulating aerodynamic entry at hyper-velocities, NASA investigated what is perhaps the most efficient way of utilizing magnetic forces with a sliding coil accelerator (ref. 22).

The method employs a coil of relatively few turns which slides over a slightly smaller, but much longer, fixed coil. A small test apparatus was built with a stationary coil 25 cm long and 1.9 cm diameter. The configuration is shown in figure 2-4. With electrical energy dissipation through the moving coil, heating becomes one of the primary limitations on the maximum velocity attainable. The payload must be capable of absorbing much of the heat generated. The test device was powered by a capacitor bank capable of storing 5,000 joules. A 0.003 kg projectile was propelled to velocities up to 420 meters per second. The acceleration was, therefore, over 3,000 g's and the kinetic energy of the moving coil about 0.6 joules. Even though not all of the capacitor energy is utilized, the efficiency is apparently very low.

It was calculated in reference 22 that an accelerator capable of sending a similar projectile to 20 km/sec would be about 40 meters long and would require a capacitor bank of 4×10^{-3}f at a charging voltage of 3.5×10^4V, for a total stored energy of 2×10^6 joules. At a final velocity of 20 km/sec (65,000 ft/sec), the kinetic energy of the projectile

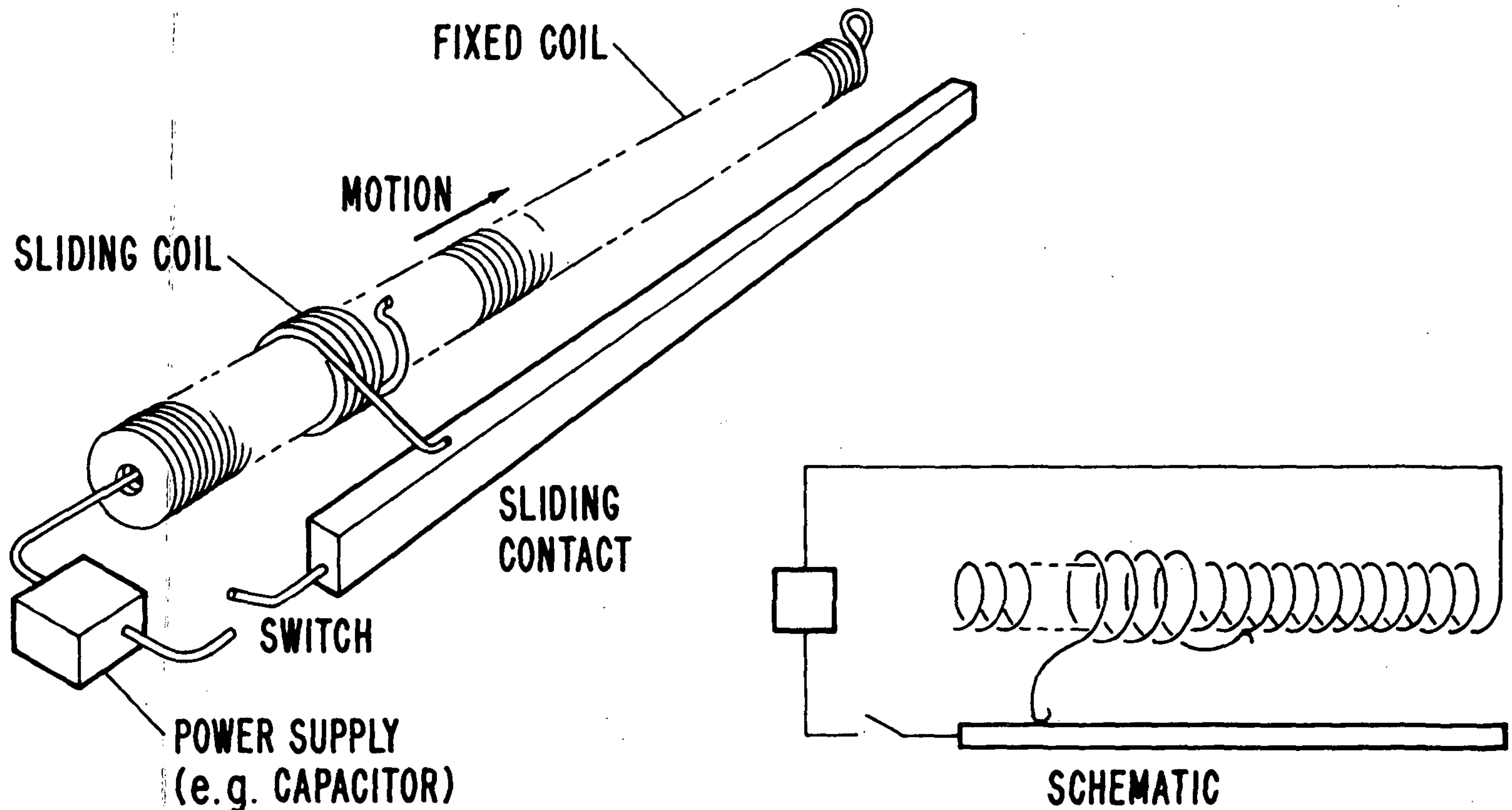

Figure 2-4 Sliding Coil Accelerator.

would be 6×10^5 joules, for a calculated 30 percent efficiency. A pictorial view of a coil for a lunar launch system is given in figure 2-5. Detailed design data is contained in Appendix A as constructed from references 22 to 25.

Laser Propulsion. - A system which has been proposed for earth escape boosters would also be appropriate on the moon. This technique makes use of a high powered laser flux to greatly increase the temperature, and hence specific impulse of a propellant. One scheme would use the high powered laser to ablate a solid propellant; another would heat seeded hydrogen in a more or less conventional nozzle. These methods are described by Kantrowitz and Rom in references 26 and 27.

Both Kantrowitz and Rom expect I_{sp}'s on the order of several thousand seconds. Using the rocket equation again ($\Delta V = I_{sp}\, g \ln Wo/W_{bo}$), it can be shown that with a velocity increment of 2,900 meters (9,000 ft) per second and an I_{sp} of 3,000 sec, the initial to final mass ratio is only 1.09, at 2,000 sec it is 1.15 and at 1,000 sec it is still only 1.32. The advantage over a conventional chemical rocket is evident since the weight of fuel required can be reduced from one kilogram per kilogram of payload to only one-tenth kilogram per kilogram of payload. This implies a fuel cost of \$55 per kilogram (\$25 per pound) of payload.

In addition to presently unknown interaction mechanisms between a laser beam and a propellant plasma, an important difficulty lies with the laser generator itself. Laser efficiency is presently very low, typically a few percent at best, and none have been built yet of sufficient size and operational duration capability.

It does not seem far-fetched to expect high powered lasers with a 20 percent operating efficiency, and the time, distance, and pointing constraints seem to be within reason in the time frame considered. Figure 2-6 shows a general schematic of an earth based laser launch vehicle (ref. 27) which would be similar to a lunar launch system.

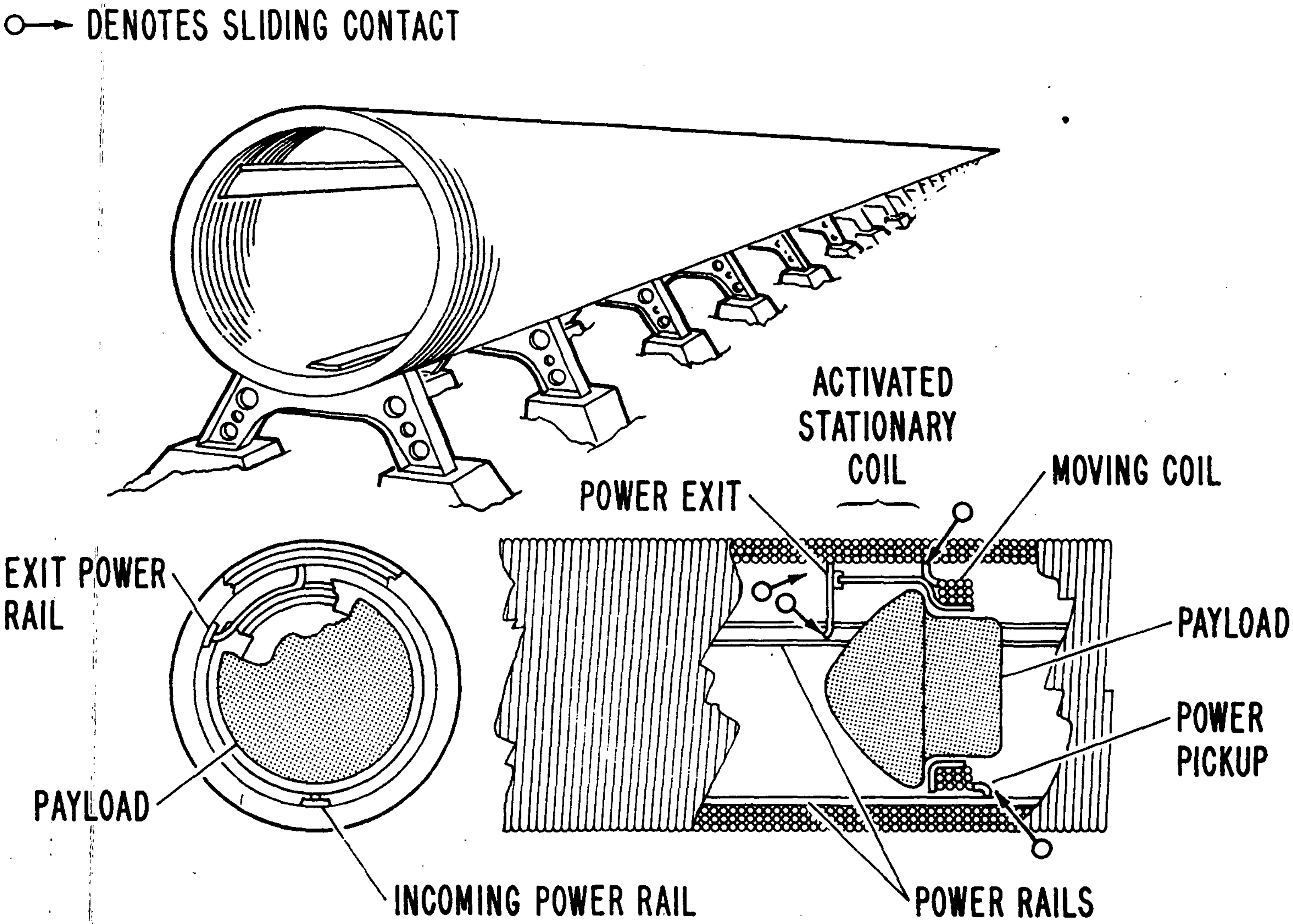

Figure 2-5 Sliding Coil Electromagnetic Launch Device for Lunar Payloads.

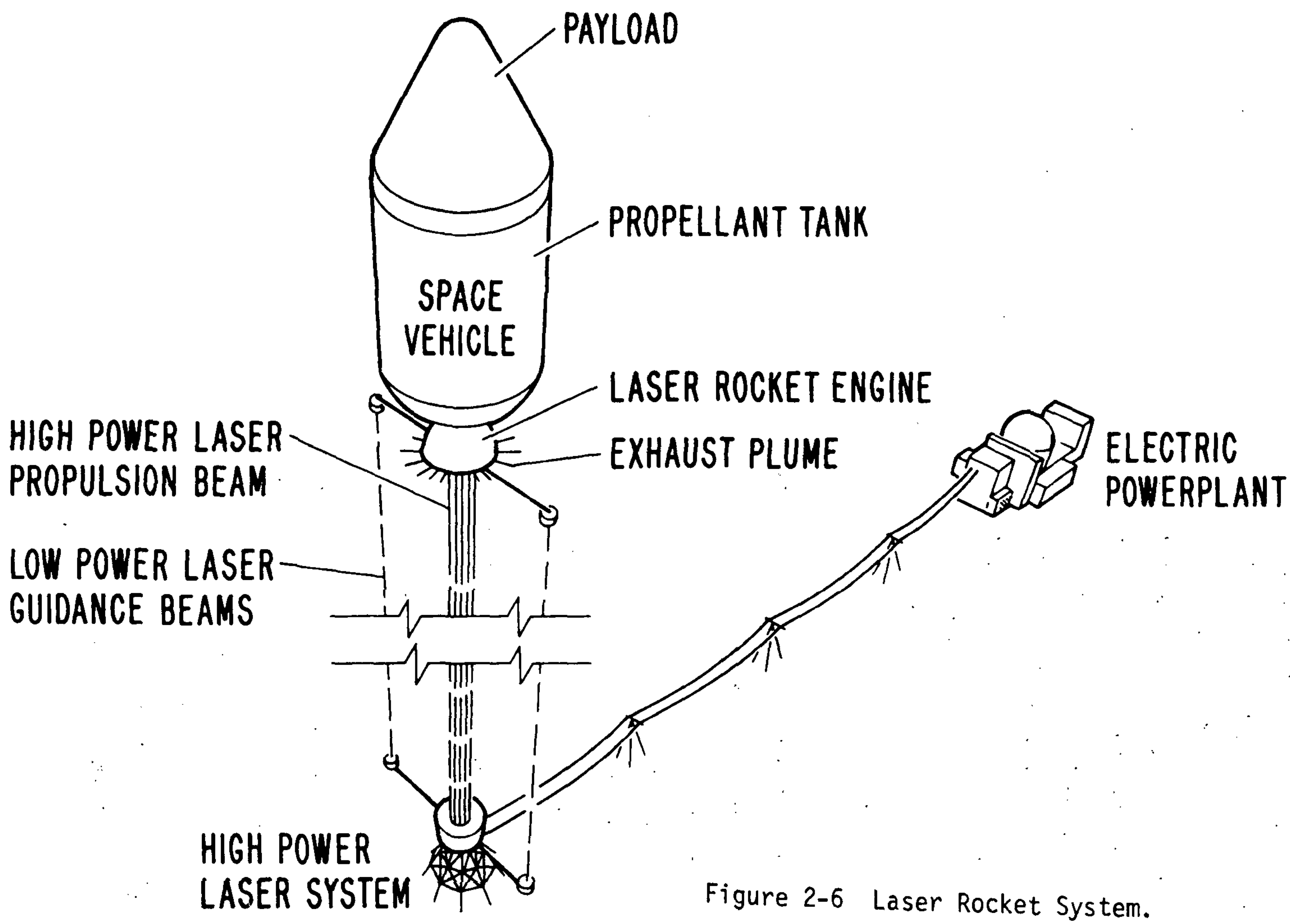

Figure 2-6 Laser Rocket System.

<u>System Selection</u>. - The cost of returning material from the moon is, by-and-large, determined by the system masses involved because most of the cost is determined by the cost of transporting equipment to the moon. The masses can be divided into two parts, namely fixed weight, and expended weight. The fixed weight cost can be amortized, and is, therefore, a function of longevity. The expendable weight is associated directly with payload weight on a per kilogram basis. The foregoing analysis has been used to estimate total system weights for both a chemical vehicle and a sliding coil accelerator. A summary is given in table 2-8. The total cost (capital costs plus recurring cost) as a function of operating lifetime, is plotted in figure 2-7. This figure shows that the advantage of electromagnetic propulsion (i.e., lower expended mass) is negated by the high fixed mass during the first ten to fifteen years of lifetime.

It is apparent that return transportation charges are a significant factor in lunar mining, but due to the entirely preliminary nature of the analysis, it is quite impossible to be confident about the weight numbers. Two things are certain, however: First, the weight of the electromagnetic accelerator will have to be reduced in order to make it economically attractive; and second, the weight can be reduced significantly with a few operational and design changes. Most obvious is the fact that the cost of the system, on a per kilogram of payload basis, is very dependent upon the launch rate--and one launch per day is not efficient use of the device. Scaling the machine down to one tenth its size and launching ten times as frequently, for example, would reduce the weight by the same factor--hopefully without greatly affecting the operational life. The use of aluminum instead of copper could reduce the weight by another factor of two, theoretically, although the increased bulk of the aluminum could affect the system configuration. It is less certain whether increasing the acceleration level would decrease the weight since the reduced length of the coil must be compensated by higher forces and hence more amp-turns in the remaining shorter coil. Additional ingenuity in the design could save

Table 2-8 LAUNCH SYSTEM WEIGHT COMPARISON*
(Payload - 13,600 kg)

	CHEMICAL ROCKET		ELECTROMAGNETIC (Sliding Coil)	
	Weight	Cost per kg of Payload (a)	Weight	Cost per kg of Payload (a)
Vehicle:				
Heat shield	680 kg		680 kg	
Fuel	13,600 kg			
Guidance	220 kg			
Motor	1,800 kg			
Structure	2,700 kg			
TOTAL	19,000 kg	\$770/kg	680 kg	\$20/kg
Launch Facilities:				
Launch pad	4.5×10^6 kg			
Track/chute			90×10^6 kg (b)	
Moving coil			6,800 kg	
Control room	4.5×10^4 kg		4.5×10^4 kg	
Assembly area	4.5×10^4 kg		4.5×10^4 kg	
TOTAL	4.5×10^6 kg	\$550 $\frac{yr}{kg}$	90×10^6 kg	\$11,000 $\frac{yr}{kg}$
Fuel or Energy:				
Energy use effic.	50%		50%	
Theoretical energy	100 kw · hr		15,000 kw · hr	
Energy	200 kw · hr		30,000 kw · hr	
Average power (@ addnl 50% eff.)	17 kWe		3,000 kWe	
Power sys penalty (@ 100 lb/kWe)	770 kg		1.4×10^5 kg	
Power dist.			4.5×10^6 kg	
Power control			4.5×10^5 kg	
Refrig.			4.5×10^5 kg	
TOTAL	770 kg	\$.094 $\frac{yr}{kg}$	4.5×10^6 kg	\$550 $\frac{yr}{kg}$

* Those numbers not found in the text or in Appendix A are the authors' best estimates.

(a) See figure 2-7 for equipment lifetime effect on payload cost.

(b) 3,000 kilogram per meter of track.

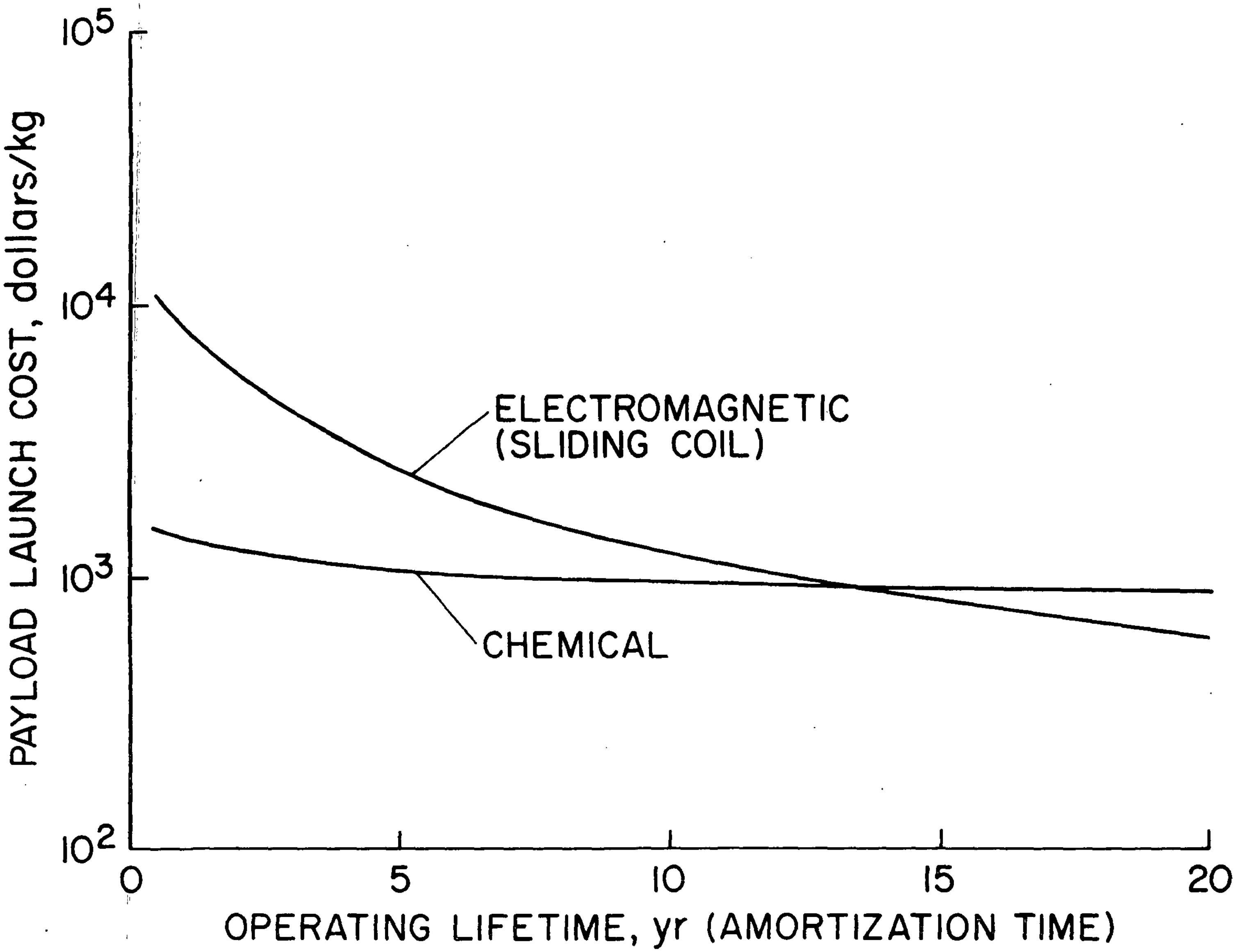

Figure 2-7 Payload Launch Cost.

weight--hopefully not cancelled by the necessary inclusion of mass due to unforeseen problems or design requirements such as sliding contact and barrel accuracy for 2,900 m/sec (9,000 ft/sec) velocity. If, on the whole, the weight could be reduced by a factor of ten, i.e., from a total system weight near 4.5×10^6 kilograms (table 2-8) to 4.5×10^5 kilograms, the launch costs could be in the neighborhood of \$40/kg (\$20/lb) of payload for a twenty year program. Theoretically, with all improvements envisioned possible, the launch cost might even be reduced to between two and five dollars per kilogram (one to two dollars per pound).

ESTABLISHING THE LUNAR BASE FOR MINING AND REFINING

Once a desirable location for mining is located, plans on how to develop the ore field must be made. Included in these plans will be detailed layouts of the lunar mining and refining complex including the mine shaft location, placements of buildings, ore stockpile area, waste disposal site, ore transport system, power station*, landing field, etc. Obviously, such plans will be dependent to a great degree on the local terrain and the type of ore being mined and refined. At this time, such details are not available. Therefore, this section will consider these parameters from a broad overall view to obtain engineering estimates of the requirements, problems and costs associated with establishing a mining operation on the moon. The mass of ore handled by the facility is an important facility sizing parameter. It is assumed that the facility will handle 4.5×10^8 kilograms of 1 percent mineral ore per year.

Background

The lunar mining and refining complex poses unique requirements imposed by its environment and remoteness. With the possible exception of low gravity (1/6 g), the lunar environment is much harsher than the terrestrial environment.

Principally, the environmental problems, (extremely high fluctuations in temperature from lunar day to night and shade to sunlight, radiation and meteoroids,) are caused by the lack of an atmosphere. Furthermore, the lack of native atmosphere means that for manned lunar operations, oxygen will have to be transported from earth or manufactured there from the reduction of oxides. Thus, the operations must be designed to protect the workers and equipment from these environmental conditions.

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* Power generation is treated by itself in Section 4 because of its importance to the overall base operation and because it will be located remote from the main base for safety considerations.

Remoteness from earth requires that the lunar operations provide emergency survival capability and to a large extent be self-contained except for the periodic resupply of consumables. Also, the quotation, "man does not live by bread alone," brings up the requirement of providing recreational and entertainment facilities for the workers since a quick trip back to earth on weekends for diversion is not an anticipated possibility even in the time period of this study. Thus, the lunar complex must include these types of facilities.

This section of the study will look at the problem of environmental protection and identify the facilities that will be part of this lunar base. Weights, and overall costs for these facilities will be estimated.

Lunar Environmental Influence on Lunar Structures

Because the moon lacks a protective blanket of atmosphere, its surface is unprotected from radiation or meteoroids and is also susceptible to extreme temperature fluctuations from lunar night to day and from sunlight to shadow. These factors are important considerations in the design and placement of lunar buildings and facilities. The feasibility of using the lunar soil to perform the protective function that the atmosphere provides on earth is discussed below.

Temperature Effects. - The lack of an atmosphere means the thermal load on part of a structure can only be dissipated by distribution through the structure by conduction or radiation (no convection). These are not very efficient mechanisms for redistributing heat through a large thin structure enclosing a large volume such as the outer walls and roofs of buildings. Thus, the severe temperature differences that can exist in a structure from its sunlit side to shady side on the lunar surface would result in large distortions and possible failure of these structures.

The lunar surface temperature cycles from approximately 90°K to 390°K from lunar night to day, a 300°C excursion in temperature. This will result in high thermal stresses in the structure; for example, a 300°C temperature change can induce a thermal stress of 7.65×10^8 N/m^2 (111,000 psi) in Am-350 stainless steel. The tensile and compression yield stresses are 9.305×10^8 N/m^2 (±135,000 psi). The 7.65×10^8 N/m^2 thermal stress can be reacted into the structure by allowing the stress to cycle between plus or minus 3.825×10^8 N/m^2. Even then the thermal stress accounts for a significant portion of the allowable yield stress. Because of the cyclic nature of the thermal stresses, fatigue must also be a design consideration.

A possible solution to this temperature problem is to place all structures (buildings), wherever possible, underground. These severe surface temperature fluctuations are quickly attenuated by the lunar soil so that at depths of 0.1 meter, the temperature fluctuations are less than 1 percent (ref. 28) and the ambient temperature is 220°K. A plot derived from figure 5 in reference 28 showing the temperature profiles with increasing depth at specific times in the lunar day is shown in figure 3-1. Therefore, if the structures are placed underground, the extreme temperature fluctuation occurring on the lunar surface will be eliminated and control of temperatures within the structure itself and the volume enclosed by the structures will be greatly simplified.

Meteoroid Hazards. - The meteoroid hazard problem can also be minimized by placing all possible facilities underground. The required depth for adequate protection is a function of the lunar soil, and the velocity and mass of the meteoroid.

Data pertaining to the frequency of occurrence of meteoroid particles, 10^{-6} grams or larger, are scarce but an estimate of cometary meteoroids from reference 29 is shown in figure 3-2. The data indicate that the total number of particles in this mass category is $10^{-7.1}$ particles per square meter per second; for particles with mass of 1 gram or greater, the expected number of particles is reduced to $10^{-14.4}$ particles per square meter per second--a very significant reduction in particle count. References 30 and 31 show that the asteroid meteoroid flux is about

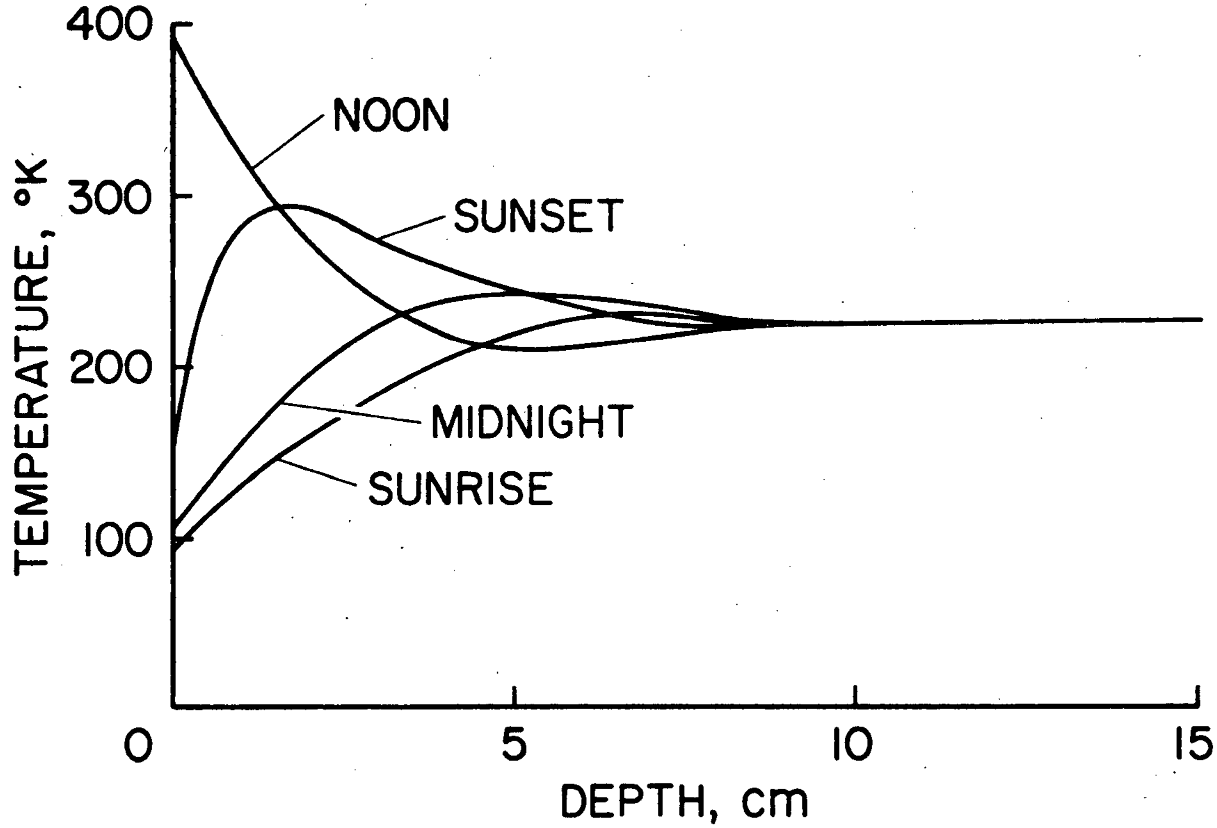

Figure 3-1 Lunar Surface Layer Temperature Profile.

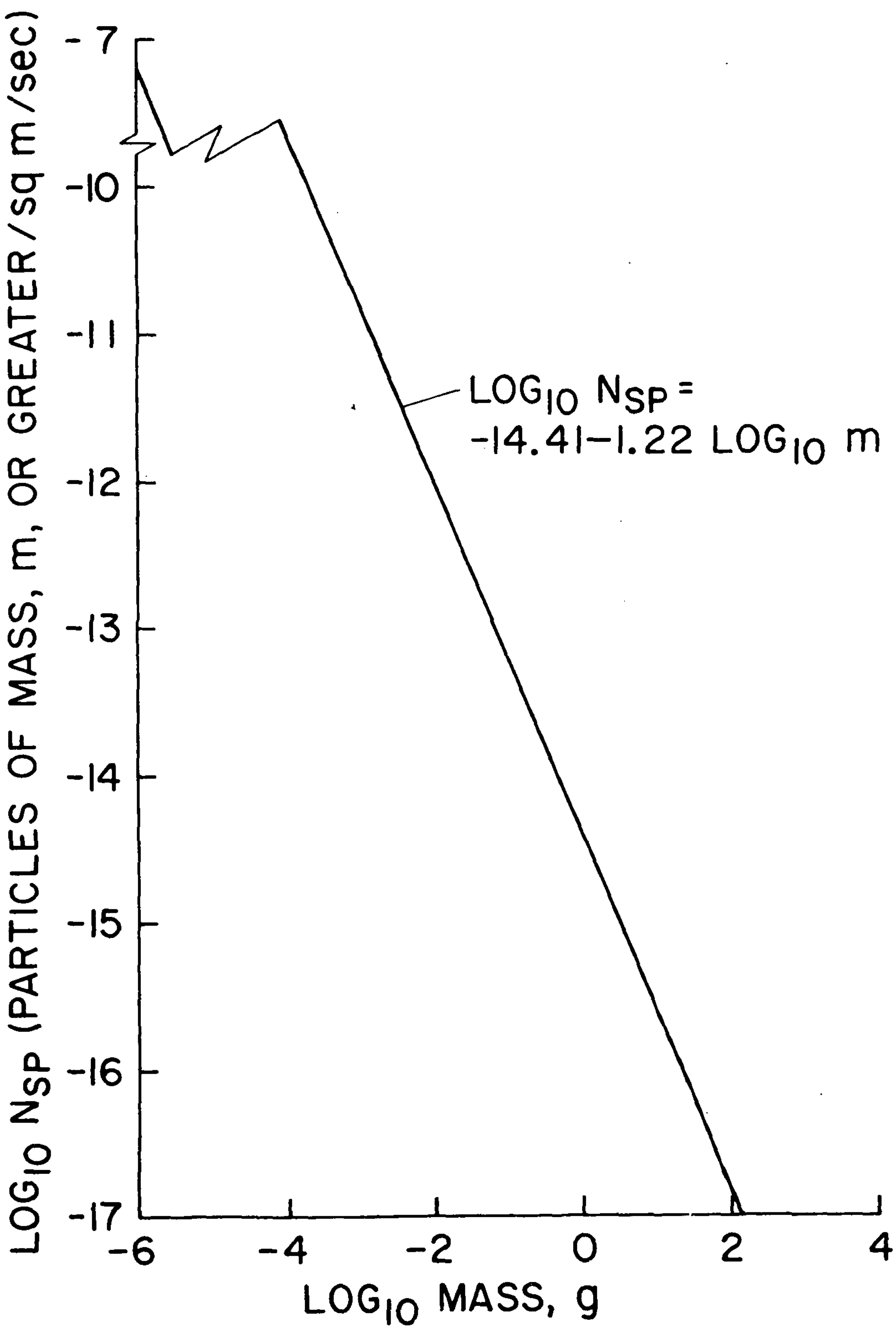

Figure 3-2 Average Cumulative Sporadic Meteoroid Flux--Mass Model for 1 A.U.

equivalent to the cometary flux.* The curve shown in figure 3-3 represents impacts by the combined cometary and asteroid particles of 1 gram or larger.

Examination of figure 3-3 shows that only two and a half impacts of meteoroids 1 gram or larger are expected to occur in a ten year period in a 1 square kilometer area. The average velocity and density of the meteoroids are 20 km/sec with mass densities of 0.5 gm/cm^3 (cometary) and 3.5 gm/cm^3 (asteroidal) from references 29 and 31, respectively. Using data from figure 3-3, the probability of at least one impact occurring in ten years is calculated to be about 94 percent; therefore, the structures should be protected from these classes of meteoroid impacts. The structure itself can be made to withstand meteoroid impact or be protected by being placed underground.

The relation between meteoroid penetration depth and the impacted material can be stated as follows (ref. 32):

$$\frac{P}{d} = \gamma \left(\frac{\rho_M}{\rho_T}\right)^{\psi} \left(\frac{V}{c}\right)^{\theta} \left(\frac{6M}{\pi\rho_T}\right)^{1/3}$$

- P = penetration depth
- d = diameter of meteoroid
- ρ = density
- M,T = subscripts denoting meteoroid and impacted material, resp.
- V = velocity of meteoroid
- c = sonic velocity of impacted material
- γ = proportionality constant (usually 0.5)
- ψ,θ = constants (common values 0.5 and 2/3, respectively)
- m = meteoroid mass

A plot based on the above equation and showing penetration depth into lunar soil versus the mass of the meteoroid is shown in figure 3-4.

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* The cometary flux is shown to be approximately 10^{-4} particles per square meter per second less in references 30 and 31 than in reference 29.

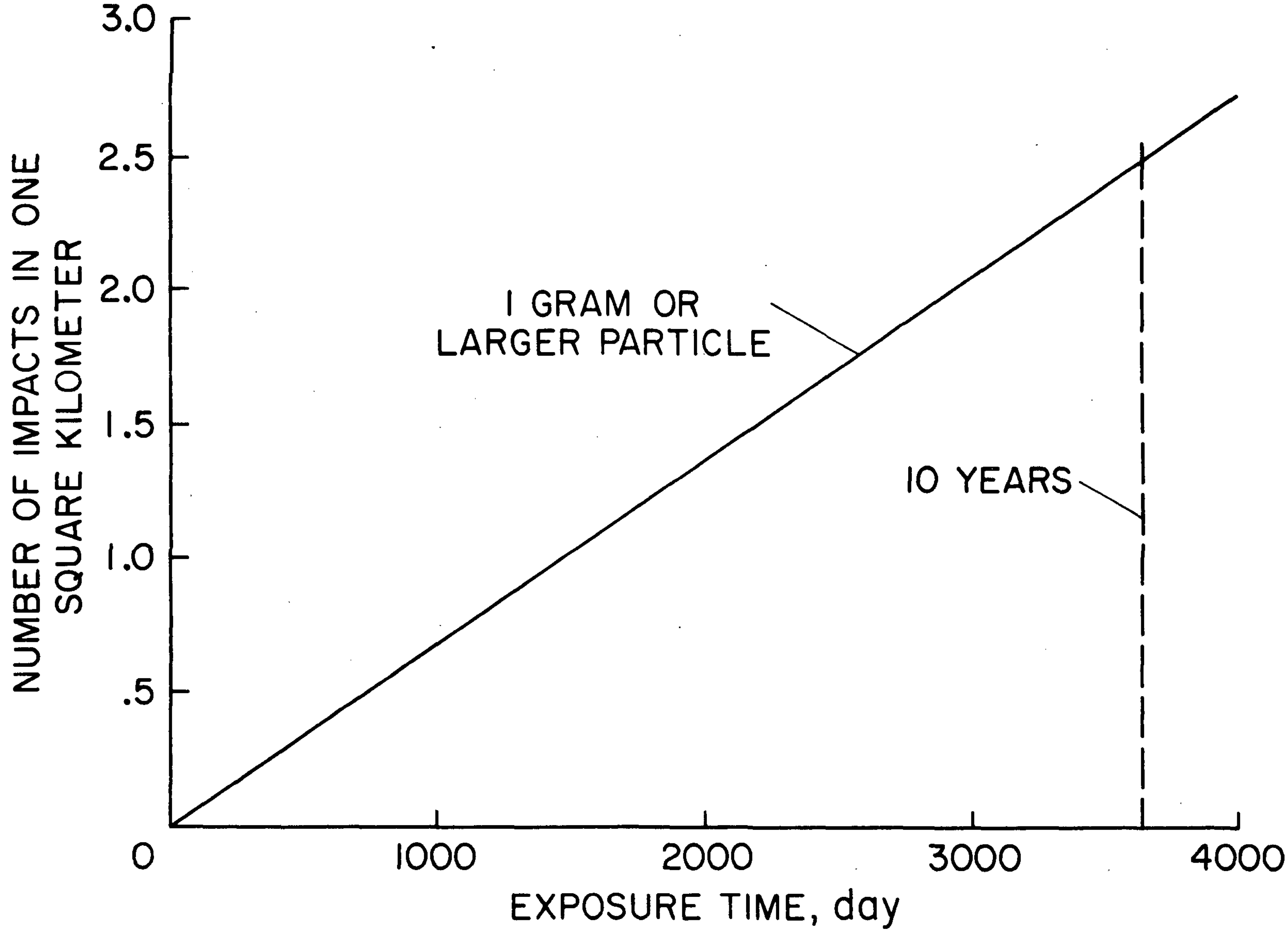

Figure 3-3 Meteoroid Impact in One Square Kilometer.

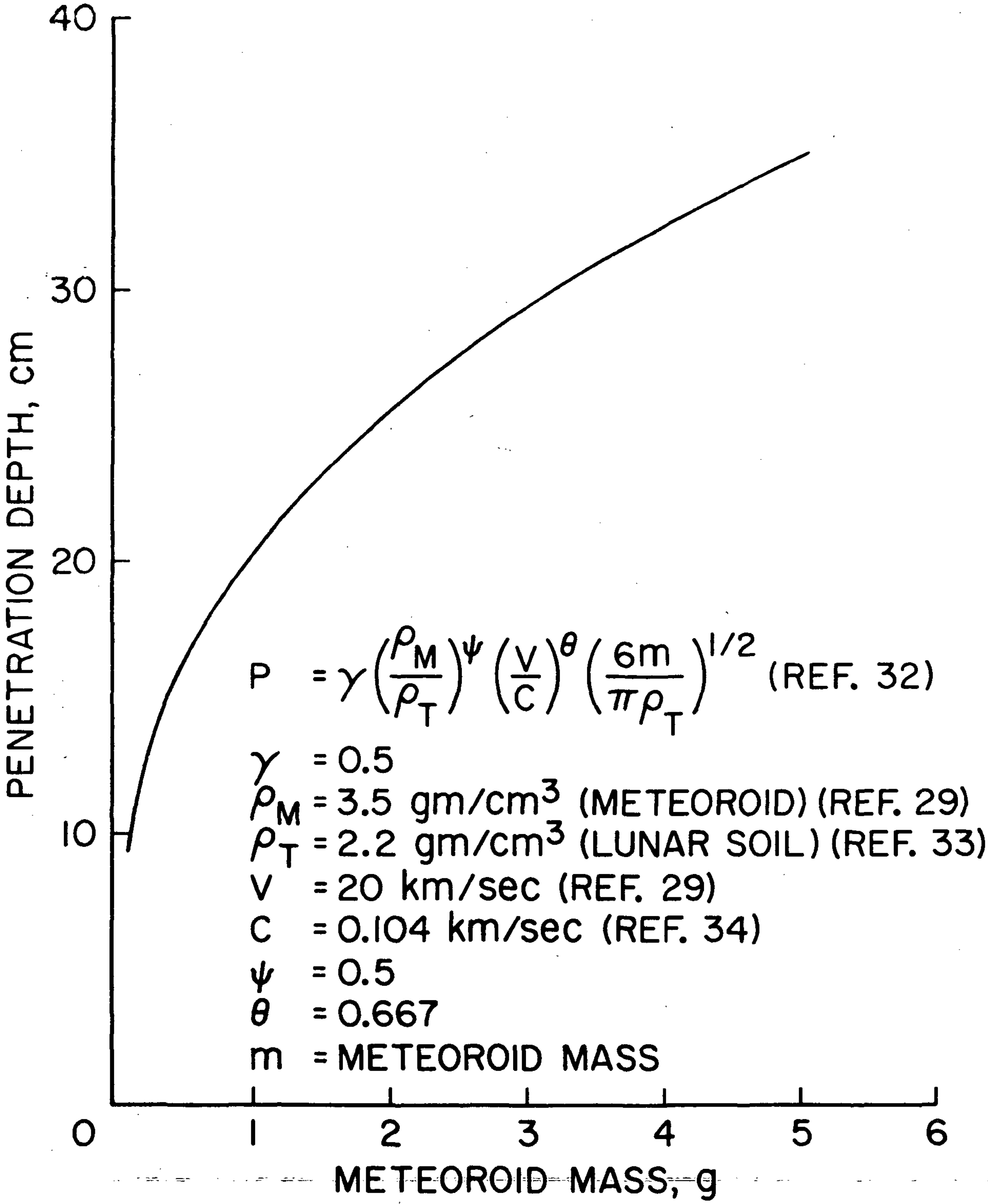

Figure 3-4 Lunar Soil Penetration Versus Meteoroid Mass.

As seen, the penetration depths are not excessive; even a 5 gram meteoroid will penetrate less than half a meter. A plot of the probability of an impact of a meteoroid of given mass or greater in a 1 kilometer area in a ten year period is shown in figure 3-5. Note that the probability of an impact diminishes rapidly so that the probability of a meteoroid of 100 grams or larger impacting in the 1 square kilometer in the ten year period is only 0.5 percent. Solving the meteoroid penetration equation for a meteoroid mass of 100 grams indicates that a cover of lunar soil one meter thick provides adequate protection. The survivability of structures within the 1 km^2 area is .995.

The structure itself will be capable of absorbing the meteoroid impacts if the mass of the meteoroids are small. Figure 3-6 shows a plot of the penetration resistance of aluminum and steel plates to meteoroid impacts. The results show that the wall thickness required to resist the impact increases rapidly with increase in meteoroid mass. Wall thickness requirements to fulfill other structural needs such as load bearing and pressure containment will be less than a centimeter thick. Therefore, if the structure is to be self-shielding, the weight increase for thickness beyond 1 centimeter will have to be charged to meteoroid protection. As seen from figure 3-6 the thickness requirement for an aluminum structure increases three-fold (which is roughly equivalent to a three-fold structural weight increase) as the meteoroid mass increases from 0.1 gram to 1 gram. Of course, the impact resistance of metal structures can be improved by using a double wall construction if the need arises, but the cost will be much higher.

Therefore, to keep the structural weight requirement minimized, the lunar structures should preferably be placed underground for meteoroid protection and depend on the structural (metallic) wall to provide an added factor of safety.

<u>Radiation</u>. - Long term lunar operations require the protection of personnel from radiation. The radiation sources of concern are the

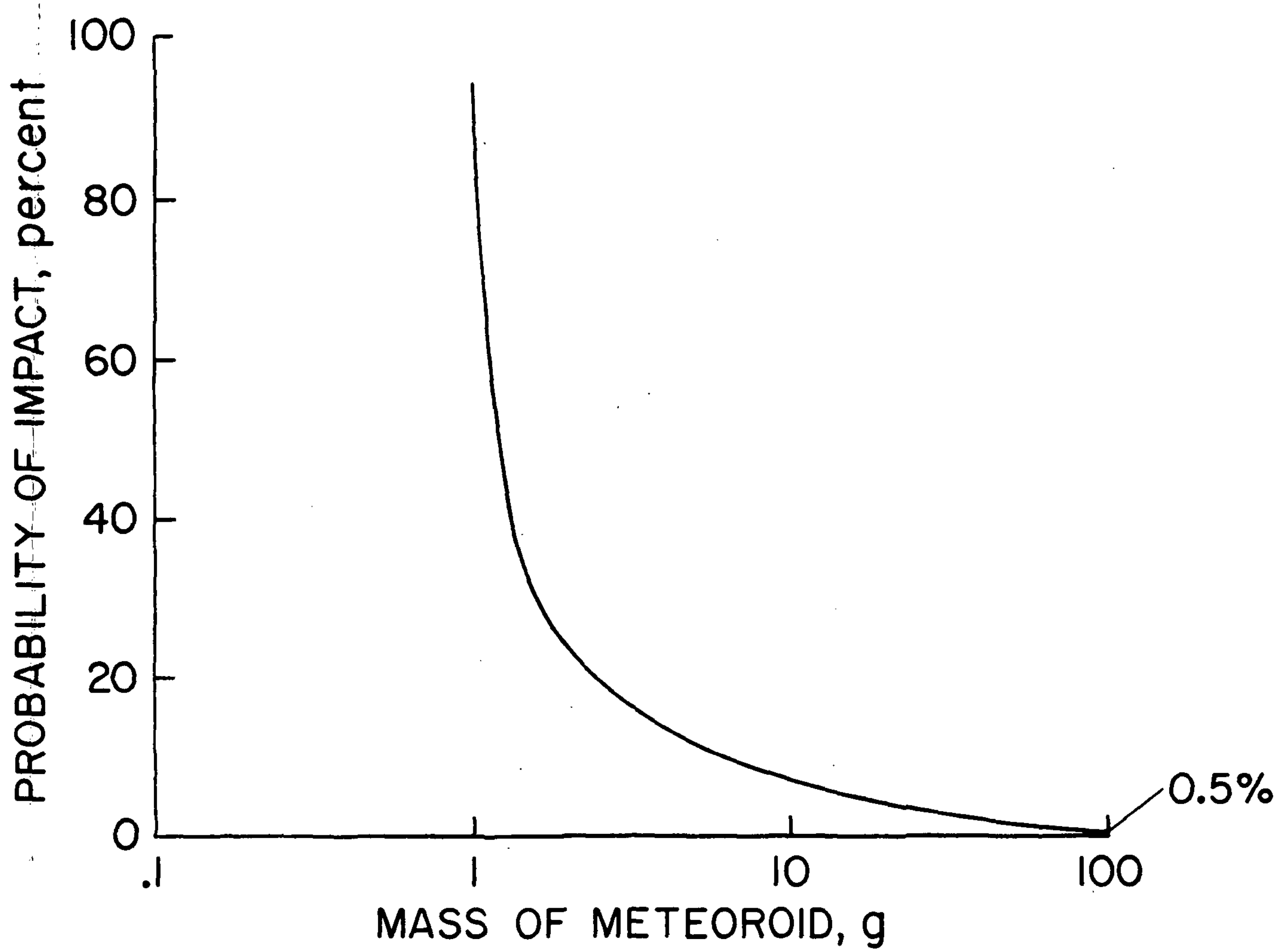

Figure 3-5 Probability of Meteoroid Impact of Mass M or Greater per Square Kilometer per 10 Year Interval.

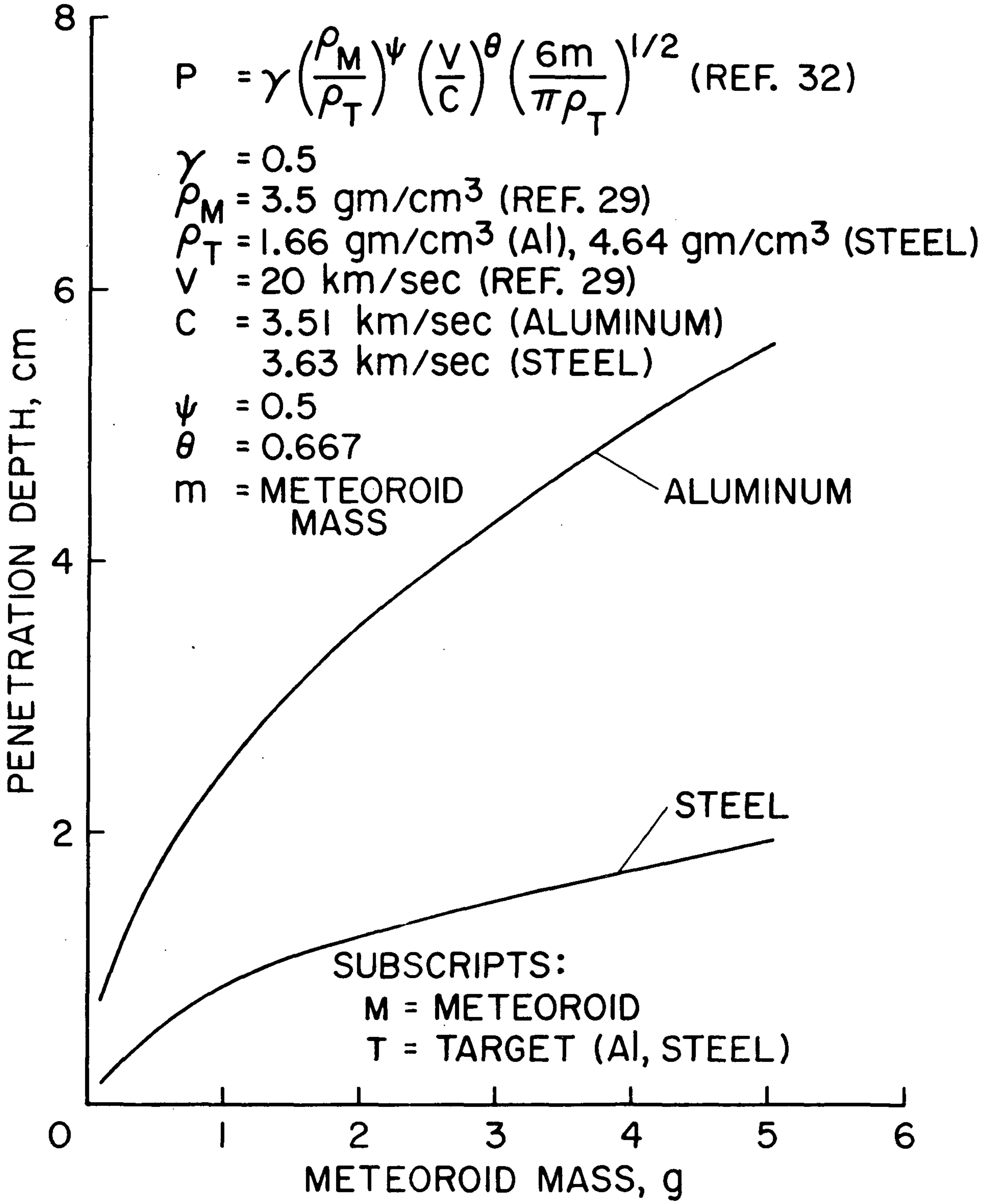

Figure 3-6 Meteoroid Penetration of Structural Aluminum and Steel.

intermittent solar flares and the constant low intensity high energy galactic radiation. Problems of man-made radiation sources such as nuclear power plants are assumed to be of no concern since they are usually solvable through siting. Radiation protection requirements based on current knowledge as recommended by the Space Science Board of the National Academy of Science set the maximum short term one year limit at 38 rems, a career limit of 200 rems and lifetime average limit of 5.7 rems per year. More details are contained in references 35 and 36. Reference 37 specifically discusses the lunar radiation environment including the use of lunar soil as shielding and allowable dose limits.

Protection from radiation due to solar events can be readily provided by the structure itself or by using the lunar soil as cover. A cover of five grams per square centimeter will provide adequate protection except for the one event in a thousand, and a cover of 40 to 50 grams per square centimeter will provide adequate shielding except for that one event in a century. If shielding adequate for the later case is to be provided, the thickness requirement for several materials is shown below:

Lunar Soil	- 23 cm
Aluminum	- 17.9 cm
Steel	- 6 cm

But, on the other hand, the galactic radiations are higher energy radiations (several orders of magnitude higher in energy than solar flare radiation) and they are more difficult to shield. Also, the secondary radiation from the galactic radiation is much more penetrating than those from solar flares. The secondary radiation is severe at depths between 10 centimeters and 4 meters (ref. 37) in lunar soil and thus these depths should be avoided for lunar structures.

Crew assignments are assumed to be nominally for one year periods, therefore, the radiation protection provided for the personnel should be conservative. A protection level equivalent to that provided by the earth's atmosphere and magnetic field would be ideal. A lunar soil thickness of approximately five meters will provide this protection. This thickness will also provide adequate shielding from the secondary radiation produced by the high energy galactic radiation. The amount of secondary radiation produced upon impact is strongly influenced by the shield material; fortunately lunar soil is an excellent shield material with secondary radiation characteristics similar to aluminum (ref. 37).

Summary. - The required thickness of lunar soil cover to provide the desired protection from temperature variations, meteoroids, and solar radiation are summarized below:

Temperature Variation (±3°C)	- 0.1 meters
Meteoroids	- 1.0 meters
Solar and Galactic Radiation	- 5.0 meters

As seen, the requirements to minimize the radiation hazard will dictate the lunar soil cover thickness. The following sections will look into the placement and the covering of the structures.

Base Construction - Lunar Mining and Refining

The general procedure or sequence that might be followed in constructing the facilities for mining and refining lunar ore are described in this section. One of the first requirements that must be fulfilled is to have an adequate transportation system, as described earlier. With the means for transporting and landing the required construction materials, equipment, and personnel on the moon, the construction of the base can proceed. Obviously, details such as the proper transportation sequencing of equipment, materials, and personnel must be planned to accommodate the optimum use of man, equipment, and materials; for example, the early conversion and expansion of the temporary landing site into a permanent landing site capable of accommodating and stockpiling of equipment and materials must be planned. As the necessary construction equipment, materials, personnel, and support facilities arrive, the construction can proceed.

The actual construction of the permanent facilities will start with the excavation and the simultaneous assembly of modularized base facility components, their placement in the excavation and final assembly of buildings, followed by the covering of the buildings with lunar soil. Of course, there are alternatives to digging down into the lunar terrain, such as setting the buildings on the surface and covering them, or burrowing into a hillside, or only half submerging the buildings and then covering them. Choices such as these are primarily functions of the local terrain and soil. This study is based on the case where the manned portion of the facility is placed underground while the taller unmanned portion of the facility is allowed to protrude above the lunar surface, but adequately covered with lunar soil.

Some of the problems and requirements dealing with design and emplacement of lunar structures have been studied in the past. Typical examples of these studies are references 38-41. References 38, 39, and 40 are studies that deal with the overall design and emplacement of the total lunar base while references 41 and 42 have looked at specific design criteria for lunar structures. Although these studies are old, their results are generally still valid and useful. Also, these studies indicate that outside of including additional requirements for protection against radiation, meteoroids, extreme temperature variations, and air leaks, if good terrestrial structural design practices are followed, the designs will be adequate.

<u>Required Facilities and Their Construction Sequence</u>. - A pictorial layout of the facilities is shown in figure 3-7. Note that the nuclear power generating plant has been located away from the major base for safety reasons (radiation primarily).

A listing of the major facilities, along with estimates of their volumetric requirements for the lunar mining/refining operation, are shown in table 3-1. The facilities have been sized for an operational crew of 150 (see table 3-2) and provide apporoximately 35 cubic meters

Figure 3-7

LUNAR MINING FACILITY
ARTISTS CONCEPT

TABLE 3-1 LIST OF FACILITIES[a]

Gross Dimensions and Volume of the Lunar Mining-Refining Complex

Facility	Dimension, Meters	Total Volume, m^3
Crew Quarter Modules (156 units)	3 x 3 x 3	4,400 (156,000)[b]
Kitchen, Dining & Rec.	3 x 12 x 30	1,100 (40,000)
Hospital	3 x 6 x 12	220 (8,000)
Emergency Facilities	3 x 12 x 24 & 25	900 (32,000)
Storage-Consumables	3 x 6 x 6 & 3 x 6 x 12	340 (12,000)
Control Room (Communication, mining, mineral dressing & refining)	3 x 6 x 18	340 (12,000)
Mineralogical Laboratory	3 x 6 x 6	110 (4,000)
Mineral Dressing & Refining		
(Low Bay)	6 x 25 x 35	5,400 (192,000)
(High Bay)	18 x 85 x 60	95,200 (3,360,000)
Equipment Storage & Repair Shop	6 x 12 x 60	4,500 (160,000)
Refined Mineral Storage	6 x 25 x 25	3,600 (128,000)
Environmental Control & Consumable Recycling	3 x 6 x 6	110 (4,000)
Miscellaneous	-	2,400 (84,000)
Spaceport & Terminal	N/A	N/A
Power Station[c]	18 x 30 x 60	34,000 (1,200,000)
TOTAL		152,620 (5,392,000)

(a) Based on operational crew of 150 with 6 guest facilities.

(b) Numbers in parenthesis are total volume, ft^3.

(c) Location will be remote from base for safety reasons.

TABLE 3-2 OPERATIONAL CREW*

Operational Function	Number in Crew
Base Superintendent	1
General Supervisors	6
Transportation	15
Mining (including Power Station Operators)	50
Mineral Dressing and Refining	40
Medical	6
Maintenance	12
Food Service	20
TOTAL	150

* Based on information contained in references 44 and 45.

(1,300 cubic feet) of free (unencumbered by equipment, etc.) space per individual. By comparison, the free space in the Gemini, Apollo, and even the Skylab programs is much less. Habitability studies show that a nuclear submarine provides approximately 10 cubic meters (400 cubic feet) of free space per individual. The large amount of free space that has been provided here reflects the more liberal requirements associated with a production type operation and, also, the hostile lunar environment with the need to alleviate the psychological effects of long term confinement (ref. 43).

As seen from table 3-1, the volume of lunar soil that will be displaced from submerging the facilities is approximately 153,000 cubic meters (5.4 million cubic feet), but the actual amount of soil that would be moved is closer to 255,000 cubic meters (9 million cubic feet). The increased volume results from having to excavate a larger volume due to sloping sides, rehandling of the soil to cover the facilities once they are in place and other miscellaneous excavations needed, such as entrance and exit tunnels.

The sequence that will be followed in the construction of the facilities is outlined in simplified schematic form in figure 3-8. The work to be done has been logically grouped, according to the sequence in which it will be carried out. One facility, the power station, must be sited away from the main base for safety; that is, to minimize the radiation and explosion hazards. The power station construction will require some special planning to allow for the shifting of men and equipment from the main base site to the power station construction site. As shown in figure 3-8, the base construction can be grouped into five phases with each phase covering a logical segment of the construction operation. But note that each phase does not necessarily end before the succeeding phase begins. (This is covered later). That is, work functions from one phase to another may overlap significantly on a time basis and the amount of overlap that occurs is a direct function of the construction crew size. The more workers, the more overlap between phases that can be accommodated and reflect the capability of doing more tasks simultaneously.

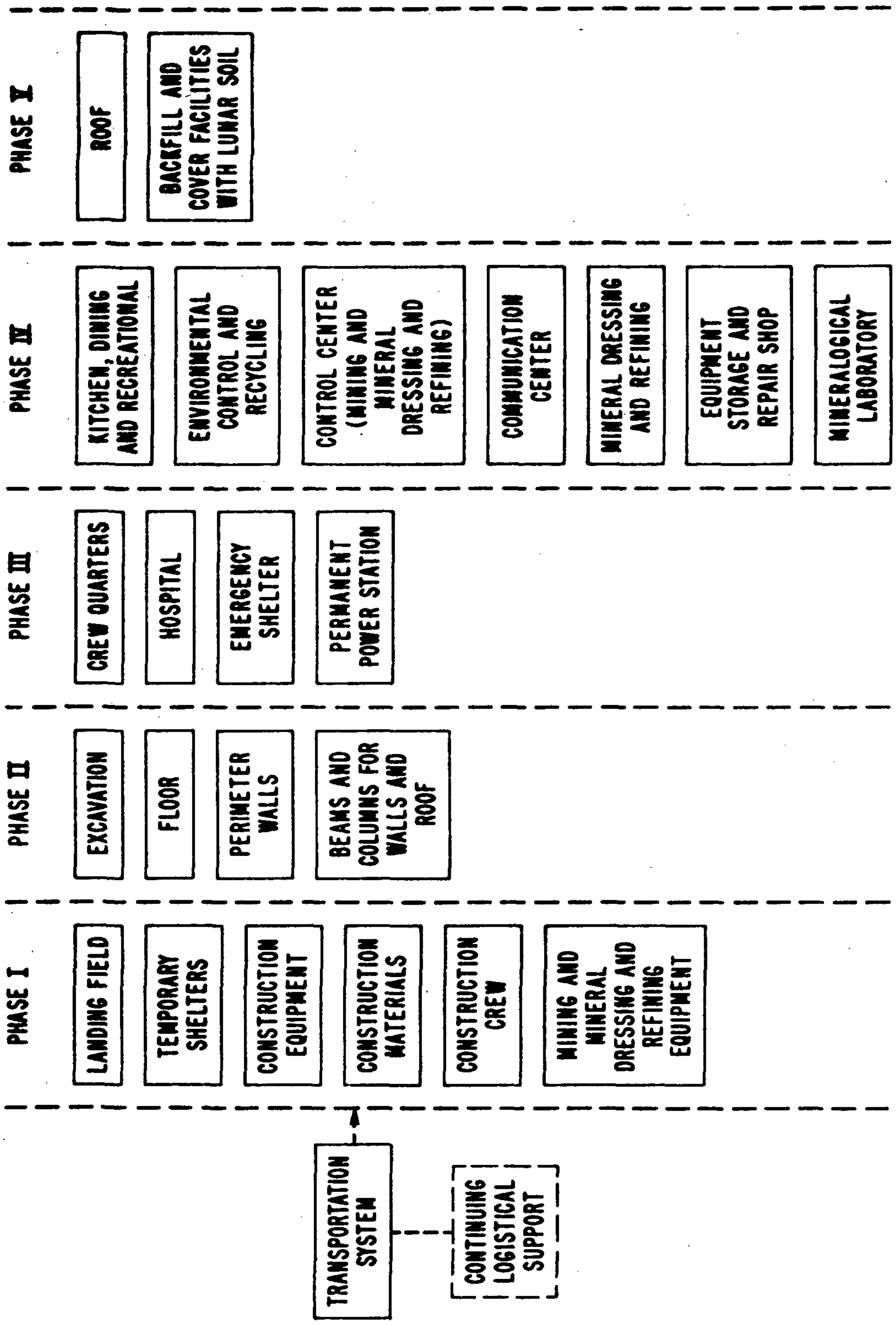

Figure 3-8 Facilities Construction Sequence.

As many of the facilities as possible will be modularized and prefabricated to allow fast and easy fabrication on the moon. Another important benefit of modularizing is that the first modular units delivered can serve as temporary facilities at the start of construction and later become part of the permanent base. The living quarter modules will be designed as fully self-contained units with built-in life support, communication, power, etc., systems. But when the modules are enplaced as part of the permanent base, their life support, etc., systems will operate from a central system to take advantage of the higher efficiency obtainable from centralized systems.

Also, the feature of being self-contained will allow the modules, in an emergency, to operate independent of the centralized environmental system, thus providing a necessary factor of safety to the operating personnel. Actually, when the emergency shelter, also a totally self-contained module, is factored into the redundancy evaluation of crew survival systems, it is seen that a triple redundancy has been incorporated in the design of these critical crew related systems for the lunar base.

Ease of assembly should be the primary goal in the design of the modules and prefabricated components to minimize the need for manual labor in the assembly process. Ideally, the pieces will slide or slip together using built-in alinement guides and simply lock in place automatically when the pieces are properly oriented. Other considerations such as weights and physical sizes, and ease of packaging (the modules and prefabricated components) will also be design constraints imposed by the transportation system's payload accommodating capabilities.

Facilities Layout. - Layout of the lunar mining, mineral dressing, and refining facilities exclusive of its power station, spaceport and terminal is shown pictorially in figure 3-9 and schematically in figure 3-10. A small growth capability in the facility size (7 percent) has been incorporated in the layout design. Overall, the base covers 10,700 square

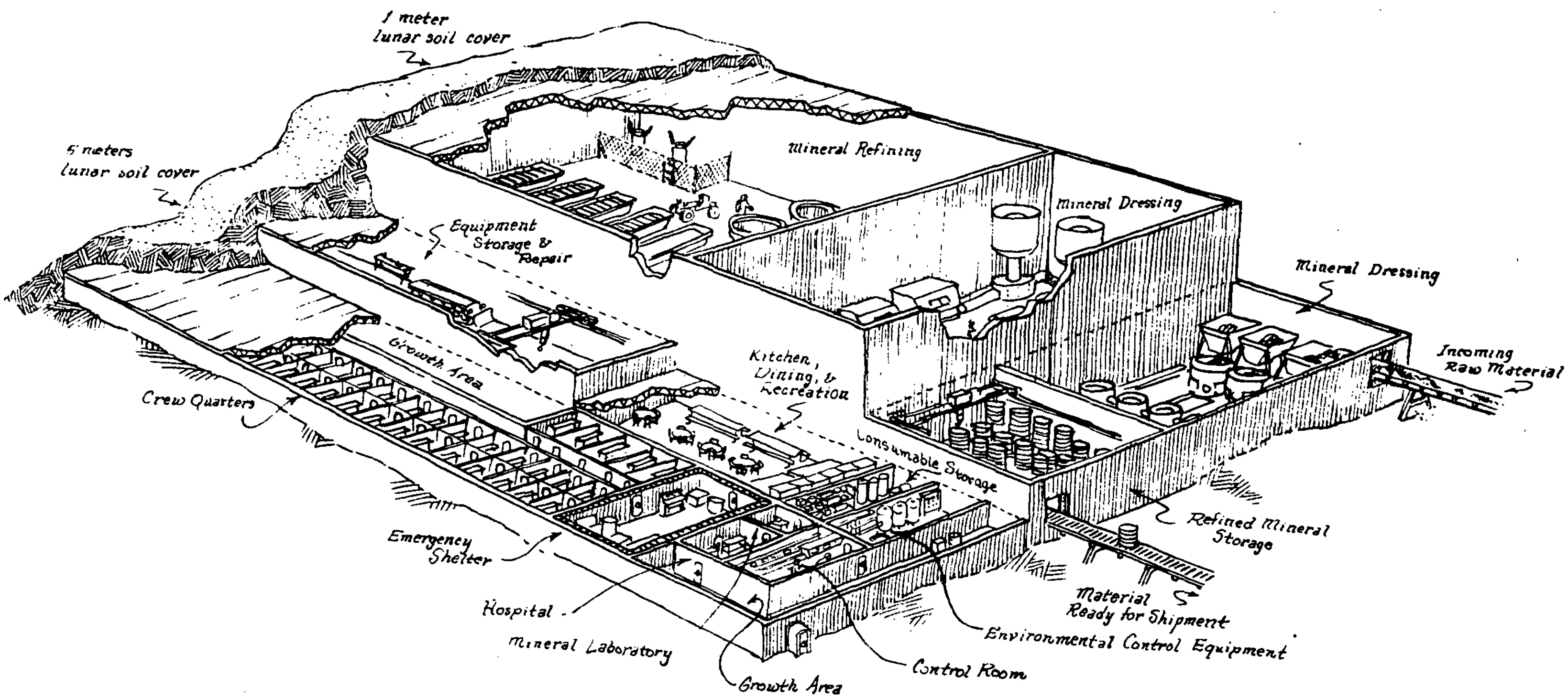

Figure 3-9 Lunar Mining Base Facility.

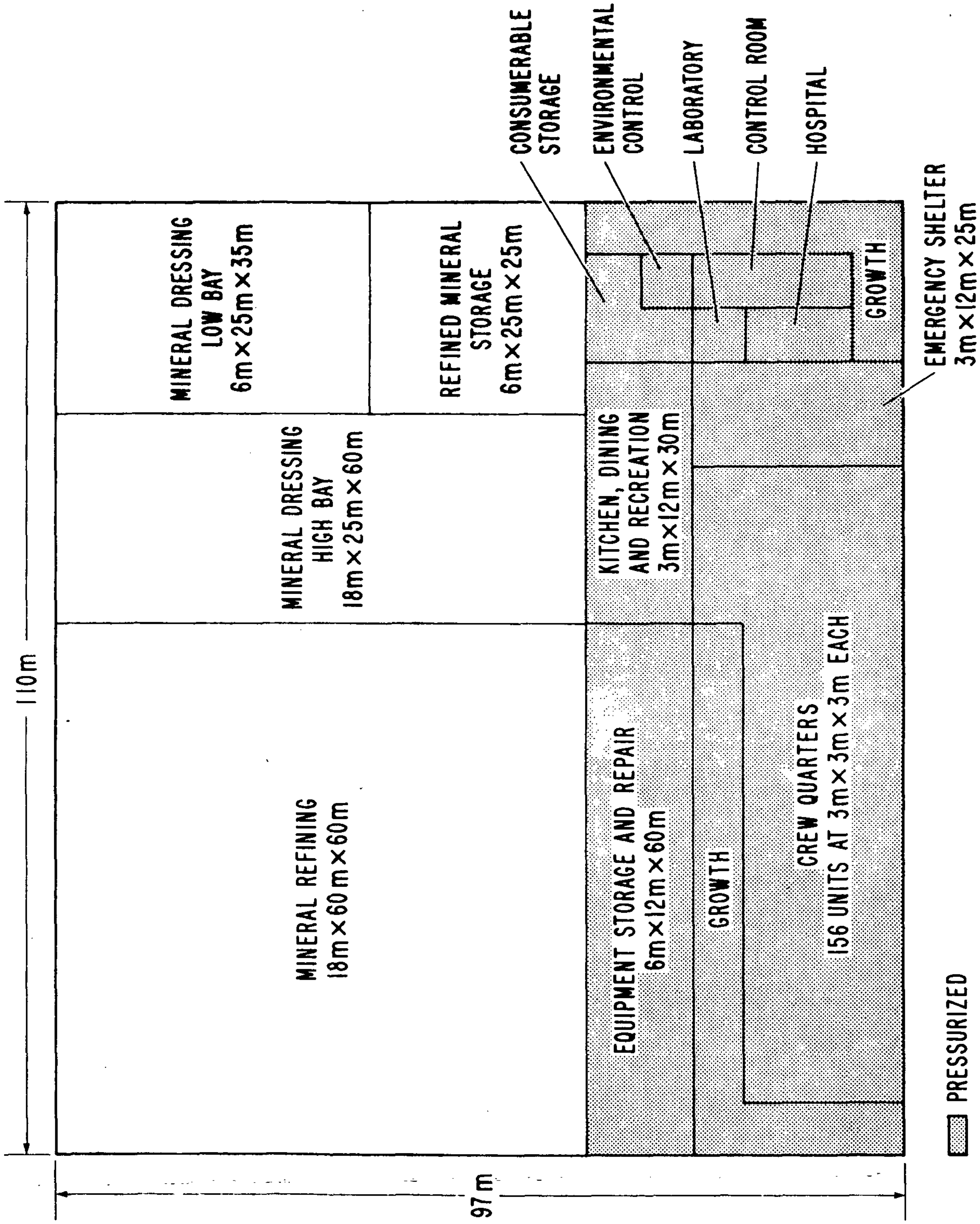

Figure 3-10 Facilities Layout and Dimensions.

meters (115,200 square feet) and encloses a volume of 118,200 cubic meters (4,192,000 cubic feet). Only 12,100 cubic meters (428,000 cubic feet) of the total volume will be pressurized and have an atmosphere; the facilities that will be provided with atmosphere are the crew quarters, kitchen/dining and recreation, hospital, emergency, control room, mineralogical laboratory, equipment storage and repair, consumable storage, and environmental control modules. Since all the mineral processing equipment is to be operated remotely from the control room, none of the volumes dedicated to mineral dressing, refining, and storage operations require an atmosphere.

The environmental protection requirements for manned lunar structures have already been discussed. Five meters of lunar soil should be provided for radiation protection while one meter is adequate for meteoroid protection. Thus, those parts of the base routinely inhabited by man will be provided with a cover of five meters of lunar soil but those portions of the base not inhabited by man routinely will be covered with only one meter of lunar soil for protection against meteoroids. To meet these five and one meter covers of lunar soil, the lunar base site will be excavated to a depth of twelve meters, the base will then be erected in the excavation and covered to the original ground level, which will result in a cover of five meters for the inhabited portions of the lunar base. But parts of the uninhabited sections of the base will rise approximately six meters above the lunar surface; these will be covered with lunar soil so that all parts will have a minimum cover of one meter of lunar soil.

Facilities Weight Summary. - An estimate of the gross weight to be transported to the moon for establishing the lunar mining and mineral processing operational facilities is summarized in table 3-3. The weights shown are believed to be conservative, based on historical trends in equipment and structural specific weights (kilogram of equipment per kilogram of refined mineral). Additional weights that may be required for the construction phase, including crew and construction equipment beyond the utilization of operational equipment and crew, is difficult to determine, but a conservative guess might be about 58,000 kilograms (150,000 pounds). This weight was not included. The degree to which the operational equipment can be

TABLE 3-3 MINING, MINERAL DRESSING & REFINING FACILITIES WEIGHT SUMMARY[a]

	Kilograms	Pounds
Basic Facility Shell Weight	1,179,000	2,600,000
Crew Quarters Modules	129,000	286,000
Consumables Storage (including 90-day supply)	77,100	170,000
Kitchen, Dining, Rec. Facilities	27,200	60,000
Hospital	15,900	35,000
Emergency Facilities	73,900	163,000
Control Room (Communication, mining, mineral dressing & refining)	22,700	50,000
Mineralogical Laboratory	13,600	30,000
Mineral Refining Equipment Mineral Dressing Equipment	500,000	1,100,000[b]
Mining Equipment (including conveyors, etc.)	244,000	540,000[b]
Equipment Storage & Repair Shop	142,900	315,000
TOTAL	2,425,300	5,349,000

(a) Based on 4.536×10^6 kilograms (10^7 pounds) of mineral per year extracted from 1 percent ore. Power station weights are covered in section 4 and range between 2.3×10^6 to 9.1×10^6 kilograms.

(b) Costs for procuring and transporting this equipment included in their respective sections.

used in the construction phase of the lunar facilities is illustrated as follows. The mining machine and conveyor system can be used to do the excavating; the mining machine will do the digging and the conveyor will be used to convey the diggings out and away from the excavation area. When the excavation is completed and the facilities have been put in place, the mining machine would then be used to feed the conveyor from the pile of excavated soil and the conveyor would convey the lunar soil back to the excavation site and cover the facilities with the lunar soil.

The total weight estimated for the lunar facility (excluding the power station) is based on a very conservative construction technique. That is, the entire base is assumed to be enclosed in a structural aluminum honeycomb shell that reacts to structural loads such as the weight of the cover of lunar soil, and is itself essentially airtight; also, each functional module that is manned also has the structural capability of resisting the overburden loads when pressurized and is naturally airtight itself. A redundant construction technique was anticipated because of the permanent nature of the operation where safety and survival of the operational crew was an important and overriding consideration in the design of the base.

Each weight estimate in table 3-3 is for the complete functional module, including its content. For example, the weight shown for the functional hospital module includes its emergency environmental control and power system weights, complete hospital equipment weights from beds and drugs to x-ray and operating room equipment, as well as the airtight structural shell or hull weight. All the weight breakdowns are self-explanatory, with the possible exception of the weight for the basic facility shell. This weight includes the weight for the entire wall running the 110 meter (360 feet) length and 100 meter (320 feet) width while varying in height from 3 to 18 meters (10-60 feet), the weight of the entire floor of 10,700 square meters (115,200 square feet), the weight for the entire roof of 10,700 square meters, and the weight for all the columns supporting the roof and walls.

Facilities Cost. - The total cost* (procuring, transporting, and constructing) for the lunar mining/refining facilities placed on the moon, assembled and ready for production, is estimated at $1.52 x 10^9$. The anticipated procurement cost for the building materials, functional modules, equipment, etc., is estimated to be about $120 x 10^6$. The cost of erecting the basic protective shell is expected to be approximately $430 per square meter ($40 per square foot*) or $2.6 x 10^6$. The cost for transporting all the materials, equipment, etc., from the earth to the moon in establishing the lunar mining/refining operation, even with an optimistic projected unit transportation cost of $550 per kilogram ($250 per pound) from the earth's surface to the lunar surface, is approximately $1.4 x 10^9$. As seen, the overwhelming segment of the cost is transportation, indicating that work either in reducing the weight of the facility or reducing the transport system operational cost or both would be beneficial. Reduction in the transportation system operational cost is the more desirable alternative because of its impact on the subsequent lunar base logistics and on other space programs.

Facilities Base Operational Requirement. - The operational requirements are those pertaining to providing the crew needs and resupplying the facility atmospheric leakage losses. The total facility operational needs include wear replacement and other items such as explosives used for breaking the ore in the mining operation. But these needs are associated with the specific areas of mining, refining, power generation, or transportation and they are assigned and covered in discussions of these areas.

The lunar base operating crew logistic requirements for consumables** are on the order of 4.5 kilograms (10 pounds) per man-day assuming that water and oxygen are recycled (based on the Skylab and space station studies). With this assumption, the yearly requirements for the base crew of 150 men will be 270,000 kilograms (600,000 lbs) assuming a 10 percent allowance for spoilage and loss.

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* Does not include power station.

** Drinking water, personal hygiene water, oxygen, and food.

Also included in the logistics requirements for the base are the make-up requirements for atmospheric leakages through the walls, air-locks, and atmospheric regeneration equipment. The leakage rate based on a unit of surface area should be less than the leakage rates in the Skylab I program. Sealing technology should have improved in the intervening 30 to 50 years; also, by using a vacuum pump in conjunction with the air-lock, these losses should be reduced drastically. It is likely that the loss per unit surface area for the lunar base can be reduced to 25 percent of that for Skylab I (from 0.0195 $kg/m^2/day$ to 0.0049 $kg/m^2/day$). The pressurized surface area for the lunar base is approximately 9,300 square meters (100,000 square feet), and the yearly leakage loss will be approximately 18,000 kilograms (40,000 pounds) per year.

Total crew consumables and base leakage losses requirements are, therefore, on the order of 290,000 kilograms (640,000 pounds) per year and the cost to supply these needs will be $\$160 \times 10^6$ per year.

POWER SYSTEMS FOR LUNAR OPERATIONS

Summary

Power requirements for a lunar mining operation could run from 10^2 to 10^{10} kilowatts depending chiefly on the quantity of mineral to be retrieved. Any one of a number of power system types could be used, from state-of-the-art solar cells with batteries to the yet-to-be-demonstrated fusion reactor. Power system weights vary from 10^4 kg/KW_e in the first case (chiefly for batteries) to perhaps 20 kg/KW_e in the latter. The installed cost, which is determined primarily by transportation charges, would be a prohibitive $\$10^{13}$ per GW for a solar cell battery system and $\$10^{10}$ per GW for the fusion system.

Introduction

Energy is probably the most fundamental requirement to a large scale lunar operation. Large quantities of energy (or high power) are required for virtually every phase of the lunar mining activity. Energy is needed for life support and environmental control, regeneration of consumables, mining and refining equipment operation, instrumentation, communication, and transportation. The source and form of the energy that might be used can vary considerably, depending on the state of energy technology and mining technology in the post 2000 A.D. time period. That is, for example, the availability of an operational fusion reactor and a mining system able to employ a fusion torch would represent a substantial change in mining operations which currently use internal combustion engines, electric motors, and explosives. The possibilities of supplying energy, then, are many, ranging from combustion of chemical fuels, use of solar energy, power from nuclear fission reactors, to controlled fusion.

Any one of a number of power system types could theoretically be used on the lunar surface. Power levels and lifetime requirements do, however, place some practical constraints on their use. The Apollo spacecraft and lunar rover use batteries. The ALSEP (Apollo Lunar Surface Experiment Package) uses a SNAP-27 RTG (Radio-isotope Thermoelectric Generator), and solar cells were used on Lunokhod-1 and the Surveyors. Power levels for lunar operation have thus far been only a few hundred watts. Due to the high cost of transporting materials to the moon (a future price of $550 per kilogram is projected for this study), the replenishment of expendable fuels becomes noncompetitive after only a few weeks of operation.

Many advanced lunar exploration/lunar base studies have been made. Frequently, they recommend utilizing adaptations of the advanced space nuclear power systems such as the SNAP-8 reactor with a Brayton Cycle conversion (refs. 46 and 47). Other studies have also shown the feasibility of using solar cells with either batteries or regenerative fuel cells for lunar night power (ref. 47 and 48). Most of these investigations have been limited to power levels of about 100 KW_e or so. Such systems, although too small for mining, would quite logically be used during the construction of a lunar mining facility.

Power Requirements

The power requirements for operating a lunar mining, refining, and transportation facility are far in excess of 100 KW, at least as required to produce those materials of interest in the quantities that they are presently consumed in the United States. In addition to production quantity, the power requirements obviously depend upon the nature of the mining operation (i.e., location and concentration of the mineral), the dressing and reducing techniques used, and the mode of the return transportation.

Power requirements for an operational facility could run, it would appear, from 20 to 200 KW-hr for each kilogram (10 to 100 kW-hr for each pound) of material processed. See table 4-1.

Since resource consumption rates for most materials of interest vary from 4.5×10^5 to 4.5×10^{11} kg/year (10^6 to 10^{12} lb/year) the lunar power generation requirement based on table 4-1 then could conceivably run from 10^3 to 10^{10} kilowatts for a single resource type. The latter figure

TABLE 4-1 LUNAR MINING POWER REQUIREMENTS

Numbers in Kilowatt-Hours Per Kilogram of Mineral

Ore Grade	10 Percent	1 Percent
Drilling Blasting	2×10^{-2}	2×10^{-1}
Loading	3×10^{-3}	3×10^{-2}
Conveying	6×10^{-3}	6×10^{-2}
Crushing Dressing	.2 - .6	2 - 6
Reducing	10 - 200	10 - 200
Support Maintenance Telemetry Instruments Life Support/ Environ. Control	2×10^{-2}	2×10^{-1}
Return Transportation	2 - 4	2 - 4
TOTAL	≈20 - 200	≈20 - 200

exceeds the current total U.S. generating capacity by almost an order of magnitude, and the average large terrestrial generating capacity by four orders of magnitude. Since not all factors will likely combine to give the maximum figure, 10^6 kilowatts--or the size of current large terrestrial stations--may be a reasonable nominal for scaling purposes. (SSPS concept is sized at 10^7 kilowatts.) (ref. 49). This provides almost an order of magnitude excess capacity when producing 4.5 x 10^6 kilograms per year of minerals which should be adequate to account for surges in power requirements during equipment start-up and electromagnetic accelerator use.

System Selection

As of the present time, no system of sufficient size to meet the needs determined for this study has been built which can operate in the lunar environment. Systems built for operation in space have thus far been only very small--a few kilowatts, while terrestrial systems of appropriate size (i.e., nuclear power plants generating a GW or so) are designed to use large quantities of cooling water. The system used will, therefore, require research, development, and construction to skirt the cooling problem. A good deal of ingenious design in the use of lunar materials and surface characteristics will be necessary in order to minimize the weight transferred to the moon.

The systems which might be used to satisfy lunar mining power requirements are described in more detail below.

Surface Solar Cells

Sunlight, falling undiminished by atmospheric interference on the lunar surface constitutes a great source of energy. An acre (4,050 square meters) of solar cells at 15 percent conversion efficiency would produce 850 kilowatts continuously during the two week sunlight period. Solar cell efficiencies could improve to 20 percent by the year 2000. The 15 percent figure should thus adequately cover uncertainties in dust and degradation. The biggest handicap associated with solar cells is the lunar night. If power is to be maintained during the lunar night, it must either be generated during the day and stored for nighttime usage or it must be generated on a sunlit portion of the surface and transmitted to the dark side. It would also be possible--but the advantages of the concept are not clear--to put large arrays in lunar orbit and transmit the energy to the surface via microwave or laser.

On a continuous day-night operation, one acre of solar cells would provide about 300 kilowatts usable power because 550 kilowatts will be required to charge either batteries or regenerative fuel cells for night power. 12×10^6 square meters (three thousand acres) then would be required to provide 1 GW. And at the rate of 50 watt-hours/kg capability of batteries, approximately 10^{10} kg of batteries would be required. The 12 million square meters (3,000 acres) of solar cells would weigh at least 20 million kilograms--a large number but dwarfed by the battery requirement. If long-lived regenerative fuel cells should become available, the 10^{10} kg of batteries might be reduced to as low as 10^8 kg. The total system weight would then be between 10^8 to 10^9 kg to generate 1 GW continuously.

The cost of such a system is quite speculative considering the range between present and projected solar cell costs. At today's costs, the solar cells and fuel cells could each cost over $\$10^{11}$, although optimistic projections might be as low as $\$10^9$ each. Transportation costs are equally uncertain, varying from $\$10^{11}$ to $\$10^{12}$ for 1 GW. These data are summarized in table 4-2.

TABLE 4-2 SOLAR POWER SYSTEM CHARACTERISTICS

1 GW

	Eff	Area	Weight (kg)	Cost	Trans. Cost ($550/kg)
Solar Cells	15%	$12 \times 10^6 M^2$ (3000 acre)	$1\text{-}50 \times 10^6$	$\$10^9\text{-}10^{11}$	$\$10^9\text{-}10^{11}$
Batteries	60%	-	10^{10}	$\$10^{11}$	$\$10^{13}$
Fuel Cells	60%	-	$10^8\text{-}10^9$	$\$10^8\text{-}10^{11}$	$\$10^{11}\text{-}10^{12}$

Nuclear Systems

The most likely nuclear lunar power system candidate would combine the characteristics of a conventional (advanced) terrestrial nuclear power station and a nuclear space power system. Basically, it would include a large nuclear reactor, turbines, etc., but would be cooled with radiators instead of externally supplied water. In addition to the difference in cooling system, significant changes in construction philosophy will be necessary to take advantage of the lunar materials and terrain. For example, it may be possible to construct some of the foundations and building with lunar soil. Obviously, too, some design ingenuity will be required to accommodate the payload size requirements to match the transportation system.

There are many types of terrestrial reactor systems. All generate heat to run steam turbines and generators, but there are several fuel forms, moderator materials, and reactor coolant fluids. Because of the necessity of using radiators for cooling, it would be wise to select a reactor which operates at high temperature so that the heat rejection temperature can be well above the ambient lunar temperature, while still maintaining a great enough overall cycle temperature drop for good efficiency. Some reactor types and characteristics are given in table 4-3.

Using the high temperature graphite moderated reactor (HTGR) system as a baseline, it is possible to establish the approximate characteristics of a large lunar power station. The Gulf General Atomic Fort St. Vrain HTGR facility will produce steam at 810°K (1,000°F) and 17 x 10^6 N/m^2 (2,400 psig). The feed water will be at 480°K (403°F) after some treatment and heating. This system will operate at 330,000 KW_e with an overall efficiency of 39.23 percent. Based on this concept, 1,540,000 KW_e would have to be rejected from a 1 GW_e plant with entrance and exit temperatures below 810°K and 480°K, respectively. According to reference 30, a radiator oriented vertically on the lunar equator would be subject to an effective sink temperature of about 330°K (600°R) during the day and about 110°K (200°R) during the lunar night. Under these conditions, the radiator area requirement would be about 0.5-1.0 square meters (5-10 square

TABLE 4-3 REACTOR CHARACTERISTICS

Type	Coolant Temp.	Coolant Pressure	Fuel	Coolant	Gen Steam Temp.	Generator Steam Pressure	Typ Eff	Work Fluid Ret Temp
Pressurized Water Reactor (PWR)	$590+^{o}K$	15×10^6 N/m^2	3% - U^{235}	H_2O	$590^{o}K$	5.5×10^6 N/m^2	33%	
Boiling Water Reactor (BWR)	Similar to PWR except coolant water is allowed to boil and sent directly to turbine.							
Advanced Gas Cooled Reactor (AGR)				CO_2	$840^{o}K$	15.95×10^6 N/m^2		
High Temp Graphite-Moderated Reactor (HTGR)	$1090^{o}K$			He	$840^{o}K$	2.41×10^6 N/m^2	up to 33%	$478^{o}K$
Heavy Water Moderated Reactor (HWR)				Organics P_2O, H_2O CO_2				
Molten Salt Reactor (MSR)			Thorium-U^{233} Breeder U^{235}, Pa				44%	
Fast Breeder Reactor (FBR)			Pu, U	Liquid Metal			44%	

feet) for each thermal kilowatt rejected (refs. 50 and 51). This comes to, perhaps, 5×10^5 square meters (5×10^6 square feet), using both sides, and a similar number of kilograms weight. The shipping cost would be over $\$10^9$.

Extrapolating the Fort St. Vrain and other equipment data, the reactor, the helium circulation system, the steam generators, and the enclosing pre-stressed concrete reactor vessel (PCRV) can be expected to weigh more than 5×10^7 kilograms (10^8 lb.). The turbines and generator will probably weigh 5×10^6 kilograms (10^7 lb.). Including auxiliary equipment, controls, structure, etc., the total weight will be about 10^8 kilograms or 100 kilograms per kilowatt. The shipping cost for the whole system will exceed $50 billion, unless lunar materials are used in construction.

Fusion

There are great hopes that fusion reactors will be the solution to man's growing demand for energy--on the earth and moon as well. It is easy to see why a controlled fusion reactor with its high power density, high temperatures, and cheap fuel is attractive. Since it has not been determined just how a fusion reaction will be started, maintained, or used, it is difficult to speculate on system weights. Conceivably, the fusion reactor could be much lighter than the reactor vessel described for fission, and if the heat is applied directly to mineral processing, much of the conversion machinery may be unnecessary.

Speaking of torroidal fusion reactors for the generation of electricity, Carruthers, et al., (ref. 52), concludes that such systems may be cost wise competitive with fission reactor systems by the year 2000. With costs at comparable levels, the more important consideration is weight since the largest part of installed cost is for transportation. If system weights can be brought down to 20 kg/KW_e (50 lb/KW_e) the shipping cost for a 1 GW system would be in excess of $6 billion. Assuming that the power station has a lifetime of 30 years, it results in a power cost of approximately 5 cents per kilowatt-hour.

LUNAR MINERAL MINING

For planning purposes, terrestrial mining methods will be used as a basis for analyzing, selecting, and optimizing proposed lunar mining techniques. Certain constraints on terrestrial mining operations would not be applicable to lunar mining, and conversely, lunar mining would be constrained by factors not relevant on earth.

Background

The progress of terrestrial mining is marked by two important factors:

1. The evolution of mining methodology has been characterized almost exclusively by the increased use of more efficient high capacity machinery--the actual processes have changed little: breakage, loading (mucking), and haulage.

2. Each mineral deposit has unique characteristics--its morphology, petrology, and minerology demand special methods of mining and carefully-selected equipment to maximize extractive efficiency.

The current mining methods employed in extracting terrestrial minerals are surface and underground mining. The choice of method depends upon the size and shape of the mineral deposit, the depth of the deposit, the economic analysis of the ore grade versus the cost of overburden removal, the value of the surface land for other uses (e.g., farming). The economies of scale, flexibility, and early productivity normally favor surface mining.

Terrestrial Mining Operations

Surface Mining. - Open-pit bench or strip mining (refs. 53 and 54) required the removal of an overburden of waste covering the ore-rich rock. Both overburden and ore-bearing rock are broken by machine drilling and low cost explosive (e.g., ammonium nitrate). The overburden is removed normally by massive power shovels capable of scooping 54 cubic meters (70 cubic yards or 100+ tons) per bite, 40 x 10^6 kilograms

(41,000 tons) per shift. In certain sites, a dragline bucket is superior to the shovel. Following overburden removal, the ore is broken and usually loaded with smaller electric shovels of 13,600 kilogram (15 ton) per bite capacity into rail cars, trucks, or occasionally conveyors. Dredging and hydraulic mining will not be discussed because of their lack of relevance to the lunar environment.

At present, nearly 90 percent of our mining tonnage is moved by surface mining methods. While this type of mining is not universally applicable to all minerals in all areas, it does have significant inherent advantages. One advantage is the greater economies attainable through increases in scale. In part, these scale factors are possible because of equipment efficiencies which are the result of research performed by other sectors of our economy. A second inherent advantage of surface mining is the greater flexibility of operation possible through this method. This flexibility is related both to the preproduction development of the property and scheduling of operations within the pit. Surface properties are traditionally brought into production in one third to one tenth of the time required by underground operations. However, as surface minable deposits are depleted or become uneconomic, it is inevitable that we must turn to large scale underground mining.

The most immediate payoff for accelerated research and development of underground mining methods lies in converting known marginal deposits (copper, zinc, silver, etc.) to minable resources. For example, the large low-grade deposits of native and porphyry copper ores are too deep for surface mining yet suitable technology for massive scale underground mining is not available. Millions of tons of 0.5 percent to 1 percent plus copper ores occurring in the Nonesuch Shale of upper Michigan constitute a major potential source of copper within the continental United States.

Low grade deposits of this type present unique environmental and economic problems because of the large volumes of ore which must be freed and transported and the volumes of waste materials which must be disposed of. Our technology is not motivated to provide solutions so long as richer grades are available. Research performed now to supply the necessary technology can ensure minimum cost impact when our nation must turn to those reserves to meet our needs.

Underground Mining. - The mining of extremely deep mineral deposits also is beset with problems. Since temperature and rock pressure increase with depth, the environmental and ground control problems associated with deep mining become critical. Safer, faster, and more economical means must be developed to mine these deposits.

Underground mineral deposits (refs. 53 and 54) are reached by a series of shafts, tunnels, etc. The latter are the result of drilling, blasting, and shoring (bracing) as necessary to assure safety to men and equipment. The working space (active mining face) within underground mines is called the stope, of which there are many types depending on the site and nature of the mineral deposit, the surrounding ground, etc. The underground mine usually requires tunnel roof-bolting or shoring to protect against roof falls. Ventilation is an absolute requirement to remove explosive or poisonous gases and dust, and to provide a means for regulating the temperature for worker comfort. Most underground mines require extensive pumping equipment to remove water seepage to the surface. Lastly, each mine must be provided with adequate lighting for visibility and safety.

As with surface mining, the mineral ore is drilled with compressed air drills and broken with permissible explosives (those that will not contribute to secondary dangerous gas or dust explosions such as liquid oxygen and occasionally compressed air). In certain mines, the mined mineral is a soft composite, in which case crawler mounted rippers, cutters, or continuous auger mining machines can be utilized to break the mineral ore from its surroundings. The broken ore is next loaded onto electric shuttle cars or continuous conveyors or lifts by means of slushers, overshot loaders, or front-end loaders, all of which employ buckets ranging in capacity from about 0.25 to 1.5 cubic meters (9 to 50 cubic feet) per bite. By necessity, the size of underground mining equipment and scale of operation is significantly smaller than in surface mining. For example, most of the equipment would not exceed 9 meters (30 feet) in length, 1.3 meters (4 feet) in height, or 3.7 meters (12 feet) in width; maximum unit weight is about 45,000 kilograms (100,000 pounds). Haulage (ore handling and transportation) may be by electric locomotive pulling a string of cars, by tired trucks (electric or diesel) of 36,000 kilogram (forty ton) unit capacity, or by belt or triple chain conveyors.

The development phases of deep marginal mineral resource deposits will require significant improvements in excavation technology to create the openings by which the deposit is to be mined. A better understanding of the geologic and hydrologic features as they affect stress distributions and the subsequent mine design is required. This, in turn, calls for improved methods to identify these critical parameters in advance of excavation. Present techniques permit only limited information to be obtained in the immediate vicinity of the mine openings and are obtainable only after a significant commitment to a mining plan is made. Advanced methods for terrestrial mining which can be employed to delineate ground conditions remotely on exploratory locations are, therefore, ugently needed.

The extraction, as well as the development stages of deep-earth mining, will require advanced mining techniques to cope with the harsher environments imposed by mining at increased depths. Completely automated systems of excavation and mineral extraction are needed to permit workers to perform their tasks away from areas of poor ground or environmental conditions while simultaneously obtaining economical mineral extraction. Required is the implementation of remote control and sensing technology to provide a mechanism for discriminating between valuable and waste material and a means of communicating this information to remote locations where feedback control mechanisms to direct the mining system can be employed.

Lunar Mining Operations

Since the earliest likely time frame for commencing lunar or planetary mining operations will be early twenty-first century, certain methodological assumptions must be defined.

Conventional terrestrial mining methods can be expected to evolve with increased emphasis on worker safety and comfort, greater productivity, and environmental protection. Therefore, it is assumed that most mining operations will be remotely controlled, highly-automated and characterized by at least an order of magnitude greater productivity and scale of operation.

As will be discussed later in this section, conventional earth deep and surface mining methods are unsuitable for direct transfer to lunar mining.

Lunar mining with conventional, remotely-controlled terrestrial mining equipment offers numerous advantages. These include decreased equipment wear due to the reduced gravitational force, lack of water which is an obstacle in most deep earth mining, roof falls should be less frequent due to lower gravity (yet cohesive strength of rock should be equivalent), apparent absence of contained explosive or poisonous gases and the lack of oxygen atmosphere precludes spontaneous dust explosions. The negative aspects of lunar mining with modified conventional earth mining equipment (beside transportation costs) include difficult operational maintenance (bearing lubrication, etc.), wear replacement (drill bits, etc.), and the effects of extreme lunar temperature variations (with surface operations).

The factors of cost, maintenance, wear, and hostile environment (for the equipment) associated with transfer of terrestrial mining methods to the moon suggest that advanced unconventional electro concepts should be considered. Examples of these concepts, are: elcecto-thermal rock boring, high-power laser breakage, liquid silicon "water" cannon breakage, on-site electrolytic furnace to reduce oxides and separate metals, and fusion "torch."

Lunar Mining

Conventional Equipment. - For optimum remote guidance and control, the drilling, explosive loading, ore-loading and initial conveying operations should be consolidated on a single, caterpillar-crawler, electric-powered vehicle similar to that shown in figures 5-1 and 5-2. The ganged-drills advance into the rock working face through holes in the blast-shield/loading bucket. Upon completion of drilling and drill retraction, the explosive loading tubes are indexed to the holes and the explosive, similar to 1.9 centimeter (3/4 inch) diameter primacord, is fed into the loading tubes from continuous reels in appropriate lengths. The nose of each section of primacord is capped with a pointed steel conical head with spring-steel flutes which dig into the drill hole and hold the length of primacord in position as the loading tube retracts. The rear end of the primacord is capped with a detonator and sleeve which uncouples from the nose of the next length of primacord. After drilling and loading the explosive at the working face, the mining rig backs off, the charge is detonated remotely by radio waves, and the machine returns to commence ore loading. Mechanical or hydraulic jacks raise the front end of the bucket/hopper/conveying system and the bucket loads the broken ore into the feed hopper which feeds the loading conveyor. This conveyor serves also as a protective canopy against possible roof falls and has sufficient strength and capability to remove the fallen rock so that the mining machine may be backed out of the critical area. It should be noted that an automatic roof-bolter could be fitted to this machine if necessary to prevent roof falls. The mining machine conveyor discharges into a second hopper which then discharges onto the narrower, 0.9 meter (36 inch) wide, continuous conveyor train. The latter is advanced by the mining machine and individual drive motors.

The mining machine and conveyor train are remotely controlled from a block-house control center. All drive motors are variable speed,

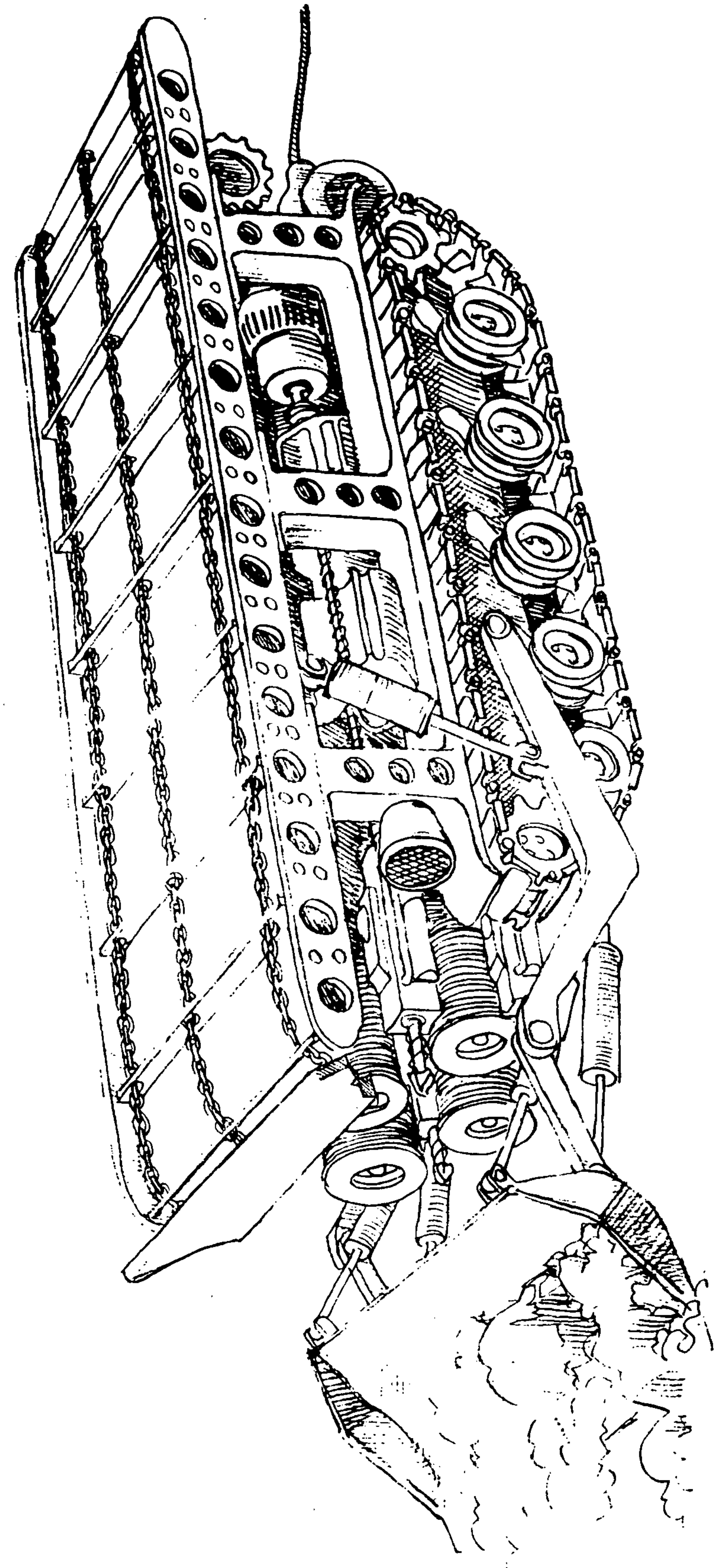

Figure 5-1 Automatic Lunar Miner.

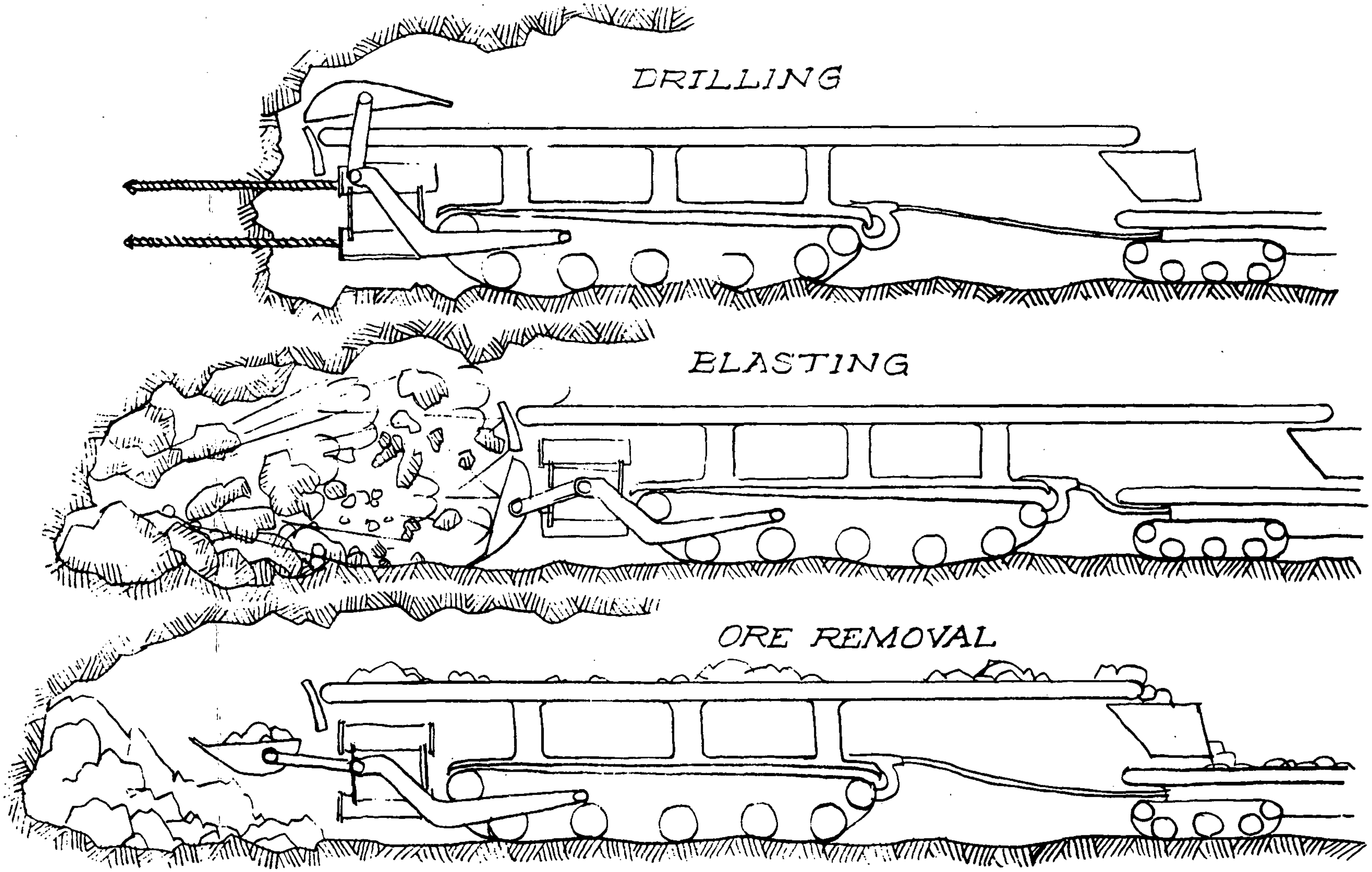

Figure 5-2 Mining Sequence--Automatic Lunar Miner.

oil-cooled with sealed carbon alloy bearings. Sensors on the drills provide force and heat-temperature feedback to the remote control station. Broad-spectrum remote sensors along with stereo TV cameras will provide "visual" feedback. Drill-angle and subsequent ore-loading determine the path, horizontal or inclined, the machine will be directed to follow. Most of the ore-tracking and machine guidance is remotely and automatically controlled by a central computer located in the blockhouse. A manual executive override mode is available to the operator for emergency situations. The following description of an automatic miner developed by Joy Manufacturing in 1960 should provide a better understanding of the type of equipment that should be available by the year 2000 with obvious improvements in sensors, guidance control, and computer artificial intelligence that has and will take place in the interim.

> The Joy Pushbutton Miner (ref. 55) consists of three basic parts: (1) the boring machine; (2) the conveyor train; and (3) the conveyor storage mechanism called the "Heli-Track." The mining and conveying portion of the machine is best understood by visualizing a 300 meter (1000 foot) long machine, headed by a boring machine and followed by sixty 5.2 meter (17 foot) long conveyors. The Pushbutton Miner boring machine is a boring type continuous miner, mounted on twin crawler assemblies. It is capable of cutting a continuously adjustable height of seam between 0.9 and 1.2 meters (36 and 48 inches) and width of 3 meters (12 feet). At all times, the boring machine and conveying line are an integral unit, moving in synchronism both forward and in reverse as coal is mined or when retreating from a mined-out area. In order to mine coal, the operator, who is located in the control cab alongside of the launching platform, first properly directs the boring machine into the coal face by hydraulically adjusting the launching platform on which the boring machine rests. After the boring machine is properly directed, he may completely control the mining process from

his position and advance the boring machine into the coal seam by controlling all operations remotely. As soon as the hole has been mined to its extremity of 300 meters (1000 feet), the machine is retracted and stored on the Heli-Track structure, which is self-propelled. The Heli-Track then moves down the highwall approximately four meters (twelve feet) in order to start the next hole.

Overall weight of the future lunar mining machine is estimated at about 18,000 kilograms (20 tons). Its overall dimensions are 2.4 meters (8 feet) high by 3 meters (10 feet) wide by 9 meters (30 feet) long. The capacity of the machine is limited by the drilling rate which was assumed to be 1.8 meters per hour for a 3.2 centimeter diameter drill, using 16 drills spaced over a 2.4 x 2.4 meter (8 x 8 foot) working face. Using conventional drills, one machine can break 3.0×10^8 kilograms (6.5×10^8 pounds) of rock per year under continuous operation. Assuming an equipment efficiency of 50 percent, this results in 1.5×10^8 kilograms of rock per year. In order to derive 4.5×10^5 kilograms (10^6 pounds) of pure mineral from 1 percent ore rock*, one machine (only 30 percent of machine capacity is used) is required; for 4.5×10^8 kilograms (10^9 pounds) of pure mineral, 300 machines are required. The number of mining machines and conveyors required and their weights and power needs as functions of production rate are shown in table 5-1. At the transportation cost from earth to moon of $550 per kilogram ($250 per pound) and an assumed equipment life of five years, the initial equipment amortization cost ranges from $50.70 per kilogram ($4.5 \times 10^5$ kg/yr) to $1.56 per kilogram ($4.5 \times 10^8$ kg/yr) for pure mineral extracted. Cost of explosives consumed is $55 per kilogram of pure mineral (1×10^{-3} kg of explosive required per kilogram of ore broken). Power requirements for the mining machine and 3,000 meter (10,000 foot) continuous conveyor (refs. 56 and 57) are estimated at 147 kW, or 1.28×10^6 kWh/year continuous operation per unit; 300 units would

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* Throughout this lunar mining section, the lunar ore is assumed to contain only 1 percent pure mineral; therefore 4.5×10^8 kilograms of ore must be mined to yield 4.5×10^6 kilograms of mineral.

TABLE 5-1 LUNAR MINING AND CONVEYING EQUIPMENT WEIGHT AND POWER SUMMARY

Lunar Mining Machine

Ore		No. of	Weight		Power
lbs/yr	kg/yr	Units	kg.	lbs.	KWh/yr
10^8	4.5×10^7	1	0.18×10^5	0.4×10^5	1.26×10^6
10^9	4.5×10^8	3	0.54×10^5	1.2×10^5	2.65×10^6
10^{10}	4.5×10^9	30	5.4×10^5	12.0×10^5	20.2×10^6
10^{11}	4.5×10^{10}	300	54×10^5	120.0×10^5	202×10^6

Conveyors (44 and 56)

10^8	4.5×10^7	1	1.9×10^5	4.2×10^5	$.02 \times 10^6$
10^9	4.5×10^8	1	1.9×10^5	4.2×10^5	$.25 \times 10^6$
10^{10}	4.5×10^9	1	1.9×10^5	4.2×10^5	2.5×10^6
10^{11}	4.5×10^{10}	5	9.5×10^5	21.0×10^5	25×10^6

Equipment Summary - Weight and Power

10^8	4.5×10^7		2.1×10^5	4.6×10^5	1.28×10^6
10^9	4.5×10^8		2.4×10^5	5.4×10^5	2.9×10^6
10^{10}	4.5×10^9		7.3×10^5	16.2×10^5	22.7×10^6
10^{11}	4.5×10^{10}		64×10^5	141×10^5	227×10^6

require 227 x 10^7 kWh/yr. Power costs would range from \$0.29 per kilogram of mineral at 4.5 x 10^5 kg/yr to \$0.05 per kilogram of mineral at 4.5 x 10^8 kg/yr (10^9 lbs/yr).

Summary of Lunar Mining Operations with Conventional Equipment. - The total cost (\$/kg mineral) of lunar mining operations with conventional equipment is shown in table 5-2.

Principal problems associated with lunar use of conventional mining methods, remotely operated as previously outlined, are the following:

1. Supply of consumables such as explosive detonating cable and drill bits.

2. Lubrication of bearings, etc., under extreme lunar environmental conditions (vacuum, temperature range, and abrasive dust).

3. General maintenance of operating equipment.

Possible solutions to breakage problems may lie in substituting "subterrenes" (thermal borers) (ref. 58) for conventional drills and piped gas (hydrogen transported from earth or LOX obtained from oxide reduction) as the explosive agent. Lubrication might not be a problem with the advent of the new "carbon/molallay" self-lubrication bearings (ref. 59) currently capable of operating at 1.3 x 10^8 n/m^2 (15,000 psi) and from 219°K to 395°K (-65° to 250°F) unaffected by dust or dirt. General maintenance would appear to be the most critical problem to resolve considering the large amount of maintenance required on current equipment operating in the much less hostile environment of earth, and the difficulties associated with monitoring (remotely) the many moving parts associated with mining and conveying equipment.

Electrothermal Boring Equipment (Subterrene). - A five centimeter (two-inch) diameter prototype thermal borer (ref. 58) has been developed

TABLE 5-2 SUMMARY OF LUNAR MINING OPERATIONS WITH CONVENTIONAL EQUIPMENT

	Kilograms of Ore Mined Per Year			
	4.50×10^7	4.50×10^8	4.50×10^9	4.50×10^{10}
Number of Mining Machines	1	3	30	300
Machine and Conveyor Weight	2.1×10^5	2.4×10^5	7.3×10^5	6.40×10^6
Machine Cost Per Kg of Refined Mineral	$50.70	$ 5.95	$ 1.79	$ 1.56
Explosives Weight, kg/yr	4.50×10^4	4.50×10^5	4.50×10^6	4.50×10^7
Explosives Cost Per Kg of Refined Mineral	$55.00	$55.00	$55.00	$55.00
Power Required, KWh/yr	1.28×10^6	2.90×10^6	22.7×10^6	227×10^6
Power Cost Per Kg of Refined Mineral	$0.29	$ 0.07	$ 0.05	$ 0.05
Total Cost Per Kg of Refined Mineral	$106.00 $ 48.13/lb	$61.10 $27.73/lb	$56.90 $25.83/lb	$56.70 $25.73/lb

and tested by the Los Alamos Scientific Laboratory. This thermal borer, or subterrene, (see figure 5-3) has successfully melted a five centimeter (two-inch) diameter hole 10.7 meters (35 feet) deep in hard rock at the rate of 76 centimeters (30 inches) per hour at an operating temperature of about 1200°C. The test unit is powered by 3 Kw_e. The Project Office predicts that within 15 years a subterrene powered by an onboard nuclear reactor will be capable of driving a ten meter (35 foot) wide tunnel at 90 meters per day (300 feet/day) with a power requirement of 10-50 MW_e. This is equivalent to displacing 24 x 10^6 kilograms (53 million pounds) of rock per day, or 9 x 10^9 kilograms (19.5 billion pounds) per year, at an estimated power requirement five times that of conventional boring and conveying equipment. Advantages over conventional methods would be a reduction in mechanical wear (drills and rock cutters), the elimination of waste removal and ease of guidance making the subterrene readily adaptable to remote or robotic onboard control.

As the subterrene advances, melting the rock at its conical nose, the molten rock is pushed aside and forced into surrounding fractures and voids. The machine subsequently freezes the rock forming an obsidian-like wall with a compressive strength 20 times that of concrete, thus eliminating the need for a support structure or roof-bolting.

A possible use of a large sized thermal borer would be to couple it to an electrolytic separator to perform the mining and refining operations simultaneously. Molten ore will be fed from the borer to the electrolytic separator where an electric field will separate the valuable minerals from melt. The desired minerals will be placed in molds and solidified for easy transport to a storage site on the surface. The molten waste material from the separator will be fed back to the borer to be forced into the surrounding rocks to form the tunnel walls. Some further details on the electrolytic separator are presented later. This concept appears to be promising but the lack of any concrete data at this time makes its evaluation impossible.

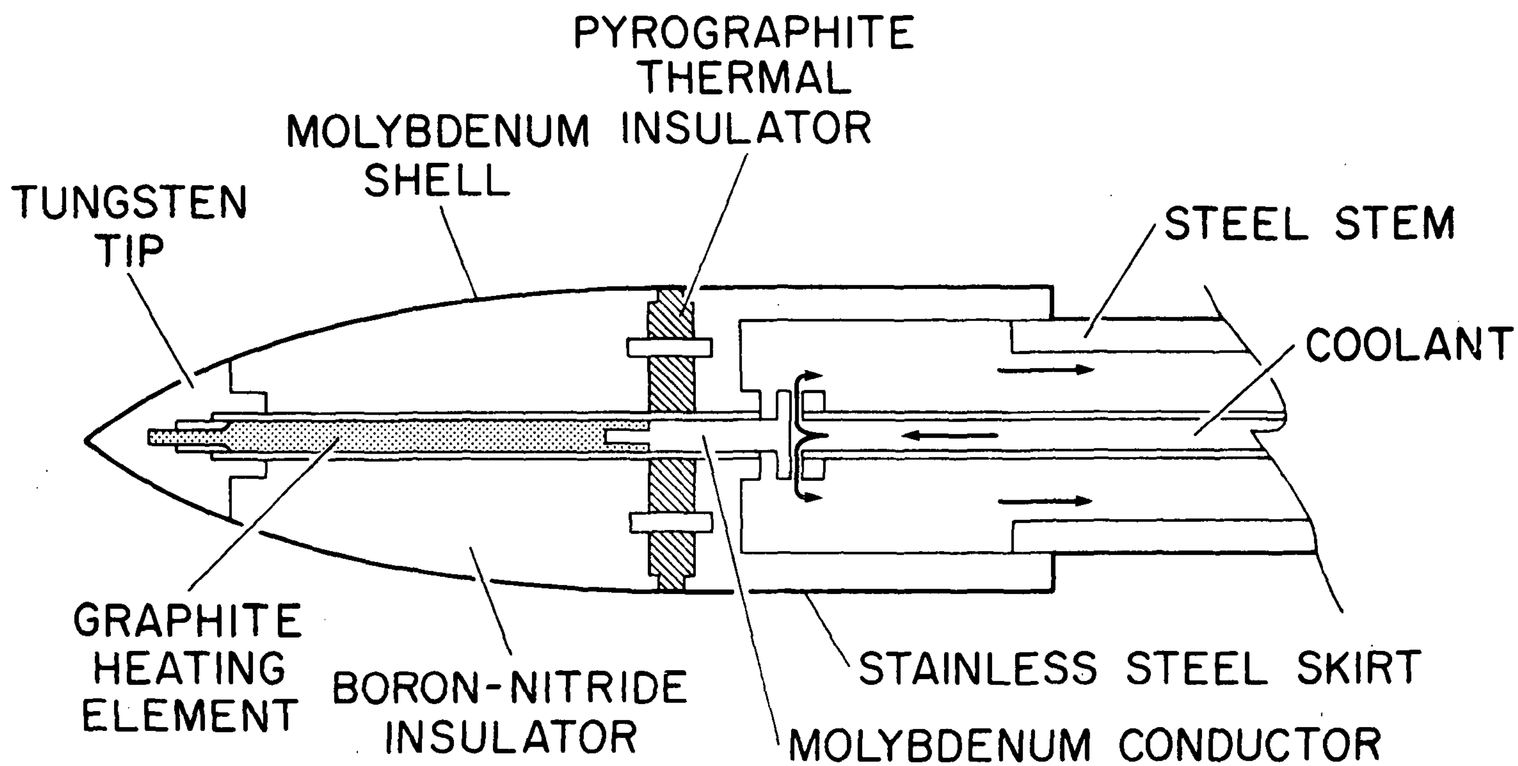

Figure 5-3 Thermal Borer (Subterrene).

Dielectric/Laser Rock Breakage. - The U. S. Bureau of Mines has been continuing research studies to understand the thermal fragmentation of rock (ref. 60). Thermal stresses are induced in rock by non-uniform heating or by temperature change in a localized region of rock restrained from free thermal expansion. The thermal failure (spalling) of rock can be achieved by impingement of heat flux from a high-temperature (and energy) heat source including gaseous combustion, carbon electrodes, ionized plasma, electron gun or laser.

The electrical properties of rocks vary greatly with composition, structure, and texture. Dielectric rocks, for example, are easily fragmented with high frequency electrical energy including microwave.

Rock fragmentation has been achieved with dielectric heating below 100 MHz in Charcoal Granite and Dresser Basalt; temperatures were maintained below 550°C. The heated volume of rock for fragmentation was less than 2 percent of the surrounding fragmented rock and energy consumption was in the range of 3.5 to 6.5 kWh per cubic meter of fragmented rock.

Lasers offer an interesting possibility in this application should their efficiency be greatly improved. Dielectric heating requires that the rock be drilled for subsequent electrode insertion; the use of lasers would alleviate this costly and technically difficult constraint. Should laser efficiency equal or exceed dielectric efficiency, power consumption in lunar mining could be reduced to approxmately one-fifth that required by conventional equipment.

Water Cannon Breakage. - A high-pressure water cannon (ref. 61), designated TS-1, has been designed and built for the Department of Transportation by Terraspace, Inc.* The Model TS-1 water cannon has been designed to produce pulsed water jets at pressures of 2×10^9 to 7×10^9 N/m^2 (300,000 to 1,000,000 psi) for experiments in hard rock tunneling.

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* D.O.T. Contract DOT-FR-00017

The method for achieving these high pressures is based on Russian technology and utilizes a unique cumulation nozzle patent for which Terraspace, Inc., holds the U.S. license. Prior experiments have indicated that water jets in this pressure range may be useful for fracturing hard rock. These experiments have shown that high pressure water jets can erode, spall and split rock and that the energy required to fracture a given volume of hard rock generally decreases as jet pressures are raised in the range from 35×10^7 to 12×10^8 n/m^2 (50,000 to 175,000 psi) and higher.

The system has been designed to permit one shot every five minutes but can be modified to permit cyclic operation at a pulse rate of approximately 10 to 20 pulses per minute. The energy per pulse was set to be a minimum of 68,000 joules (50,000 ft-lbs), and the nominal design point finally selected was 127,000 joules (93,500 ft-lbs). The jet diameter is 0.69 centimeter (0.27 inch).

Power requirements for the water cannon have been calculated to range from 1.0 MW_e per 10^9 kg of ore to 1.0 MW_e per 10^{11} kg of ore; about equivalent to conventional mining equipment power requirements.

A serious drawback to the use of a remotely-controlled water cannon in lunar mining application is the projected cost of transporting water from earth to the moon. The existing cannon uses about 1,900 kg/min (4,150 lbs/min) to blast about 113,000 kilograms (250,000 pounds) of rock, or 27 kilograms (60 pounds) of rock (ore) per kilogram of water. Thus at the nominal earth/lunar transportation cost of $550 per kilogram ($250 per pound), the water would impose a cost of about $20 per kilogram of ore. It is conceivable that molten lunar silicates from the refining operation could be (viscosity and operating temperatures permitting) substituted for water in a specially adapted system. If this concept proved feasible, the water "silicate" cannon would offer an attractive method for lunar rock breakage.

On-Site Electrolytic Furnace/Fusion Torch. - Possibly the most cost-effective, practical, but yet least proven concept for extracting and reducing lunar minerals to pure metal would be the utilization of an on-site electrolytic furnace or fusion torch to melt the heterogeneous rock and to electrochemically separate the selected metal ions while in melt solution utilizing the differential electrochemical potentials of each metal. The fusion torch and the electrochemical separation concepts are described further in the following section on mineral dressing and refining.

MINERAL DRESSING AND REFINING

This section discusses all the processes that the ore goes through from the time it leaves the mine shaft or pit until it emerges refined into a pure basic mineral. This section of the study is divided into two subsections; first, mineral dressing, which is the mechanical preparation and concentration of the ore, and second, mineral refining where the ore is processed into its pure elemental form.

Because this study is of an operation that is expected to occur approximately 30 years in the future and in an almost totally alien environment, innovative processes encompassing possible future developments in refining and the constraints of the new environment on refining are included. Those processes currently used in mineral dressing and reduction were carefully assessed and formed the basis of the processes discussed in this part of the study. The advanced methods are hypothesized using those new technologies that are expected to emerge in the time period appropriate to study. The lunar environment plays a strong role in the evolution of refining procedures arrived at in the study.

Mineral Dressing

Background. - The process of mechanically preparing and separating the valuable ore or mineral from the mixture of ore and gangue is referred to as mineral or ore dressing. This is usually the first process that the ore undergoes after being mined. The ore dressing can be as simple as a water wash and hand-picking the rich and valuable ore, or be a much more elaborate procedure using complex equipment. For the majority of ores, the elaborate procedure is necessary. A schematic flow diagram of the mineral dressing process is shown in figure 6-1.

The ore delivered from the mine is an aggregate of different sizes, ranging from 20 to 200 centimeters generally, and the first step in the process is to put the ore through a series of crushing and screening operations to reduce the ore to approximately 0.5 to 2 centimeters for

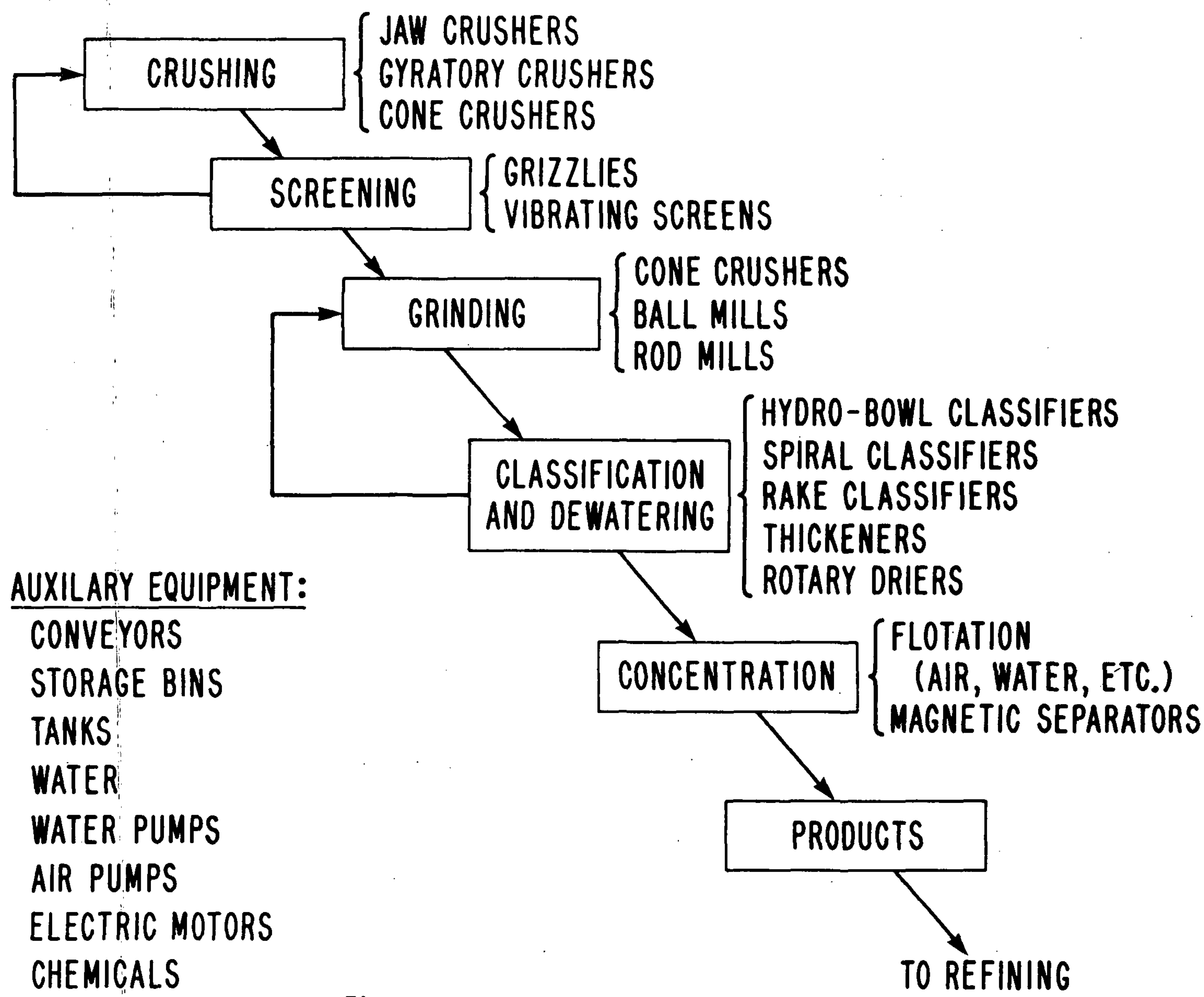

Figure 6-1 Terrestrial Mineral Dressing.

feeding to the grinding operation. The second operation, screening, overlaps the crushing and grinding operations, and its purpose is to separate those pieces which require further crushing or grinding from those that can be sent to succeeding processing operations. In ore dressing, it is often necessary that the ore be reduced to a specific size, depending on the mineral, before the valuable minerals are unlocked and the process of concentrating can proceed. The third step, grinding, reduces the ore to the desired sizes which can be 10 microns or even smaller. The crushing and grinding operations are often done in a series of steps to increase the capacity and efficiency of these operations. The process of classification, the fourth step, is the sizing procedure (further screening) to assure that the grinding process achieves the desired ore size so that the ore can be concentrated. The method used in the fifth step, concentrating, is largely dependent on the mineral. For example; magnetic separation can be used with magnetic minerals, electrostatic separation can be used with minerals possessing electric properties, gravity separation can be used with minerals of differing densities, and surface properties can be used to effect separation by flotation. The concentrate or product as referred to in figure 6-1 will be sent on for processing (refining) to the base mineral.

The type of ore and the location of the mine will dictate whether the mineral dressing process will be primarily a dry or wet operation, the number of intermediate steps that each of the five major operations will have, as well as the equipment choice for each process step. Listings of representative equipment (terrestrial) used in each of the five operations along with their pertinent statistics may be found in reference 45. Flow diagrams for the mineral dressing operations of several minerals are also covered in reference 45.

Discussions of current mineral dressing technology and how it could be adapted to lunar mineral separation are covered in the following paragraphs. The constraints and shortcomings of current mineral dressing technology for lunar mining applications will be addressed and some possible solutions, based on future (circa 2000 A.D.) technology, will be discussed.

Current Terrestrial Mineral Dressing Technology. - The principal methods used to process the ores subsequent to mineral refining have not changed appreciably in several decades, although equipment sizes have increased to meet increased production requirements and the process efficiency has been improved by automation and the use of computer control. Automation has significantly reduced process cost by improving efficiencies and reducing labor so that lower grades of ores are being processed economically.

The current technology used in mineral dressing is the result of evolutionary changes over the years. For example, historically, as new power sources such as the steam engine and the electric motor became available, they were adapted into the ore dressing process. As newer and better chemicals became available, they too were adapted into the process. Automated process controls are being used more and more to improve efficiency and to keep process costs controlled as labor costs increase. This has led to current mineral dressing processes based on old methods with patchwork of modern accessory technology. But this has resulted in surprisingly economical processing systems.

Future Terrestrial Mineral Dressing Technology. - Changes and refinements to current processes will continue as new techniques are introduced into the process chain to reduce costs. The rate at which these changes occur will be strongly affected by ore grades and availability, economics (labor and equipment costs) and market requirements. If past performance in this area is an indicator, only slow adaptive changes, the minimal, can be expected. This will be unfortunate because, in the immediate future, severely restrictive environmental laws can be expected to be passed. These laws will require rapid or immediate changes in processes to limit polluting the environment. The quality requirements for effluent water and air will require drastic process changes and sharp increases in process costs. The ore processing industry will probably be unable to meet these stringent requirements by taking the adaptive add-on type of approach to solving the problems. Thus, the industry may have to look to new innovative methods such as those discussed later in this section for lunar ore processing. Unfortunately, these technologies are not being developed currently and will not be available soon. If the mineral industry fails to meet the environmental restrictions, then it may be forced to depend even more heavily on external (other countries) sources for minerals.

Lunar Mineral Dressing - Background. - The progress in mineral dressing procedures, as noted above, is not expected to change drastically unless the industry is confronted with the question of survival. Since projections of the future to the degree of detail required to realize quantitative results are not feasible here, the base mineral dressing technology for lunar use that has been chosen for this study is an adaptation of current terrestrial technology. Differences in lunar and terrestrial environment are accounted for. As with terrestrial ores, the detailed mineral dressing processes to be used will be dependent on the kind and types of ore that will be processed. Obviously such details are currently lacking for lunar ores, but fortunately on an overall basis, the procedures and requirements for equipment and cost can be determined. The basic equipment requirements including weights, power, and sustaining (worn parts) have been determined parametrically and are presented subsequently.

There is the possibility, albeit a slim one, that very high grade ores (80-100 percent) will be found and no mineral dressing will be required. But because this possibility is slim, an arbitrary ore grade of 1 percent was picked as the basis for this study because it is a convenient number to use in calculations and the results that are obtained can be easily extrapolated to other ore grades.

The equipment requirements for mineral dressing, both initially and sustaining, are very substantial. In particular, the sustaining requirements for the equipment make conventional mineral dressing an expensive operation. This leads one to the conclusion that lunar ore cannot be economically mined and returned to earth with conventional mineral dressing methods. Therefore, more advanced methods which will eliminate the high initial equipment weight and high sustaining requirements are needed or a transportation system which reduces transport costs an additional three orders of magnitude* is required. An even more desirable situation would be the elimination of the mineral dressing operation entirely. Several advanced methods that approach just that are discussed later.

Mineral Dressing Processes for Lunar Use. - The lack of air (vacuum) and water in the lunar environment are the primary reasons why terrestrial mineral dressing processes must be modified prior to lunar application. Of lesser concern is the wide surface temperature fluctuation from lunar day to night ($\Delta T \approx 300°C$) and the lower gravity (1/6 g). Table 6-1 summarizes the basic differences that exist for each of the five major categories of mineral dressing. The change to a dry, airless environment will not affect the first three categories significantly but does affect the classification and concentration processes strongly.

For the case of concentration, if the particle is magnetic or capable of taking a surface charge, the lunar ore can be concentrated magnetically or electrostatically. These properties of the ores are shown in tables 6-2 and 6-3. If the ore is non-magnetic or non-electrostatic, a separator-concentrator based on separating through ore density differences (e.g., centrifugation) could be designed to solve this problem. Such a device will work well even in the airless lunar environment but will require uniformity in particle size and this could pose a problem, but a solvable one. The separation or concentration is effected by placing the mixture in a container and agitating it so that the heavier particles will "sink" to the bottom while the lighter particles will "float" to the surface. A difference in density and uniformity of particle sizes are the key requirements for this technique. The densities for the more abundant lunar ores

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* Based on 1 percent ore; where in all probability the ore richness will be at least 10 percent and reduces the requirement to two orders of magnitude.

TABLE 6-1 MINERAL DRESSING MODIFICATION FROM TERRESTRIAL TO LUNAR

Mineral Dressing Operation	Requirement		Remarks
	Terrestrial	Lunar	
Crushing	a) Crushing Equipment b) Feed system c) Power	Similar to Terrestrial	Weights for the lunar equipment should be optimized considering the transportation cost. See ref. 45 for types.
Screening	a) Screening Equipment b) Feed system c) Water	Dry Screening only Otherwise similar to terrestrial	Weights of equipment for lunar use should be optimized. Only dry screening on lunar surface. See ref. 45 for types.
Grinding	a) Grinding Equipment b) Feed system c) Water d) Special liquids e) Special atmosphere	Dry grinding only Otherwise similar to terrestrial. Low "g" may be a problem.	a) Power requirements for wet grinding are 60-90% that of dry grinding. b) Ball & liner in dry is 10 to 25% that in wet. c) Capacity in dry is less than wet. d) Choice not obvious See ref. 45 for equipment description.
Classification	a) Classification equip. b) Feed system c) Air d) Water	Some of the terrestrial equipment could be modified for lunar application.	Modification would be to eliminate the air & water from the process and depend on centrifugal and gravity forces to effect separation or through screening. See ref. 45 for types of classifiers.
Concentration	a) Concentration equip. b) Feed system c) Air d) Water	Some terrestrial equipment could be used directly. Others must be modified.	Modification would be to eliminate the air & water from the process and depend on magnetic & electrostatic type devices. See ref. 45.

TABLE 6-2 RELATIVE MAGNETIC ATTRACTABILITY[45]

	Substance	Relative Attractability
Strongly Magnetic	Iron (taken as standard)	100.00
	Magnetite	40.18
	Franklinite	35.38
	Ilmenite	24.70
Weakly Magnetic	Pyrrhotite	6.69
	Siderite	1.82
	Hematite	1.32
	Zircon	1.01
	Limonite	0.84
	Corundum	0.83
	Pyrolusite	0.71
	Manganite	0.52
	Calamine	0.51
Non-Magnetic	Garnet	0.40
	Quartz	0.37
	Rutile	0.37
	Cerussite	0.30
	Cerargyrite	0.28
	Argentite	0.27
	Orpiment	0.24
	Pyrite	0.23
	Sphaerite	0.23
	Molybdenite	0.23
	Dolomite	0.22
	Willemite	0.21
	Manganesite	0.15
	Gypsum	0.12
	Zincite	0.10
	Cinnabar	0.10
	Cuprite	0.08
	Cryolite	0.05
	Galena	0.04
	Calcite	0.03

TABLE 6-3 RELATIVE EMPIRICAL MINERAL CONDUCTIVITIES[45]

Mineral	Source	Voltage	Reversible*
Flake Graphite, C	Texas	2,800	N
Quartz, Gold, SiO_2	Dakota	10,140	RN
Corundum, Al_2O_3	Transvaal	13,728	N
Hematite, Fe_2O_3	England	6,240	N
Ilmenite, $FeTiO_3$	India	7,020	N
Magnetite Sand, $FeO\text{-}Fe_2O_3$	California	7,800	N
Chromite, $FeCr_2O_4$	S. Rhodesia	5,616	N
Rutile, TiO_2	Virginia	7,332	N
Pyrolusite, MnO_2	New Mexico	4,680	N
Microcline, $KAlSi_3O_8$	Canada	7,488	N
Labradorite $(NaAlSi_3O_8)(CaAl_2Si_2O_8)$	Labrador	4,992	N
Enstatite, $MgSiO_3$	Transvaal	7,800	RN
Pyroxene, $RSiO_3$	Canada	6,084	RN
Amphibole-Hornblende, $Ca(MgFe)_3(SiO_3)_4$	Canada	7,020	RN
Nephelite, $K_2Na_6Al_8Si_9O_{34}$	Canada	6,240	N
Garnet, $R_3R_2(SiO_4)_3$	New York	18,000	N
Rhodolite, $2Mg_3Al_2(SiO_4)_3$ $Fe_3Al_2(SiO_4)_3$	N. Carolina	16,380	RP
Almandite, $Fe_3Al_2(SiO_4)_3$	New York	12,480	N
Chrysolite, $(MgFe)_2SiO_4$	N. Carolina	9,204	RP
Zircon, $ZrSiO_4$	N. Carolina	11,700	RN
Topaz, $(AlF)_2SiO_4$	Virginia	12,480	RP
Kyanite, Al_2SiO_5			

* N - Not Reversible
RP - Reversible Positive
RN - Reversible Negative

based on the Apollo samples are shown in table 6-4. Fortunately, Silicon-dioxide, the most abundant compound on the moon, has a much lower density than the desirable ores which should help the separation process. Other processes such as the use of magnetic fluids (ref. 62) to separate by differential flotation are possible. A process based on magnetic fluids will work by changing the effective density of the magnetic fluid by varying the magnetic field applied to the fluid, a simple procedure. As the effective density of the magnetic fluid is increased, the ores can be made to float differentially and can be easily separated. Again, note the density differences of ores shown in table 6-4.

TABLE 6-4 DENSITIES OF ORES

Component	Approximate Percentage	Specific Density
SiO_2	41-47	2.28-2.66
FeO	16-22	5.7
TiO_2	3-1	4.17
CaO	8-12	3.346
Al_2O_3	8-14	3.5 -3.9
MgO	7-16	3.58

Lunar Mineral Dressing. - An extensive survey of the mineral dressing equipment and their operational requirements was done and the information extracted from the survey formed the basis of the results shown here. The survey failed to reveal any totally new mineral dressing concept being developed by the mining industry that could be adapted to lunar applications which will reduce the basic requirements of equipment weight and sustaining logistics. Some conceptual ideas that require further study that may reduce the equipment weight and logistic weight requirements are advanced at the end of this section.

The results shown here are for a hypothetical mineral dressing operation requiring three-stage crushing and two-stage grinding with classification by screening after each stage of crushing and grinding with concentration of the ores by magnetic or electrostatic separation. Lifetimes for the basic equipment, excluding wear replacement, are assumed to be 10 years. The production rate of refined mineral assumed for this study was placed at 4.5×10^5 to 4.5×10^8 kilograms (10^6 to 10^9 pounds) per year--a range arrived at, after a review of United States requirements (ref. 63) of typical metallic minerals. Ore richness was assumed to be 1 percent.

A review of mineral dressing procedures in handbooks (e.g. refs. 45 and 64), equipment manufacturers literature and personal contacts in industry and other government agencies (e.g. Bureau of Mines) resulted in the specific weight, power and refurbishment weight requirements summarized in table 6-5. The results shown in figures 6-2 to 6-4 were obtained using the data in table 6-5. These results are shown as minimum-maximum bands reflecting variations in requirements for power and equipment that occur due to differences in ore characteristics (hardness, friability, abrasiveness, etc.). Note that the results in these curves can be extrapolated to ore grades other than the base 1 percent merely by dividing the ordinate scales by the new ore content in percent or by multiplying the abscissa by the ore content in percent.

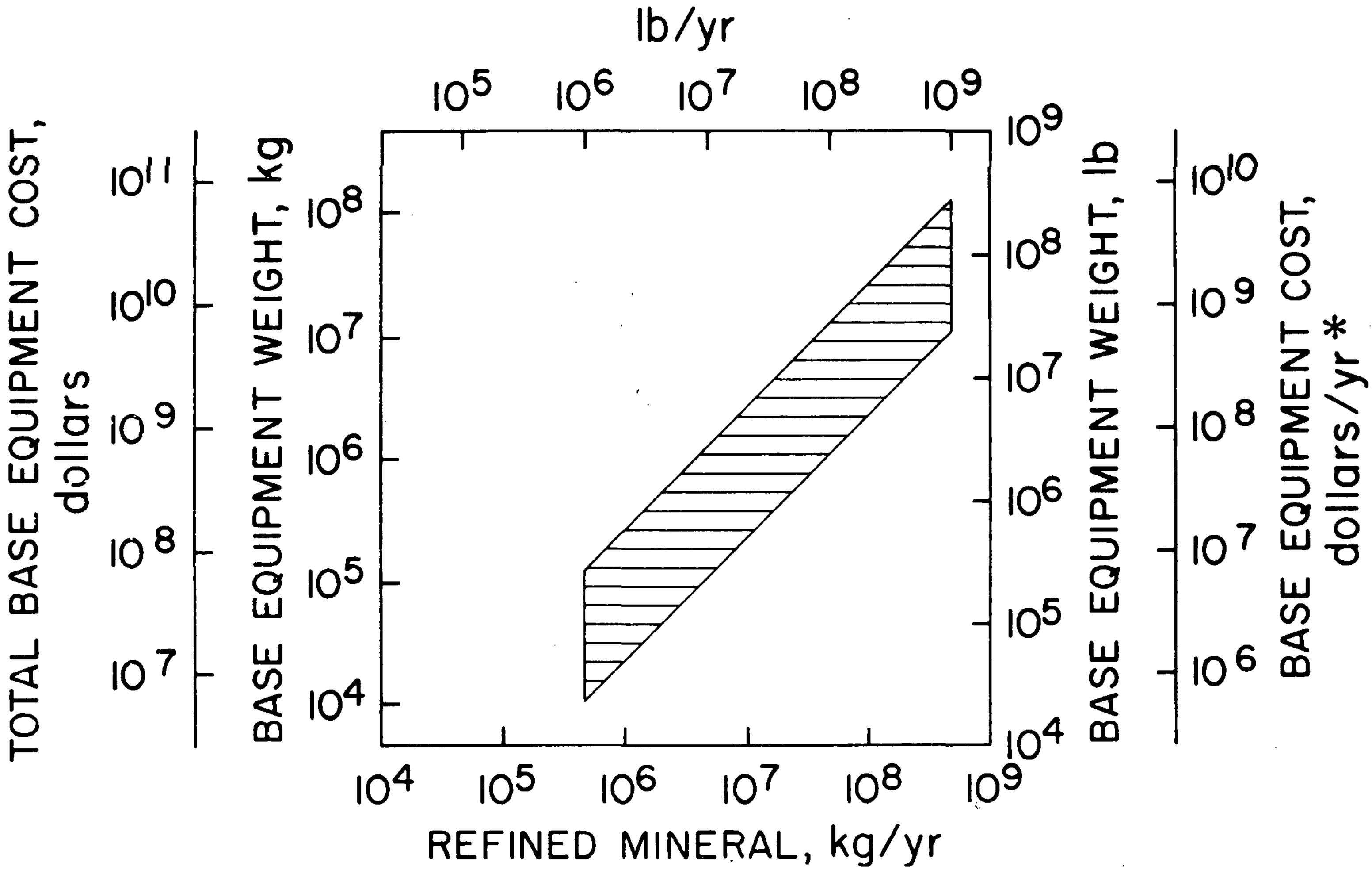
The costs shown in figures 6-2 and 6-3 for the equipment and equipment refurbishment are for the cost of the base equipment delivered on the moon and the cost of replacement parts also delivered on the moon. Cost of transportation from the earth to the lunar surface is the nominal value of $550 per kilogram ($250 per pound). Of the total refurbishing requirement, 92 percent is for the grinding operation and 6.9 percent is for the crushing operations and are primarily for replacement of liners, balls, and rods for this equipment. Thus, technologies which can alleviate or eliminate this problem would be useful. Some such technologies that could be promising are discussed later.

TABLE 6-5 SUMMARY OF REQUIREMENTS - BASIC LUNAR MINERAL DRESSING*

Electrical Requirements:		
Electrical Energy	15.40×10^{-3} - 52.9×10^{-3}	KW-HR/kg of ore
	7.00×10^{-3} - 24.0×10^{-3}	KW-HR/lb of ore
Electrical Power	17.60×10^{-7} - 59.5×10^{-7}	KW/kg of ore/yr
	8.00×10^{-7} - 27.0×10^{-7}	KW/lb of ore/yr
Base Equipment Requirements:		
Weight	2.30×10^{-4} - 28.0×10^{-4}	Mass of Equip. / mass of ore/yr
Cost**	5.70×10^{-3} - 69.0×10^{-3}	Total Equip. Cost,$ / mass of ore/yr
Worn Equip. Replacement Rqmts:		
Weight	2.20×10^{-4} - 22.0×10^{-4}	Mass of parts/yr / Mass of ore/yr
Cost	12.12×10^{-2} - 121.2×10^{-2}	Dollars / kg of ore
	5.50×10^{-2} - 55.0×10^{-2}	Dollars / lb of ore

* Based on data in reference 45.

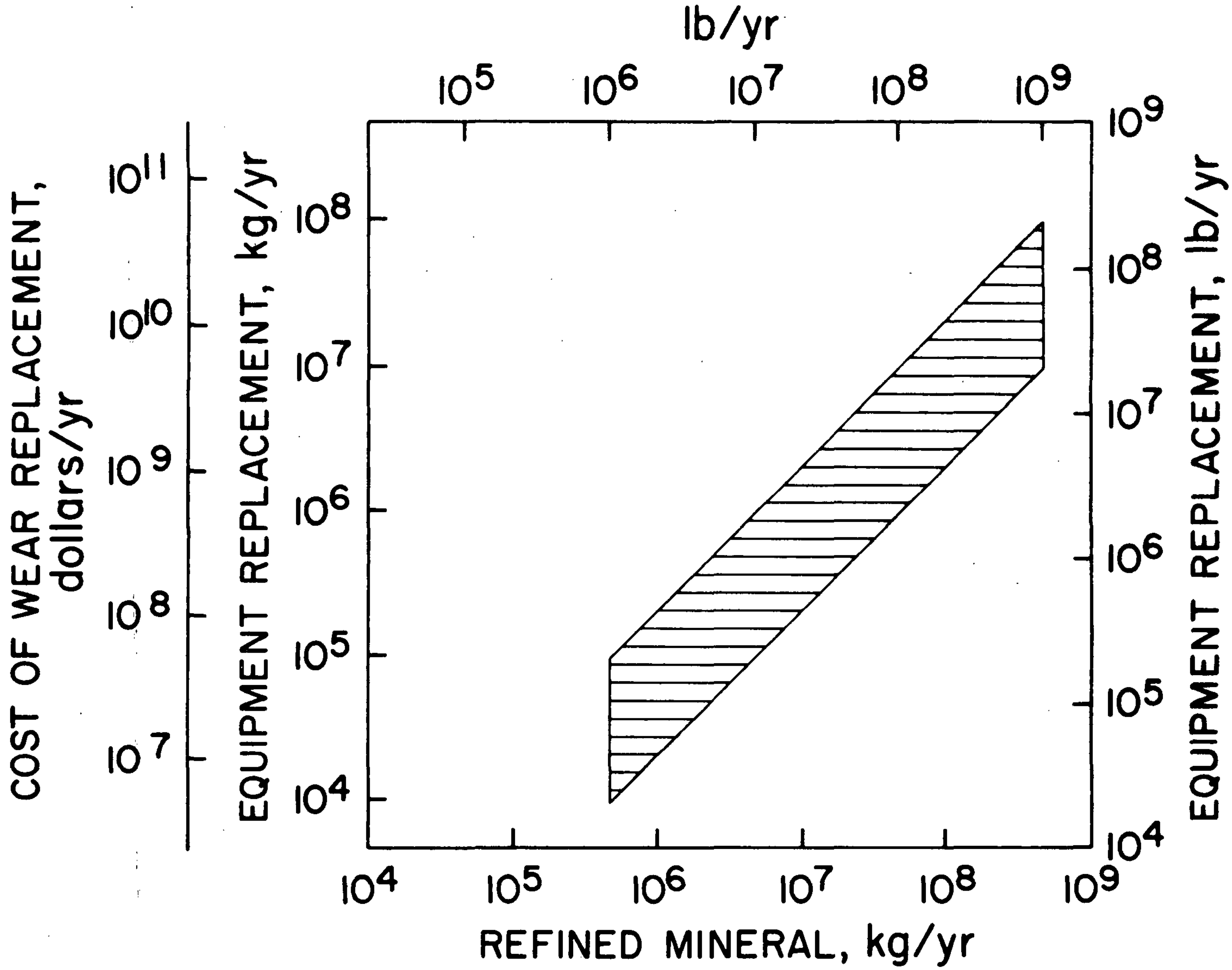
** Basic equipment lifetime assumed to be 10 years.



CURVE IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATES BY ORE CONTENT IN PERCENT

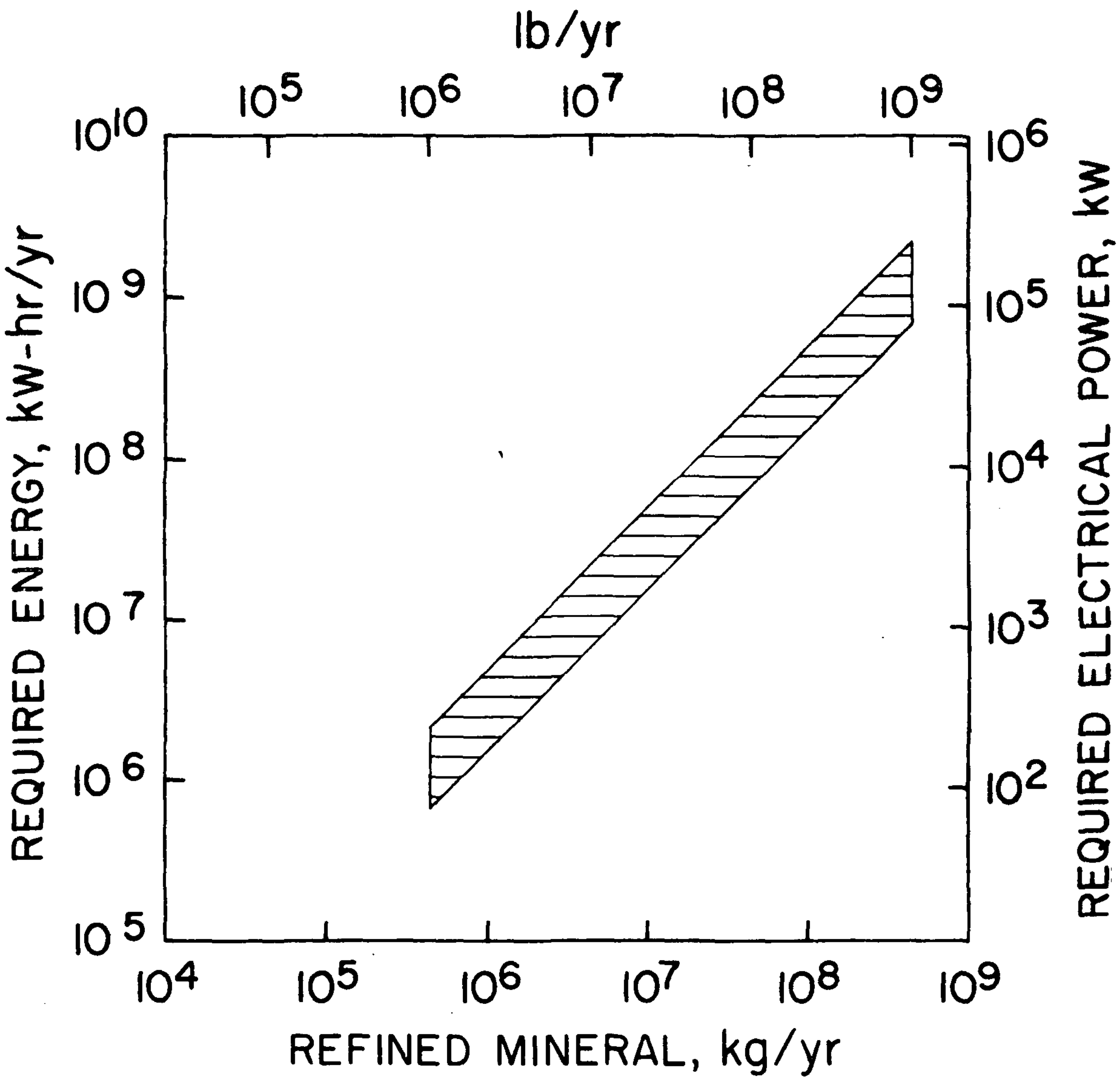
* BASED ON 10 YEAR EQUIPMENT LIFETIME

Figure 6-2 Mineral Dressing--Base Equipment Weight and Cost.



CURVE IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATES BY ORE CONTENT IN PERCENT

Figure 6-3 Mineral Dressing--Weight and Cost of Replacing Worn Parts.



CURVE IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATES BY ORE CONTENT IN PERCENT

Figure 6-4 Mineral Dressing--Power Requirement.

The basic equipment costs on earth for heavy equipment such as used in mineral dressing are expected to be about $2.20 per kilogram ($1.00 per pound) in general and somewhat higher for specialty components and accessories, about $11.00 per kilogram ($5.00 per pound). By comparing the equipment and transportation costs, it becomes clear that the transportation cost is dominant and equipment cost can be neglected for computational purposes. With this kind of disparity in costs, in an actual case, some tradeoffs that examine reducing the weight of the equipment and allowing its unit cost to rise until the combined transportation and equipment costs are minimized would be justified.

An interesting result of the analysis was the high yearly equipment refurbishment (particularly crusher jaws, rods and balls) requirement of the mineral dressing operation shown in figure 6-3. The refurbishing weight requirements for a year are about one-half the initial basic equipment weight. This results in a refurbishment (wear replacement) cost increment of about $22.00 for each kilogram ($10.00 for each pound) of refined mineral. The basic equipment amortization cost assuming a nominal ten year lifetime (which is a half to a quarter of the lifetimes for comparable earth equipment) results in a cost increment of only $2.20 per kilogram of refined mineral, almost negligle in comparison to the refurbishing cost.

The total power requirements for the mineral dressing operation are shown in figure 6-4. These results are the sum of the maximum power required to operate the equipment; no factor for surges in power demand due to equipment failure or start-up has been allowed. The electrical energy requirements for mineral dressing amount to approximately 2.2 kilowatt-hour per kilogram refined mineral; the associated electrical cost at $0.10 per kw/hr should be less than $0.25.

Equivalent terrestrial electrical energy costs are usually less than \$0.02 per kilowatt-hour. A comparison of the energy cost (\$0.25/kg), equipment amortization cost (\$2.20/kg), and equipment refurbishing (\$22.00/kg) cost, indicates that the dominant cost for mineral dressing will be the equipment refurbishing cost. This cost further breaks down roughly into 96 percent transportation cost and 4 percent hardware cost.

Future Lunar Mineral Dressing Processes. - "Necessity is the mother of invention," or conversely, "the lack of necessity stifles innovation," is an appropriate quotation for describing the technology development for terrestrial mineral dressing. The ample supply of cheap water, power, air and replacement parts for equipment has resulted in economical processes which take advantage of the economy from increased size of operation; thus, innovative breakthroughs in technology have not been necessary. However, on the moon, the lack of these traditional mediums affecting mineral dressing and the high cost of replacement and refurbishing of equipment necessitates innovation.

Several innovative ideas using advanced technologies that could abate some of the unique lunar mineral dressing problems are discussed below. Because these are still largely untried ideas, quantitative data is singularly unavailable. These advanced technologies could become state-of-the-art about the year 2000 or possibly earlier.

Some work in using lasers to change rock characteristics to aid terrestrial tunneling has shown some encouraging results. That is, when rock is exposed to a high power laser beam, the tensile and compressive strength deteriorates and the rock crumbles readily. Therefore, if one could expose the lunar ore either by using the laser in the mining process or as part of the mineral dressing process, the lunar ore could be made to crumble easily in the crushing and grinding operation; and, in an ideal case, reduce wear in this equipment to an extent where the wear replacement costs could become negligible. Weight and cost of laser systems cannot be calculated now because of the lack of data, but they should be substantially lower in comparison to the grinding and crushing equipment weights. Improvements in the current conversion efficiency of electrical energy to laser energy is necessary.

A process based on thermal shock breakage of the rock may be helpful in reducing the rock in size and possibly permuting it to a more friable state. The rocks in this process would be heated to appropriate temperatures as high as 500°C and then exposed to a blast of liquid oxygen as they leave the heater and fall into a storage bin. The liquid oxygen would be obtained from the refining process where the oxides are reduced to pure mineral and oxygen. Again, data are lacking and quantitative calculations have not been done.

Other methods such as chemical treatment of the ores to make them more friable and high electrical frequency disintegration of the rocks are also possibilities for the future. If seed money for research of these kinds of technologies (which can also be applicable to terrestrial mineral dressing) were made available, questions of their feasibility and economics could begin to be answered.

Mineral Refining

Background. - The process of reducing the mineral into its pure form from its oxides is referred to as mineral refining or ore refining. Most terrestrial refining processes require an ample supply of cheap air, water, oxidizers, reducing agents, chemicals, heat, and electrical power. The process to be used is dependent on the ore being refined. For example, iron ore is reduced by a process called smeltering in a blast furnace where the iron ore, coke, and limestone are placed in alternating layers in a container (furnace); hot air is forced through the layers, combustion occurs, and the composite mixture is heated and melts. The high temperatures resulting from the burning coke cause the limestone to react with the molten iron ore so that the pure molten iron and molten impurities (slag) flow to the bottom of the furnace, with the slag floating on top of the molten iron. The molten slag and iron are drawn off separately. Aluminum ore, on the other hand, is refined by taking the crushed ore and treating it with sodium hydroxide solution which dissolves the aluminum oxide but not the impurities. The solution is cooled and the aluminum hydroxide is precipitated and converted to aluminum oxide by heating. The aluminum oxide is then electrolized in a molten cryolite bath and pure aluminum is deposited on the cathode and oxygen is given off at the anode. A sketch of this process is shown in figure 6-5.

The two examples above are typical of the current ore reduction processes used. Some differences in the chemicals, number of chemical treatments, drying, etc., in the detailed processes will occur depending on the physical/chemical nature of the ore being refined.

Ore refining, like mineral dressing, is marked by processes which are as old as when the minerals were first generally mined and refined, and are not likely to change drastically unless circumstances dictate the change. For example, the first type of ore smelting furnace used is illustrated, along with a modern blast furnace, in figure 6-6. Note that the equipment has improved but the basic process is identical even to the placement of the ore and fuel (coal or coke) in the furnace. These terrestrial types of ore reduction processes are not readily adaptable to lunar use.

Current or projected terrestrial refining processes which are feasible for adaptation to lunar application do not exist. Thus new concepts based on fusion, electrochemical, and thermal technologies for lunar application are discussed in the following sections.

Lunar Mineral Refining. - The problems and difficulties that would be encountered in the lunar ore refining process have been discussed earlier. Before discussing the advanced concepts that can make lunar ore refining feasible, a discussion of the alternatives may be fruitful. There are three alternatives: (1) no lunar mineral refining will be done;

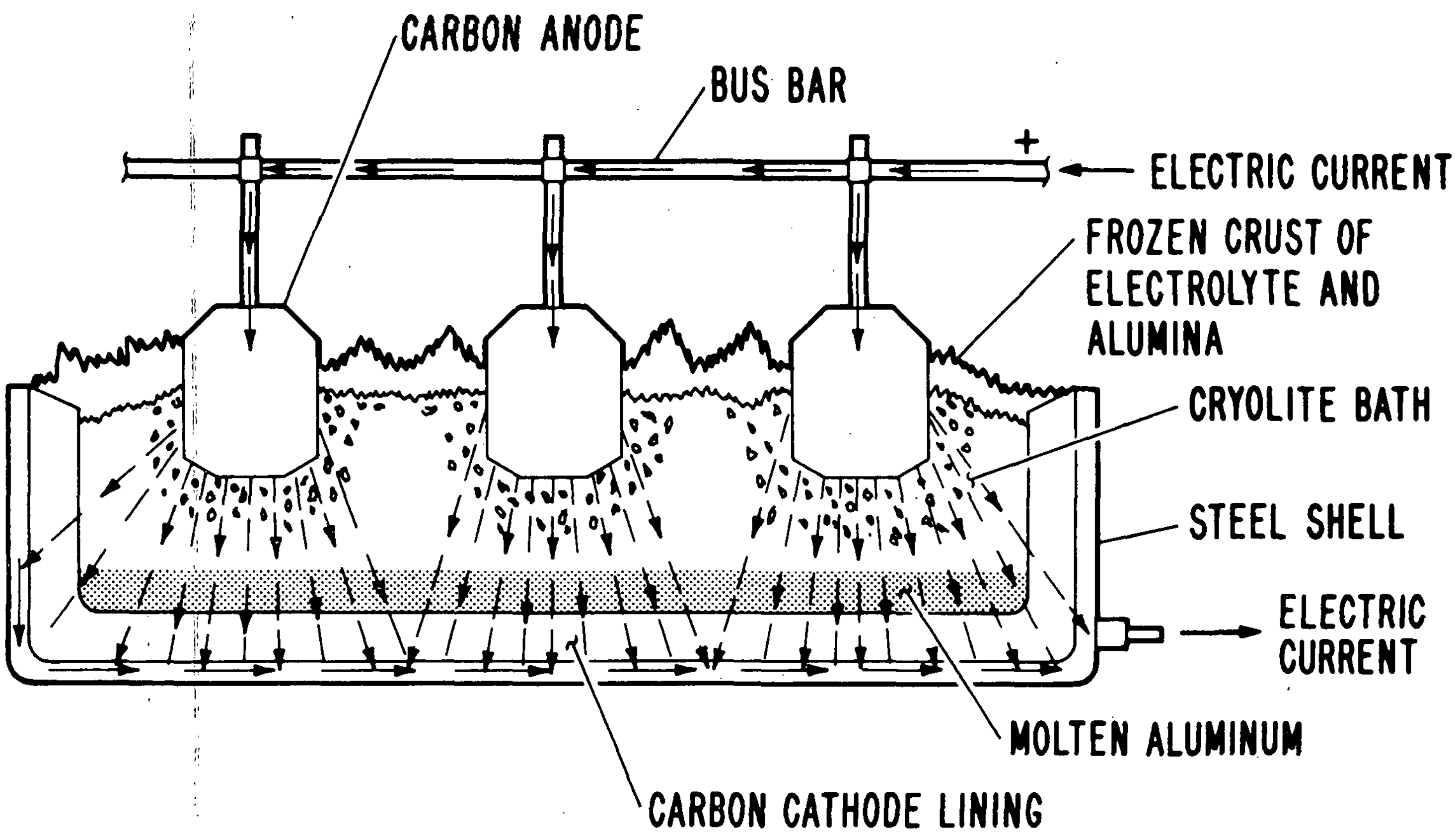
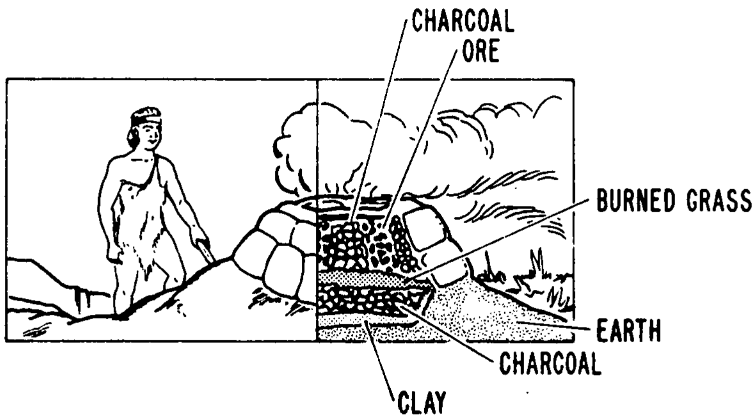
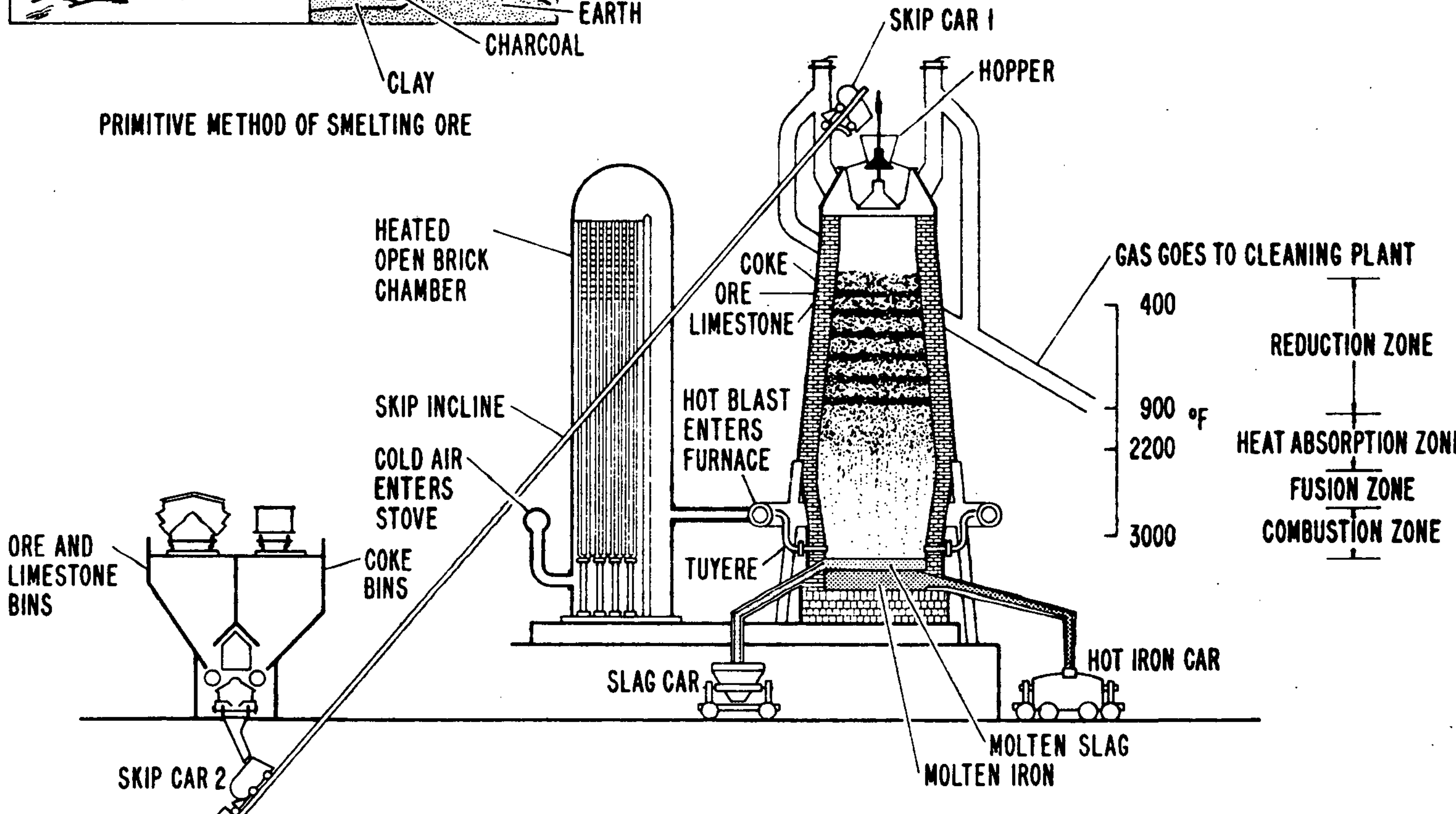


Figure 6-5 Schematic Diagram of Electrolytic Cell for Aluminum Refining.



PRIMITIVE METHOD OF SMELTING ORE



CROSS SECTION OF THE GENERAL CONSTRUCTION OF A MODERN BLAST FURNACE

Figure 6-6 Historical Comparison of Ore Refining Methods.

the concentrated ore will be brought back to earth for refining; (2) the lunar mineral refining will be done by adapting through brute force methods the earth refining technology; or (3) lunar mineral refining will be configured using new advanced methods now in the conceptual phase. Of these three alternatives, the third choice is probably the only viable alternative. High transportation costs make the first and second alternatives too costly; the first, because apparently valueless material is brought back, and the second, because large quantities of consumables (air, chemicals, water, etc.) must be transported to the moon.

But if some use of the lunar soil could be found which would make it valuable (for example, as a plant nutrient--demonstrated on a preliminary basis with lunar soil from the Apollo samples at the Manned Spacecraft Center), then the first alternative, the concentrated ore, could be profitably brought back to earth. Also, the reduction of transportation costs to the lunar surface by several orders of magnitude below the $550 per kilogram ($250 per pound) that has been arrived at in this study could make the first and second alternatives feasible. However, these occurrences are not very likely.

Advanced Lunar Mineral Refining Technologies. - Ideally, the methods that will evolve for mineral refining on the moon should be considered as part of an overall process encompassing all three steps (mining, dressing, and refining of the ore). That process should advantageously utilize the lunar environment of vacuum, low gravity, and low temperature (shade and underground), while skirting the problems that occur when adapting earth processes for lunar use (low g, lack of water, air and fuel, high refurbishing requirements, etc.).

Primarily, the winning of pure metals from the ore in oxide form requires that the energy released when the oxide formed be returned to the system. For example, for reducing iron ore using coke, the chemical equation can be written as:

$$Fe_2O_3 + 3CO \rightarrow (2Fe + 3CO_2) + 5500 \text{ calories} + 3CO$$
$$\rightarrow 2Fe + 198{,}500 \text{ calories} +$$
$$+ (3CO + \frac{3}{2} O_2 - 204{,}000 \text{ calories})$$
$$\rightarrow 2Fe + 3CO_2 - 5{,}500 \text{ calories}$$

The plus sign with the heat energy term denotes the process absorbs or requires that much energy, while the negative sign means the reaction releases that much energy. The energy input required for reducing several metallic oxides is shown in table 6-6. The order shown is in ascending energy requirement per oxygen atom in the oxide; note that the order based on energy requirement per unit weight of the pure mineral is different and results from differences in material densities and oxide forms. With the exception of manganese oxide, substantially higher energy inputs are required to reduce the oxides listed after chromic oxide.

The required energy for the reduction process on the moon will be supplied as thermal or electrical energy or in combination.

Controlled Thermonuclear Energy: The possible availability of controlled fusion energy in the near future appears to be improving since 1969 with the breakthrough by the Russians with their Tokamak (refs. 65 and 66) and because of current United States and Russian laser induced fusion research (refs. 67-69). The availability of nuclear fusion can revolutionize the refining process by making available a source of extremely high temperatures (greater than 50×10^6 degrees Centigrade). These high temperatures are the result of the fusion reactions and occur in the fusion reactor. The resulting products of the fusion reaction are in the plasma state and can be tapped and used as a torch, the fusion torch. Schematic sketches of the fusion torch (ref 70) are shown in figures 6-7 and 6-8 respectively.

The fusion torch will simultaneously vaporize and ionize the ore, and the ionized ore will flow through a duct with a transverse electric

TABLE 6-6 APPROXIMATE HEAT OF REDUCTION AND SPECIFIC REDUCTION ENERGY REQUIREMENTS

Oxide	Heat of Reduction CAL. / Oxygen Atom	Specific Reduction Energy KW - HR / kg Oxide	KW - HR / kg Mineral
$Au_2 O_3$	- 3,700	-0.029	-0.033
$Ag_2 O$	7,000	0.035	0.038
Cu O	38,500	0.561	0.701
$Sb_2 O_3$	55,300	0.662	0.792
Co O	57,600	0.894	1.137
Ni O	57,800	0.898	1.140
$Mo O_3$	57,800	1.400	2.099
$W O_3$	65,200	0.983	1.236
$Fe_2 O_3$	66,200	1.446	2.064
Fe O	66,200	1.070	1.380
$Fe_3 O_4$	66,500	1.335	1.843
$Sn O_2$	69,000	1.064	1.350
Zn O	83,500	1.203	1.496
$Cr_2 O_3$	91,000	3.180	6.115
Mn O	96,500	1.584	2.042
$Si O_2$	100,500	3.940	8.360
$Ti O_2$	109,000	3.180	5.290
$Al_2 O_3$	126,000	4.318	8.150
Be O	135,000	6.290	17.440
Mg O	146,100	4.250	7.085
Ca O	151,600	3.156	4.430

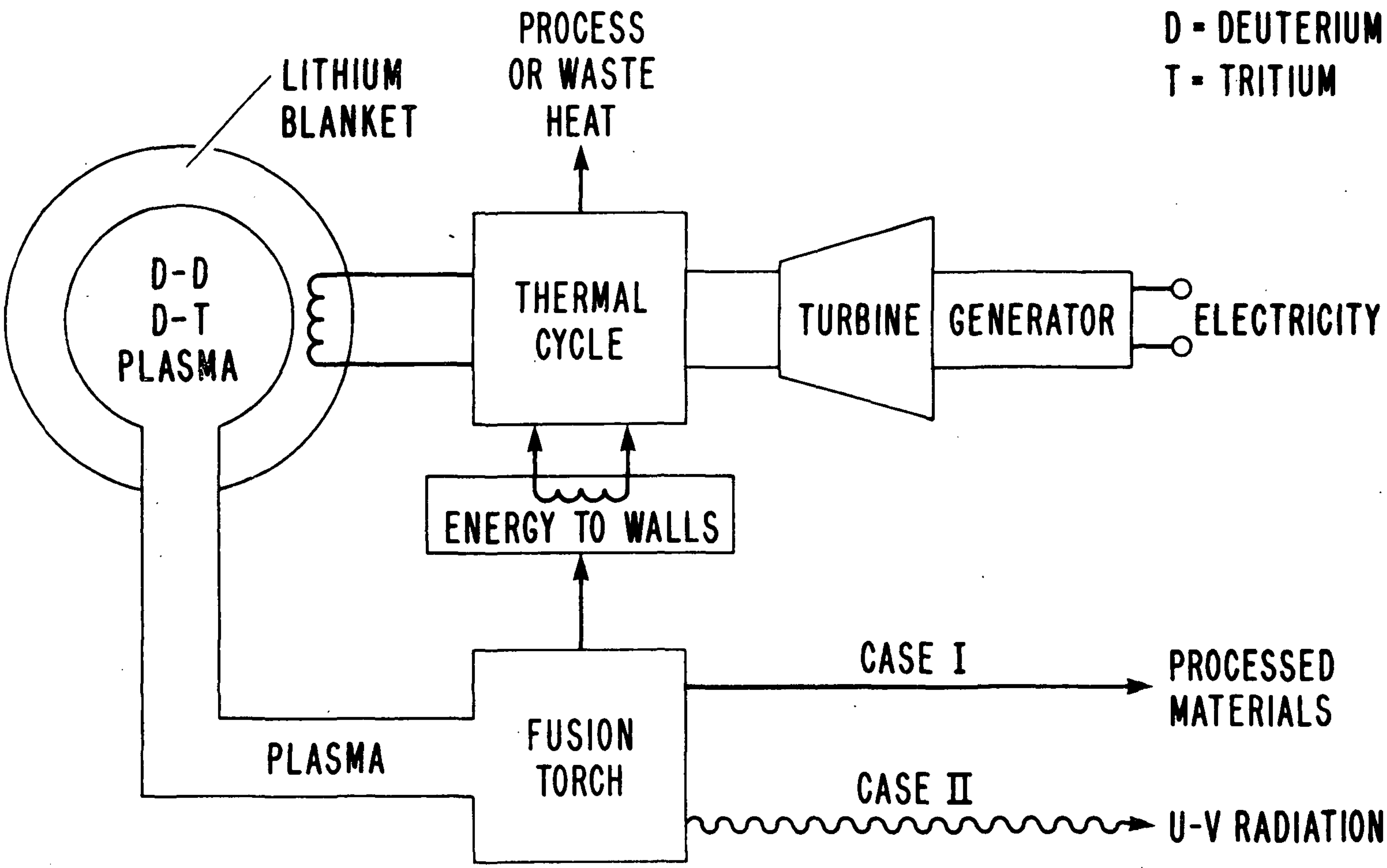


Figure 6-7 Energy Conversion with Fusion Torch D-D and D-T Fuel Cycles.

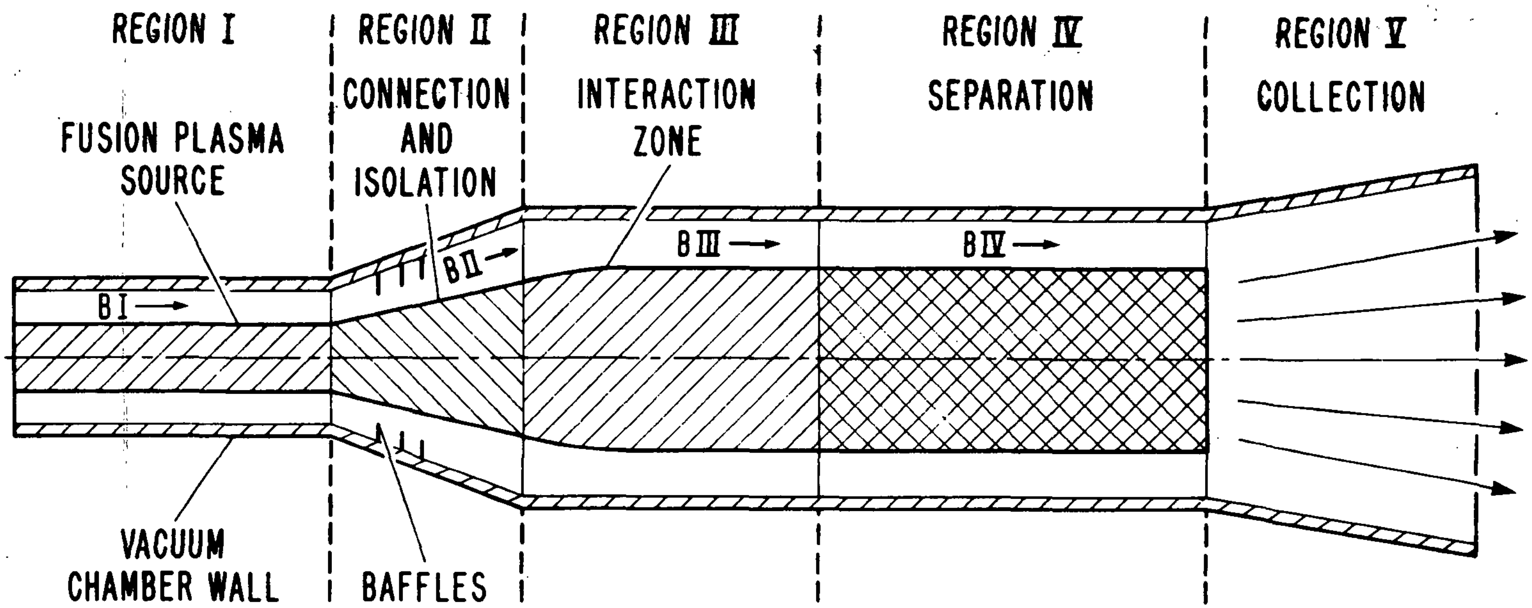


Figure 6-8 The Fusion Torch.

field to separate the streamlines. The electrostatic susceptibility of ions varies depending on material, and thus the flow of ionized materials should separate into fairly well-defined streamlines. Each streamline of ionized material that is of interest will be neutralized, condensed, collected, and solidified in the desired form for shipping. The undesired material streamlines could simply be vented in a direction away from the mining camp and where it will not interfere with other lunar operations.

Concept details have not been derived in this study but some details on cost (refs. 71-73) for the fusion reactor are available. Since it is expected that the fusion reactor itself will be the most costly component of this concept, an estimate of the refining costs based on the cost of fusion power alone has been made. The basic equipment cost when available is expected to be around $500 per kilowatt-electric (refs. 71-73) for a system efficiency of 45 percent. For lunar application, the lack of cooling water will require space radiators, and higher reliability will be desired; these plus the transportation costs ($550/kg) could increase the power system cost delivered on the moon by a factor of 2 and even more. An increase of 5 times in the cost was estimated as the upper limit in cost even with the complexity of the radiators. Using the factor of 5 will increase the equipment cost delivered on the moon to $2500 per kilowatt-electric for a system efficiency of 45 percent. The fusion torch's efficiency is virtually 100 percent because the plasma is tapped directly from the reactor and no conversion cycle efficiencies need be considered. Thus the cost will be about $1100 per kilowatt-thermal. The amortization cost for the equipment, using a 10 year lifetime, is $0.0125 per kilowatt-hour. Fuel costs ($0.0000035 per kilowatt-hour) (ref. 74) are, by comparison, negligible.

The energy requirements for vaporizing materials are shown in table 6-7 for several typical terrestrial materials. These values are based on one atmosphere ambient pressure, and thus for lunar applications, these values should be conservative. But since rapid, almost instantaneous, vaporization is desirable and overheating of the vaporized products

TABLE 6-7 HEATS OF VAPORIZATION AND SUBLIMATION (Refs. 75-77)

Substance	MP °C	BP °C	Heat of Vaporization KCAL/MOLE	Heat of Vaporization KCAL/Gm	Heat of Sublimation At 25°C & 1 Atm. KCAL/MOLE	Heat of Sublimation At 25°C & 1 Atm. KCAL/Gm
Al	659	2500	70	2.59	76	2.81
Al_2O_3	2037	3300	-	-	456	4.47
Au*	1063	2950	82	0.42	90	0.46
Be*	1284	2400	74	8.22	80	8.89
BeO*	2530	4120	112	4.48	155	6.22
Ca	850	1350	40	1.00	43	1.08
CaO	2600	3500	-	-	150	2.68
Cr	1850	2620	83	1.60	96	1.85
Cu	1083	2570	73	1.15	80	1.26
Fe	1539	3070	81	1.45	95	1.70
Mg	650	1105	30	1.25	35	1.46
MgO	2800	2770	-	-	130	3.25
Mn	1244	2095	54	0.98	-	-
Ni	1455	2910	90	1.53	-	-
Pt*	1769	4100	112	0.57	130	0.67
SiO_2	1420	2600	72†	2.57†	88†	3.14†
Sn*	232	2750	65	0.55	72	0.61
Ta*	2980	-	-	-	190	1.05
Ti	1660	3260	-	-	112	2.33
TiO	1850	-	-	-	139	2.17

* Have not been found in the Apollo samples.

† Estimated from values for Silicon.

unavoidable, a factor of three on the theoretical energy was allowed in the analysis of the energy requirements for the lunar fusion torch application.

A rough estimate of the refining cost based on the fuel cost and the energy requirements was made. The range in energy requirements for materials of interest is covered by beryllium* metal on the high end and tin* on the lower end. Based on these materials, a hypothetical bound in the power, energy, and cost ranges for lunar material refining using the fusion torch has been determined and is shown in figure 6-9. The energy calculations were based on the following equation

$$E = WF\ (0.45\ H_eSiO_2 + 0.55\ H_eX)$$

E = Energy

W = Weight of processed material

F = Inefficiency factor

H_eSiO_2 = Heat of vaporization, silica

H_eX = Heat of vaporization, mineral

for known lunar composition of at least 45 percent silica and 55 percent mixture of other minerals including the 1 percent ore. The power that the fusion reactor has to supply for the production range (4.5×10^5 to 4.5×10^8 kilograms per year) covered in this study (assuming concentration of the 1 percent grade ore to 25 percent by the mineral dressing process) ranges from a low of 1.3 megawatts to a high of 4.6 gigawatts. The upper limit is probably conservative for the reasons stated earlier but is useful as an upper bound. The related refining cost can be expressed as,

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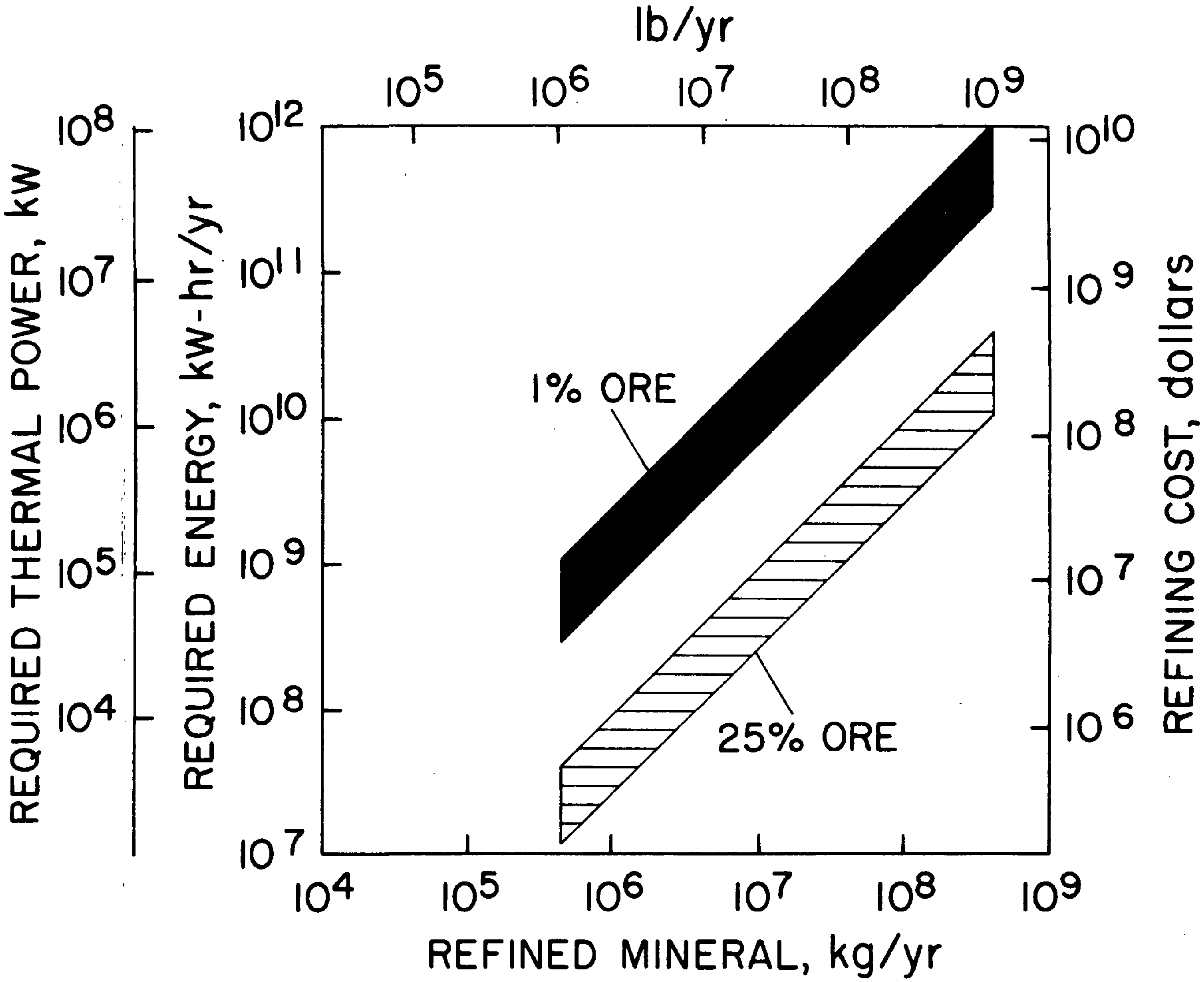
* Note: These elements have not been found in the Apollo samples but represent extreme values and thus were used. See next subsection for bounds using other materials.



SOLID BAND IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATES BY ORE CONTENT IN PERCENT

Figure 6-9 Refining by Vaporization.

$$C = E\ (\$0.0125)$$

$$E = \text{Energy, kilowatt-hour-thermal}$$

$$\$0.0125 = \text{Cost of electrical energy}$$

The energy cost ranges from $0.32/kg to $1.11/kg of refined mineral.

The above refining costs are approximately on the same order of cost as terrestrial refining costs (ref. 63), an encouraging sign for this concept.

The fusion torch could also be used directly on the mined material without mineral dressing or could be used with a staged arrangement directly to mine and refine the ore. That is, the mining will be by melting with one fusion torch while the melted material is fed into a second fusion torch for the vaporizing, ionizing, and separation. Of importance also is that this fusion torch concept could be used for terrestrial mining/refining. This concept should be studied further so that the components are defined and the economics better determined.

Electro-Chemical Refining: This process requires that the material be melted with a subsequent application of electrical or magnetic fields to the melt to separate the constituents. Some related work in this area (examining the migration of metallic ions in solid silicates subjected to an electric potential) is being done by Professor W. Luth of Stanford University and others. Discussions with Professor Luth indicate that the migration in the molten state should be much faster than the migration rates in solids.

Melting of the lunar material can be done by using a fusion torch or electric furnace. Melting of most of the composite lunar material, which is largely silica, will occur within the range of 1500-2500°C. Table 6-8 illustrates the terrestrial physical properties for some materials with the same chemical composition as those which make up the lunar material. These values are applicable for a one atmosphere environment.

TABLE 6-8 HEATS OF FUSION AND REDUCTION AND OTHER PHYSICAL DATA(86,87)

(1 Atmosphere)

			Heat of Fusion		Heat of Reduction	
Substance	Melting Point,°C	Specific Heat CAL/g°C	KCAL/MOLE	KCAL/GRAM	KCAL/MOLE	KCAL/GRAM
AL_2O_3	2030	0.3	26	0.255	378	3.71
BeO*	2530	0.4	17	0.680	135	5.40
CAO	2600	0.23	19	0.339	152	2.71
Fe_3O_4	1597	-	33	0.142	266	1.15
MgO	2800	0.32	18.5	0.462	146	3.65
MnO	1785	0.21	13	0.183	96	1.35
SiO_2	1420	0.25	-	-	201	3.35
TiO_2	1840	0.22	15	0.188	218	2.73

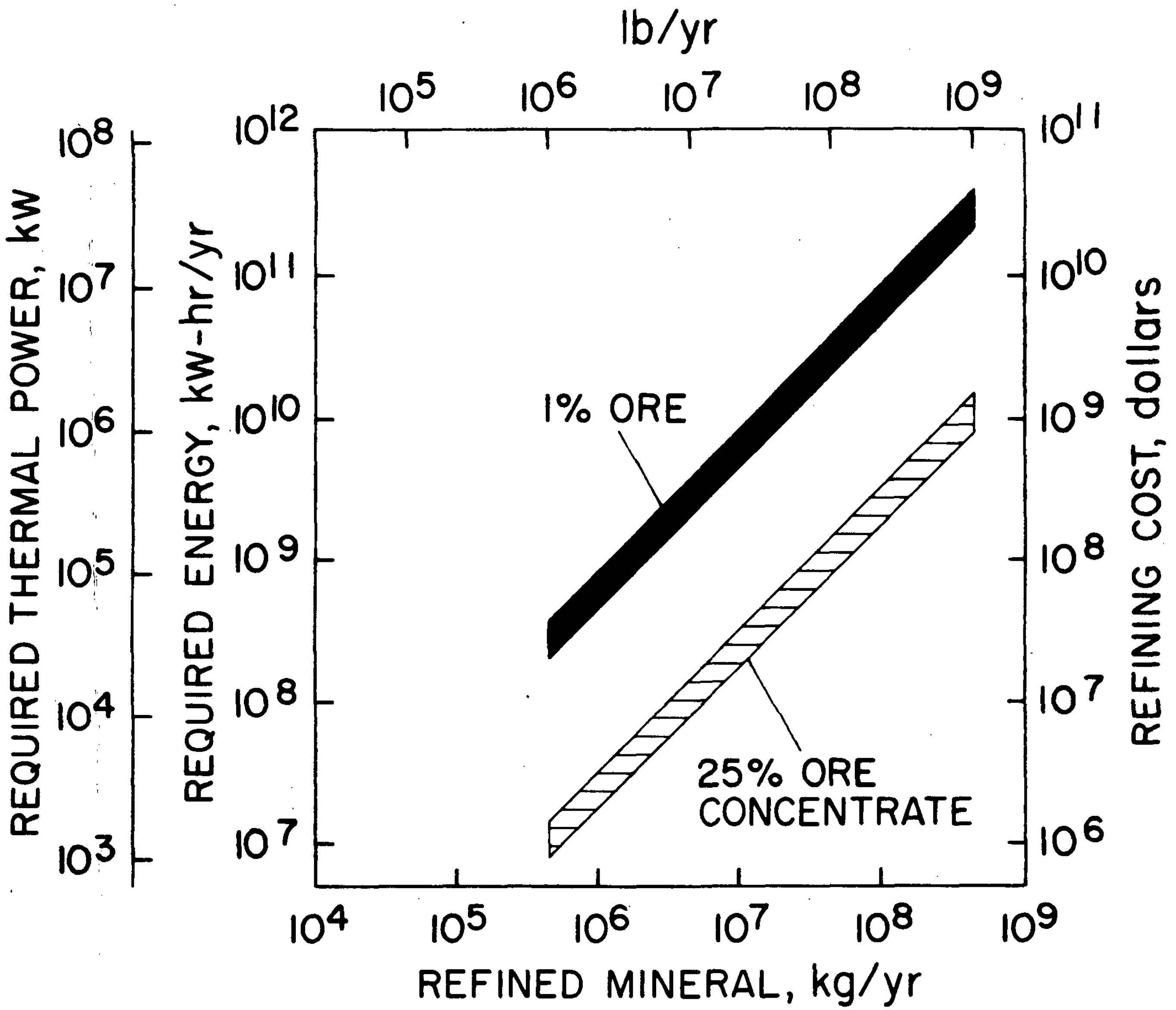
* Beryllium oxide has not been found in the Apollo samples.

Because the moon has no atmosphere and is thus essentially a vacuum, the data in table 6-8 can only be used to estimate the energy requirements. Under vacuum conditions, the melting temperatures will generally be slightly higher; therefore, estimates of energy requirements made using these data may be optimistic.

Details such as the electric or magnetic field required to effect segregation of minerals in the melt are lacking currently; more theoretical analysis and possibly experimental analysis should be done to obtain basic data. Quantitative equipment weight and cost associated with this concept are not determined at this time.

Estimates of the ranges in total energy requirements for melting and reducing (oxidation energy or heat of formation) the oxides of some common lunar minerals are shown in figure 6-10. The band covers the range in energy requirements expected for common lunar ores. The power and cost associated with the energy requirements are also shown in the figure.

The total energy required to separate the ore into its basic chemical elements is represented by the heat of reduction. In this method of refining, this energy will be supplied in two forms; thermal energy (represented by the sum of the heat of fusion, and the heat energy to raise the temperature from 25°C to the melting point) and electrical energy (applied as an electrical field to the melt). The requirements for energy were calculated using the data shown in table 6-8 and a mineral content of 1 percent as well as the case where the mineral dressing process has been able to concentrate the 1 percent ore to 25 percent mineral content by weight. Minerals used to obtain the upper and lower bounds are aluminum oxide and ferric oxide respectively. A process efficiency of 50 percent was assumed and the material being processed was assumed to be 45 percent silica and 55 percent mixture of other minerals. Energy requirements for aluminim oxide and ferric oxide were appropriately used for the 55 percent mixture in calculating the total energy requirements.



SOLID BAND IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATE BY ORE CONTENT IN PERCENT

Figure 6-10 Electro-Thermal Refining (Cost, Power, and Energy Requirement).

$E = FW(.45\ H_ES + .55\ (H_EAl \text{ or } H_EFE))$

E = Energy

F = Reciprocal of process efficiency

W = Weight of material processed

H_ES = Energy to reduce silica

H_EAl = Energy to reduce aluminum oxide

H_EFE = Energy to reduce ferric oxide

The energy requirements are on the same order of magnitude as those for the fusion torch even though the materials that represent the bounding requirements are different. This indicates that within an order of magnitude the gross energy requirements for refining lunar minerals are bounded adequately in this study.

The cost shown in figure 6-10 is based on 10 cents per kilowatt-hour (electric) cost for energy and results in a cost range of $2.40 to $3.90 per kilogram ($1.10 to $1.80 per pound) of refined material assuming 25 percent ore (concentration from mineral dressing). The cost of 10 cents per kilowatt-hour is probably conservative. With direct tapping of thermal energy from the power generator, be it fusion, fission or solar, the cost could be reduced an order of magnitude (see previous section). This will reduce the refining cost range to 24 to 40 cents per kilogram (11 to 18 cents per pound) of refined mineral, a cost more compatible with terrestrial refining costs (ref. 63).

Thermal Vaporization Refining: With adequate thermal energy and a means of precisely controlling the temperature, a refining process that will successively vaporize the desired minerals by holding the temperature at their boiling points could be developed. This is the refining concept used in oil refining, distilling of alcohols, etc. so successfully.

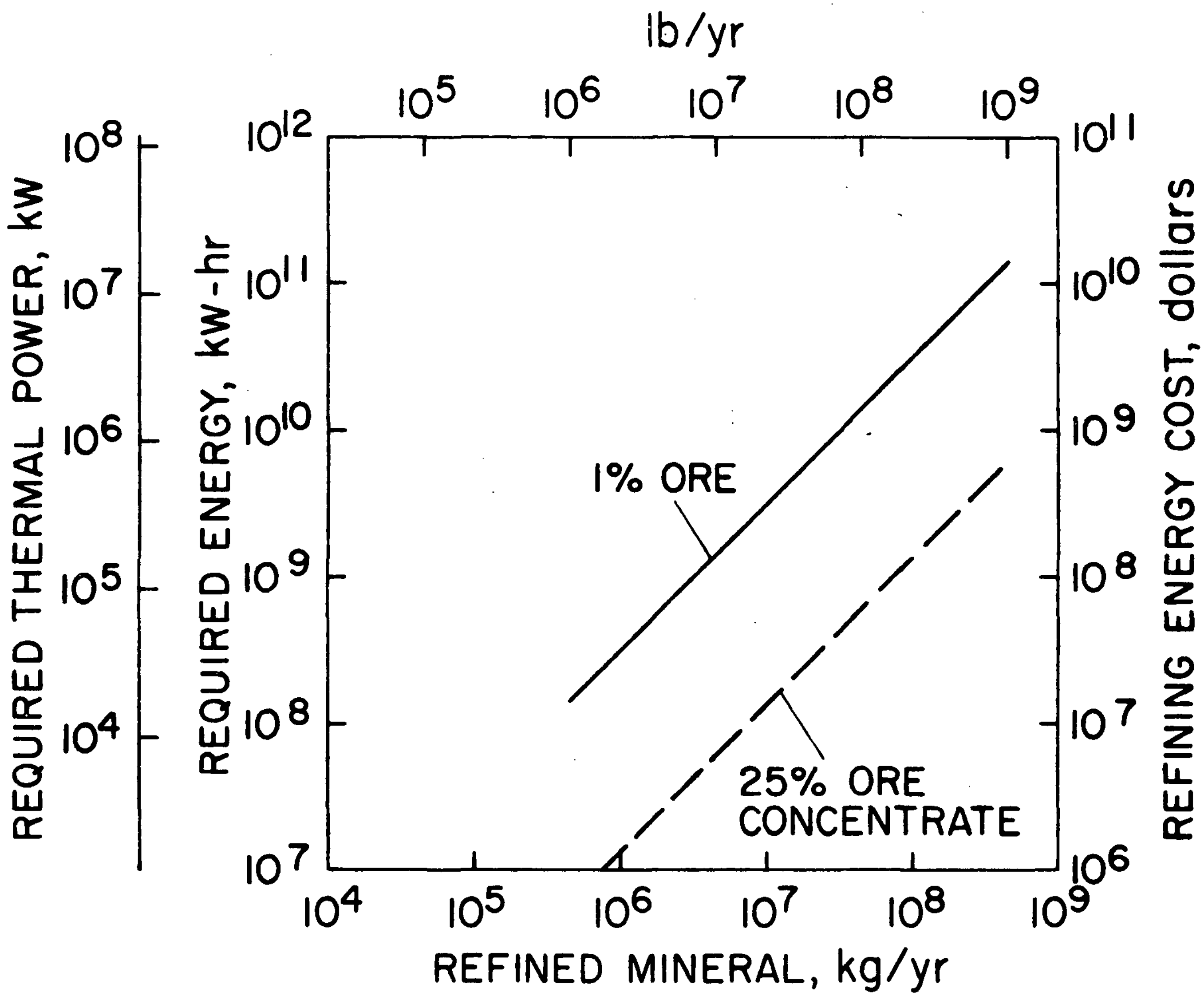
The boiling points for several materials are shown in table 6-7. The natural vacuum of the moon should be helpful in reducing the boiling point and increasing the vaporizing rate. Once the material is vaporized, those materials of interest will be condensed and recovered while the undesired mineral vapors will be vented to the lunar vacuum.

Equipment requirements for this concept should be rather modest and consist primarily of the boiler and condensor. The primary difficulties will be the temperature control and the condensing operation heat rejection equipment (radiators), although the lunar night cold could prove very helpful to this operation. Costs and weights for these components have not been determined due to lack of equipment data and basic vacuum based physical properties for minerals essential to equipment sizing.

Differential Melting-Refining: If this concept can be verified experimentally, it could be a good method for concentrating or a first crude refining step. Since melting points differ with minerals, if a mixture of ores is heated successively to specific melting points of ores and the temperature held constant, and the melting ore is not a solvent for the other ores, the desired molten minerals can be individually drawn off successively until all the desired minerals have been extracted. Even then, the mineral obtained by this method is not expected to be very pure because as it melts, the other minerals will at least partially dissolve in it. Also, since this is a melting process, ores in oxidized or alloy form will tend to remain in that form.

This concept is the simplest and probably the closest to the terrestrial form of ore smelting. With the use of a chemical reducer this concept becomes analogous to the terrestrial ore smelting process. For example for iron ore smelting, the chemical reducer is the coke and limestone.

The nominal energy and power requirements for this concept have been estimated and are shown in figure 6-11. The results show the most likely or probable requirements based on evaluation of values of specific heats and heats of fusion. The energy and power requirements are much



SOLID LINE IS FOR 1% ORE - FOR OTHER GRADES OF ORE, DIVIDE THE ORDINATES BY ORE CONTENT IN PERCENT

Figure 6-11 Refining by Differential Melting.

lower than the previous concepts because the process does not result necessarily in a pure mineral but rather in a concentrated oxide. The energy cost per kilogram of mineral for the case of 25 percent concentrated ore is about $1.30 based on 10 cents per kilowatt-hour.

APPENDIX A -- ELECTROMAGNETIC PROPULSION

Linear Induction Motors

The first large scale accelerator application of a linear induction motor came in 1946 with the development of the Westinghouse aircraft launcher, the Electropult (ref. 19). The primary coil was built into a carriage which pushed the aircraft. The secondary consisted of a winding in slots of a ferromagnetic structure which was mounted in the ground. Current collection for the primary was by means of brushes running alongside the secondary member. Some of the pertinent specifications of the system, which was finally abandoned because of high initial cost, are given below in table A-1.

TABLE A-1 CHARACTERISTICS OF AIRCRAFT LAUNCHER (ref. 19)

Shuttle car weight	2,088 kg	4,600 lb
Tractive force	75,600 N	17,000 lb
Final Speed	98 m/sec	220 mph
Developed power	7,457 KW	10,000 hp
Track length	421 M	1,382 ft
Accelerator length	305 M	1,000 ft
Deceleration length	116 M	382 ft
Power input	12,000 KWe	12,000 KWe
Power duration; max.	15 sec	15 sec

Determination of the system efficiency is important for lunar operation. A comparison of the 7,457 KW (10,000 hp) and 12,000 KWe numbers from table A-1 would imply a 62 percent efficiency. However, a 75,600 Newton (17,000 lb) force acting through a distance of 305 meters (1,000 ft) in 15 seconds is only 1,490 KW (2,000 hp), and for the input power of 12,000 KWe this results in a 12 percent actual efficiency.

In a study done for the U.S. Department of Commerce (ref. 20), a set of specifications was generated for a high-speed ground transportation system. Similar to the Electropult, the primary winding is mounted to the moving vehicle. The secondary is a fixed vertical beam. The primary is in two sections, one riding on each side of the vertical rail. Various schemes of rails and air bearings are suggested for support of the car. Some of the specifications are given below in table A-2.

TABLE A-2

HIGH SPEED GROUND TRANSPORTATION SYSTEM SPECIFICATIONS* (Ref. 20)

Vehicle top speed	250 mph
Vehicle frontal area	110 sq ft
Power at 250 mph	2500 hp
Motor output force	1.2-2.4 lb of thrust/in^2 per side of motor area
Motor weight	0.7-1.2 lb weight per lb output force
Efficiency	80-85 percent
Input Voltage	2.3-13.8 kV
Input frequency	≈ 1 Hz per 1 mph operating speed
Pole pitch	8.5-9.5 in.
Number of poles	10 or more
Primary winding material	Copper
Secondary member material	Composit Al with steel inserts
Secondary member size	1 in. thick, 16-22 in. tall
Primary cross section	3-5 in. wide x 6-9 in. tall
Air gap clearance	1/4 in. each side
Onboard power supply wt	4,000-10,000 lb
Aerodynamics drag @ 250 mph	≈ 3,000 lb

A linear induction motor for a lunar launch system would necessarily have some variations from an earth transportation system. For one thing, an unlimited free supply of air for gas bearings will not be available and, hence, rolling or sliding contacts may be preferred in order to save the weight of expended gas. In order to avoid sliding contacts (for electrical pick-up), it would seem wise to keep the primary windings on

* Units have been left in the form presented in the reference.

the fixed track, and make the moving piece a passive element. Since, however, sliding contacts may be desired for stability anyway, it may be advantageous to use a moving primary and save the weight of a primary winding along the entire track. This configuration would be basically the same as in a high-speed ground transportation system and is like the one used for the Westinghouse Electropult aircraft launch system.

If the numbers from the Department of Commerce study can be scaled, it is possible to extrapolate the size of a lunar launch system. The weight requirement should be quite scalable considering the permeability of magnetic materials, etc. Unfortunately, the weight efficiency of the studied motor is only 0.71 to 1.21 kilograms of motor per Newton (0.7 to 1.2 pounds of motor per pound) of output force, limiting the acceleration to little over one g.

If, on the other hand, the rotor is attached to the payload, the acceleration can be increased since about 8.28×10^3 to 16.56×10^3 Newtons of force per square meter (1.2-2.4 pounds of force per square inch) of motor area can be obtained. The secondary is 2.54 centimeters (1 inch) thick with a specific weight of 7×10^3 kg/m^3 (0.25 lb/in^3), hence, the secondary may generate 5 to 10 Newtons of force for each kilogram of motor secondary. Even this performance is marginal, however, for lunar operation. An operational system based on these parameters and accommodating a reasonable payload would develop something less than 10 g's. For example, to provide 8 g's acceleration with a 13,600 kilogram (30,000 lb) payload, the total output force would have to be over 4.5×10^6 Newtons, and the secondary will weigh some 54,400 kilograms with an area of 325 m^2 (120,000 pounds weight and 3,500 ft^2 area). If the sliding secondary were 3 meters (10 feet) deep and 107 meters (350 feet) long, the primary winding weight would be about 1,490 kilograms per lineal meter (1,000 lb/linear foot). If it were necessary to make the secondary shorter, the primary weight will increase proportionately. If electric power distribution and support structure weight requirements are added, the total weight is about 2,980 kg/m (2,000 lb/ft).

A cross section of the vehicle configuration is given in figure A-1 and some details of the motor configuration and mounting are given in figures A-2 and A-3, as taken from reference 20.

Sliding Coil Accelerator

The sliding coil accelerator is perhaps the most efficient electromagnetic generator of force per unit weight. It takes advantage of the high magnetic fluxes that can be generated with coils. The simple principle on which the devices operate is two-fold; first that an electric current passing through a conductor generates a magnetic field around it, and second that a conductor experiences a force when its magnetic field interacts with an external magnetic field. The force is proportional to the gradient of the field, $F \alpha \; dB/dx$, which is easily stated, but not so easily determined theoretically, since field interactions are complex. The force (following the "right hand rule") is perpendicular to the plane of the field and current, and has the magnitude $F = Bl\, i \sin \phi$, where ϕ is the angle between the field and current, or:

$$F = (\vec{B} \times \vec{i})\, l$$

The magnetic field can be strengthened effectively by winding the conductor into a helix. The field strength in a helix or solenoid is approximated with the formula:

$$B = \mu_o \frac{Ni}{2\,l} \left(\frac{0.5\,l + X}{\sqrt{r^2 + (0.5\,l + X)^2}} + \frac{0.5\,l - X}{\sqrt{r^2 + (0.5\,l - X)^2}} \right)$$

B is the field strength in webers/m^2

μ_o is the magnetic permeability of vacuum (in this case) $= 4\pi \times 10^{-7}$ webers/amp·m

N is the number of coil turns

i is the current in amps

l is the length of the coil in meters

and r is the radius of the coil in meters

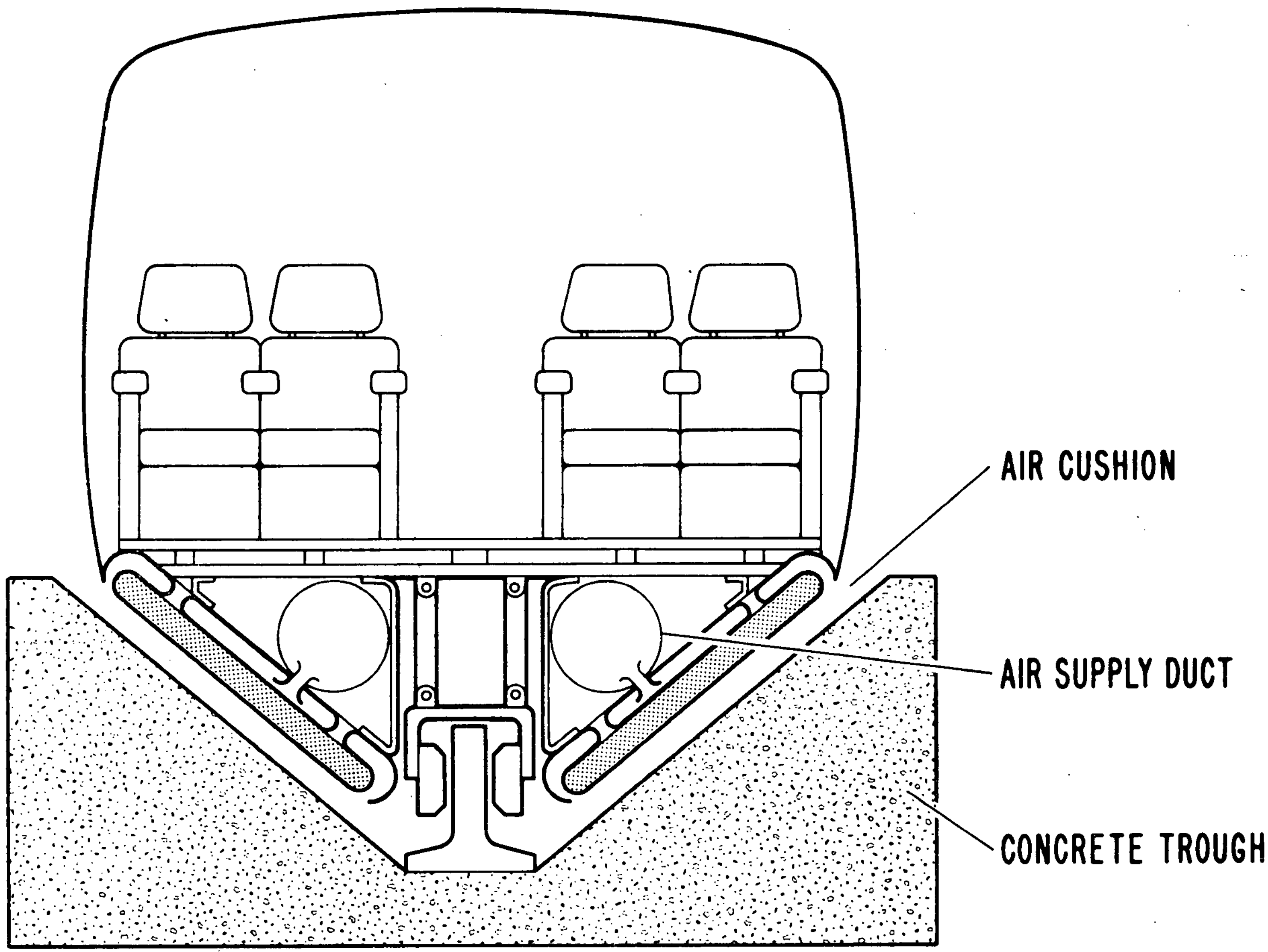


Figure A-1 High Speed Train Supported on Air Cushion.

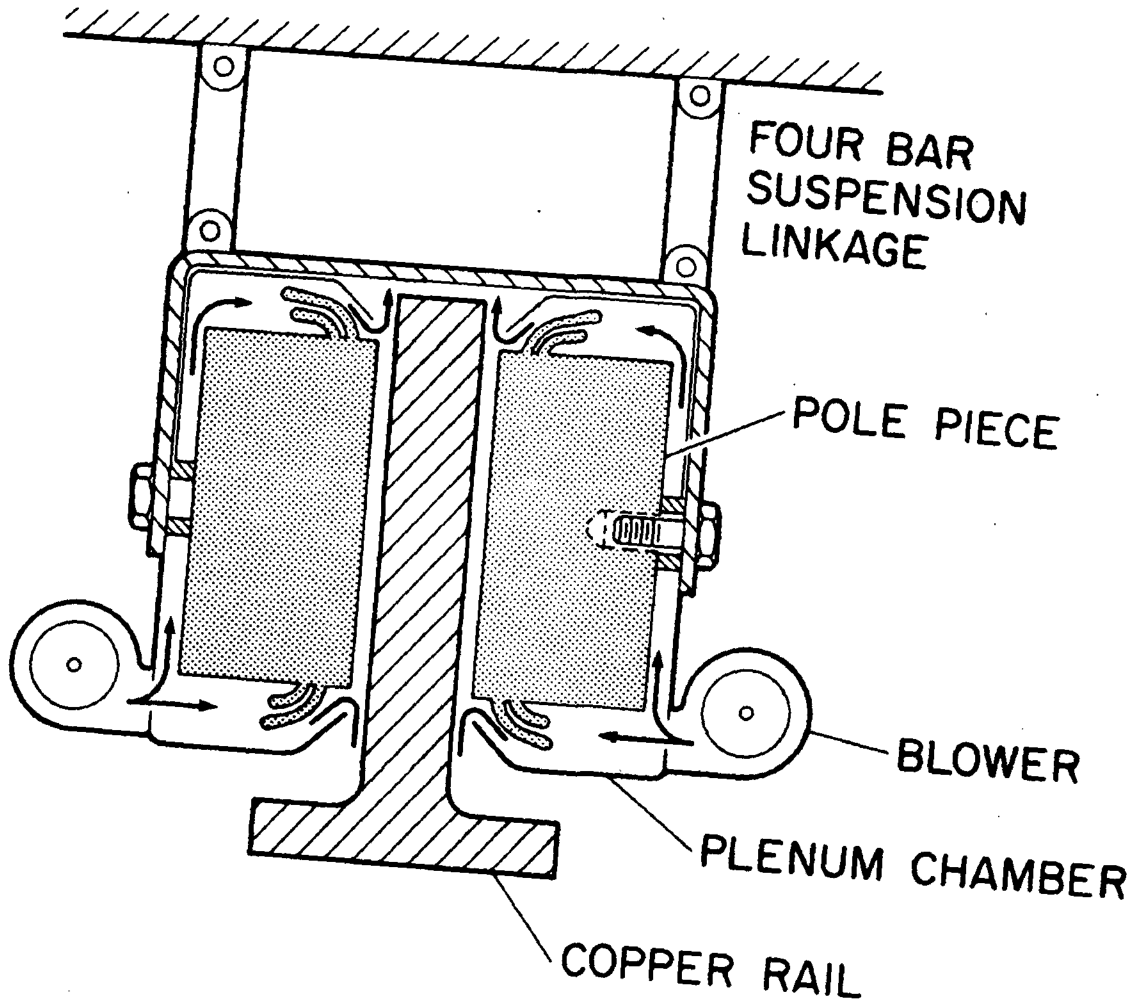


Figure A-2 Air Cushion Pole Piece Suspension.

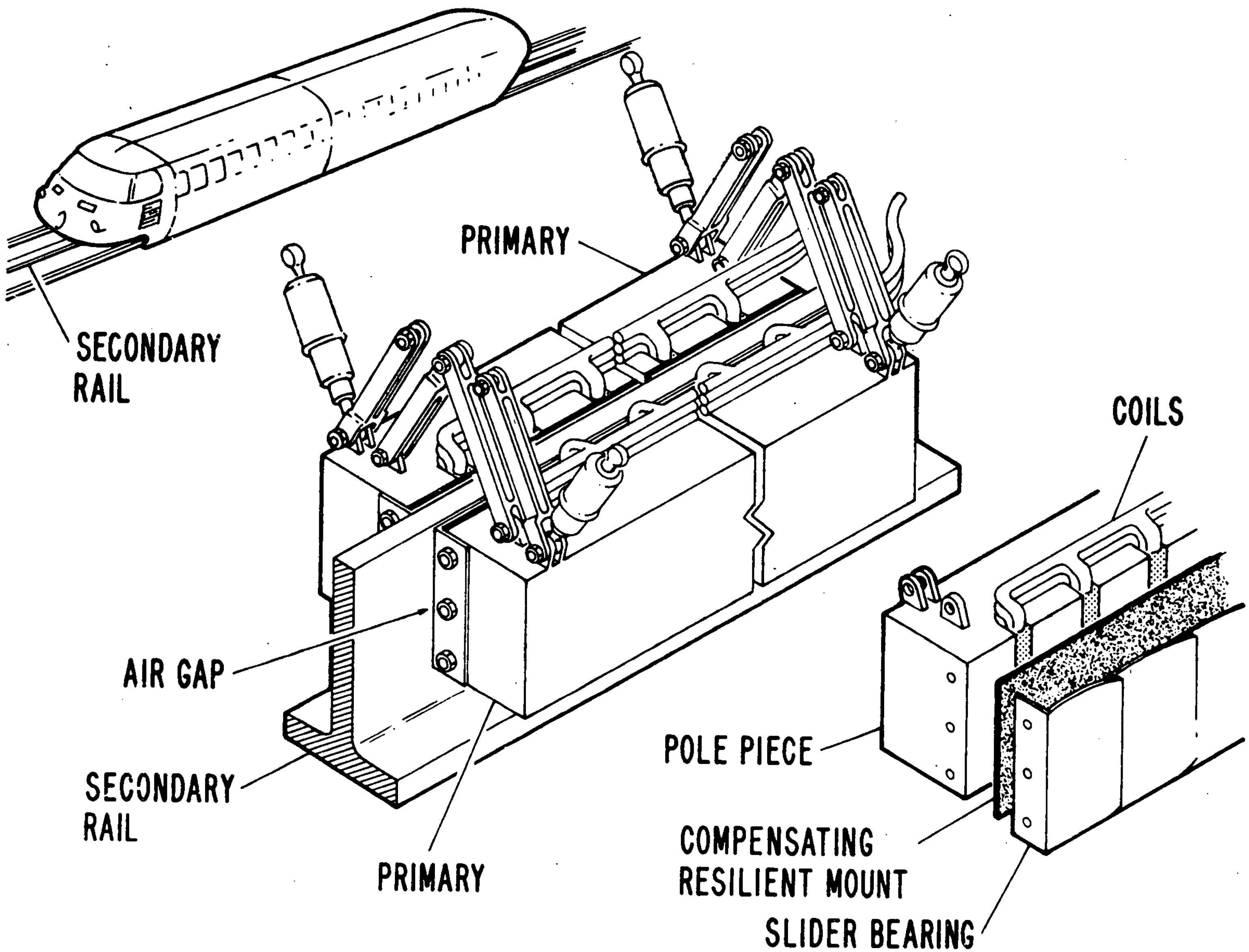


Figure A-3 Self-Acting Air Slider Bearing.

The variables are depicted in figure A-4.

If another conductor is placed in the field created by the solenoid, it will experience a force, or more specifically, a continuum of non-colinear forces since the field is neither constant in magnitude nor direction. The force can be divided into a radial component (which would constitute the entire force, if the field were not diverging) and an axial component (due to the field divergence). From the "right hand rule," it is apparent that the axial force is, as we have said, proportional to the field gradient.

A plot of the magnetic field strength around a solenoid from the above formula is given in figure A-5. The figure shows that for a given coil length, l, the flux inside the coil will be higher, the smaller the radius, r, of the coil. The important point is that the gradient of the field is in all cases greatest at or near the mouth of the coil.

It is also true that the axial force generated between two coils will be proportional to the gradient of their mutual inductance, since the mutual inductance is, by definition, proportional to the flux of one coil intercepted by the other. It is more rigorously true that the axial force between coaxial coils is proportional to the total inductive gradient, $F \alpha \; dL/dx$, but in the configurations of concern, the only variable inductive parameter is the mutual inductance. Hence:

$$F \; \alpha \; \frac{dM}{dX} \; \alpha \; \frac{dB}{dX}$$

More specifically, it is found that $F = \frac{1}{2} L^2 \frac{dL}{dX}$

The total inductance of the system is $L = L_1 + L_2 \pm 2M$, where L_1, and L_2 are the individual inductances and M is the mutual inductance. Since the inductance of a coil is given by the formula:

$$L = \frac{N^2 \; \mu \; A}{l}$$

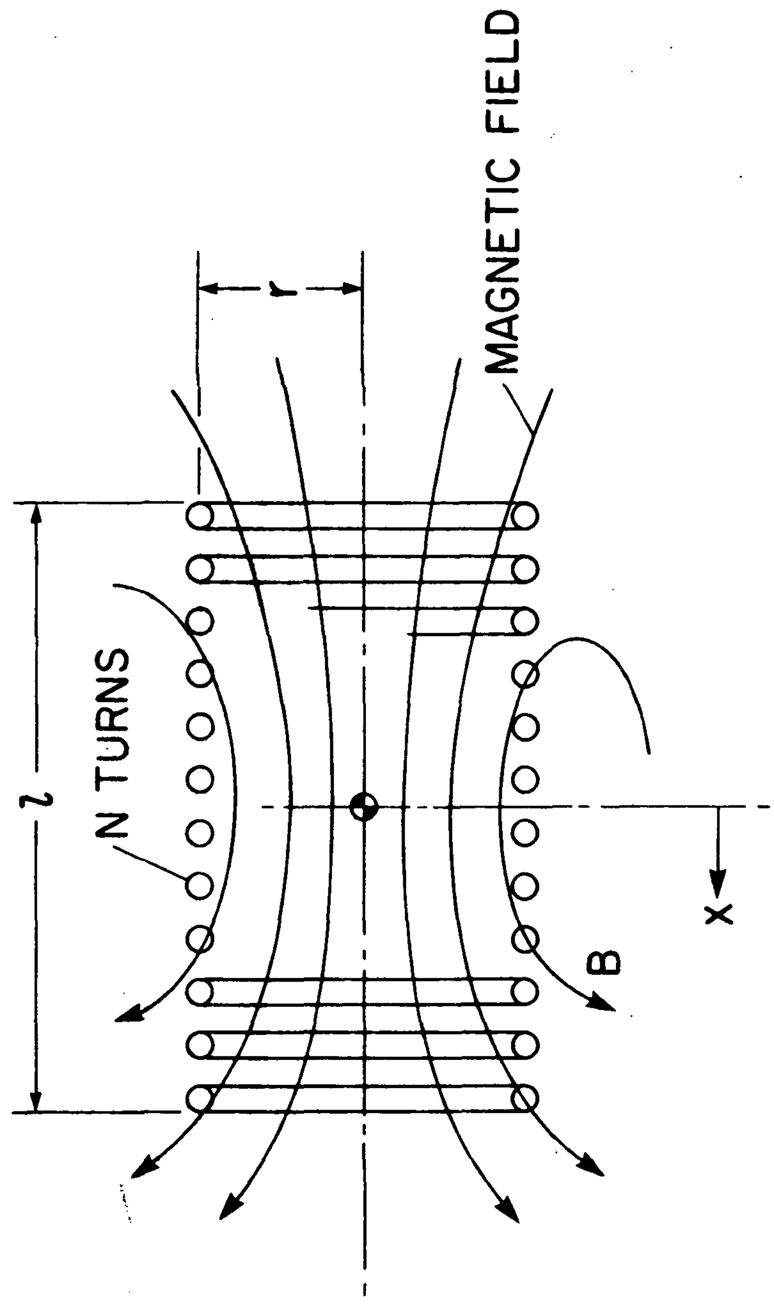


Figure A-4 Solenoid Parameters.

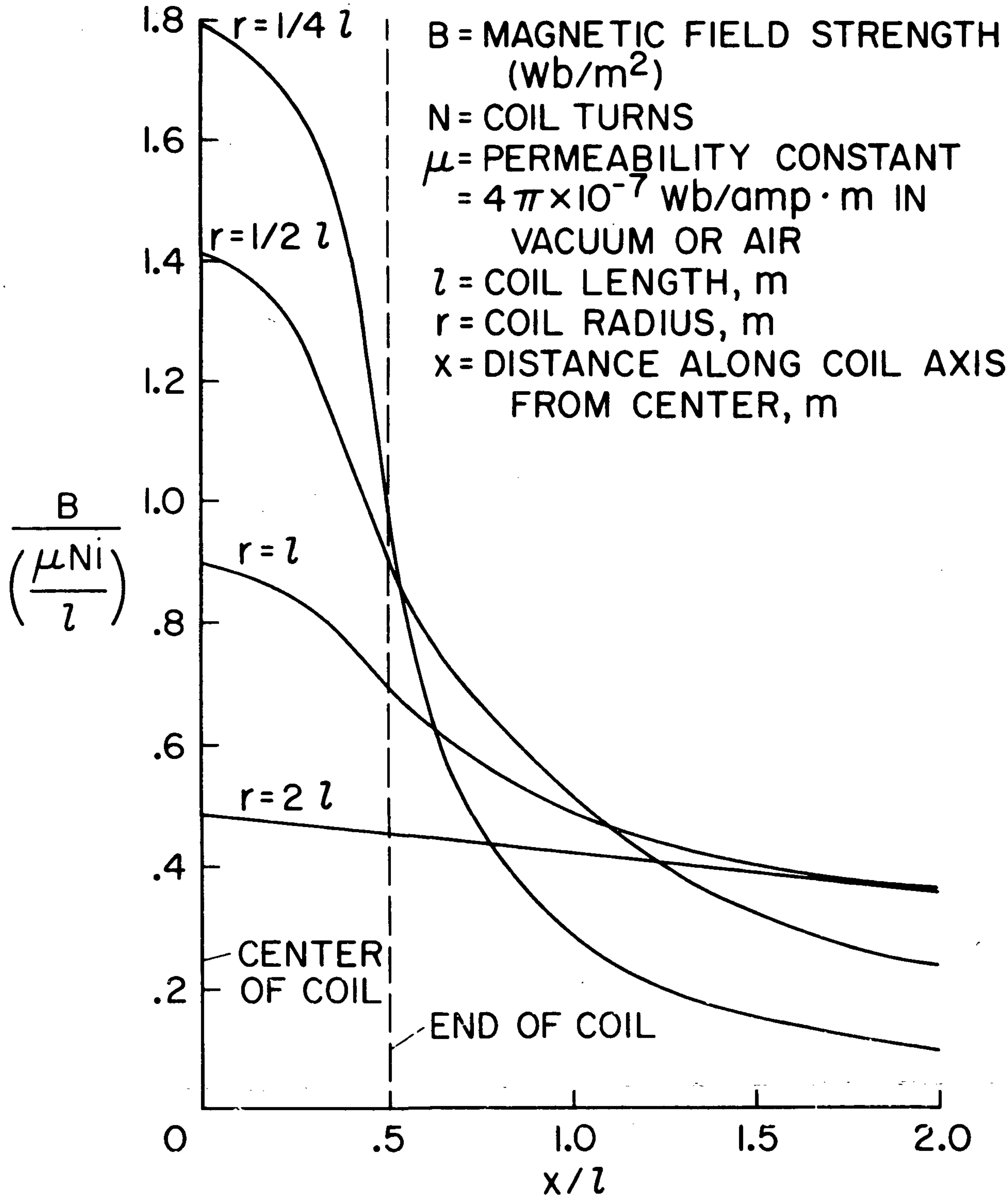


Figure A-5 Solenoid Field Strength.

where L is the inductance in henrys

N is the number of turns

μ is the permeability of the magnetic circuit ($4\pi \times 10^{-7}$ webers/amp-meter in free space)

A is the cross sectional area of the coil (m^2)

and l is the length of the coil (m)

The only variable in the inductance circuit is the mutual inductance. The mutual inductance is also related to the coil inductances by the formula:

$$M = K\sqrt{L_1 L_2}$$

where K, the coefficient of coupling, is nearly unity for transformers with steel cores, is about 0.5 for "close-coupled" circuits without ferromagnetic cores, and varies between, say, 0.01 and 0.1 for loosely coupled circuits. If L_1 and L_2 are the same order of magnitude, then M can vary from zero to that same level, or actually, about half that level for the sliding coil accelerator. Since L_1 and L_2 can be held constant with sliding contacts, the inductive gradient dL/dx is strictly proportional to the gradient of the coupling coefficient.

The force of attraction between two coils (or more generally, two cylindrical current sheets) is given by a rather complex formula developed in reference 23. Fortunately, the design can be parametric (i.e., flexible), thereby allowing some simplifications that reduce the complexity of the formula considerably. It is found, for example, that much of the formula disappears if the two current sheet diameters are equal, an assumption which is not unreasonable. Further, the force between the current sheets is maximized when the coils are as short as possible and as close as possible (without being nested).

The force in dynes can be simplified to the equation:

$$F = 2\pi \frac{N_1 N_2 i_1 i_2}{\lambda^2} \quad [W]$$

where N is the number of turns of a coil

I is the current in a coil (abampere)

$\lambda = l/a$ where l = coil length, a is the coil radius

and [W] is a nondimensional function

If the current is measured in amperes and the permeability is assumed as unity (vacuum in this system of units), the force can be expressed in newtons as follows:

$$F = \frac{1}{2} \frac{\mu N_1 N_2 i_1 i_2}{\lambda^2} [W]$$

The effect of λ on [W], an elliptic integral function, and the consequent effect of λ on the produced force ($F \alpha \frac{W}{\lambda^2}$) is plotted in figure A-6. If all the maximizing conditions are used, i.e., the coils are butted, the coils are of the same diameter, each coil has the same number of turns, the same length, and carries the same current, then one can plot Ni as a function of λ. This is shown in figure A-7 for various relative permeabilities, with the assumption of a 1,330,000 Newton (300,000 lb.) output force.

Once Ni is known, the size and weight of a coil can be determined (if the shape is defined) merely by assuming that the current will be uniformly distributed over the coil cross section and that all resistance losses are absorbed by the copper winding. Since the wires will be closely packed, the windings merge to become a cylindrical sheet and the wire current carrying capacity as defined for single wires in such sources as ref. 24 are not valid. Once the required payload mass is known, the dimensions can be determined. A schematic of a sliding coil accelerator is shown in figure A-8. Four sample calculations are summarized in table A-3. Case 1, with Ni = 10^9 shows a bleak situation; a coil weight of 3.75 x 10^6 kilograms (seven million pounds) is needed to produce 1,330,000 Newtons of thrust, less than 1/20 of a g acceleration using standard material properties. Case 2: If the resistivity of copper can be reduced by a factor of 10, the relative permeability of

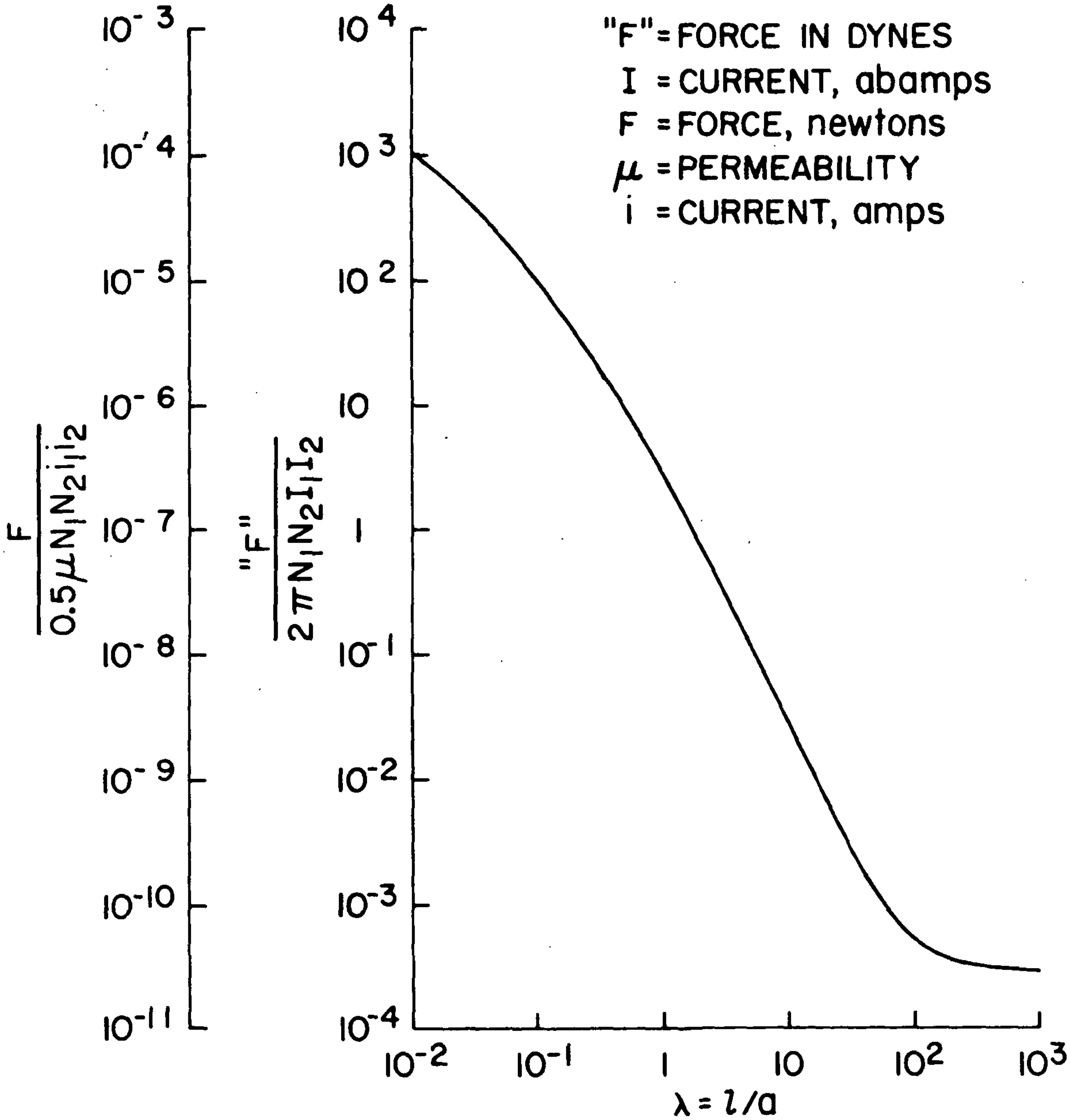


Figure A-6 Force Between Coaxial Coils.

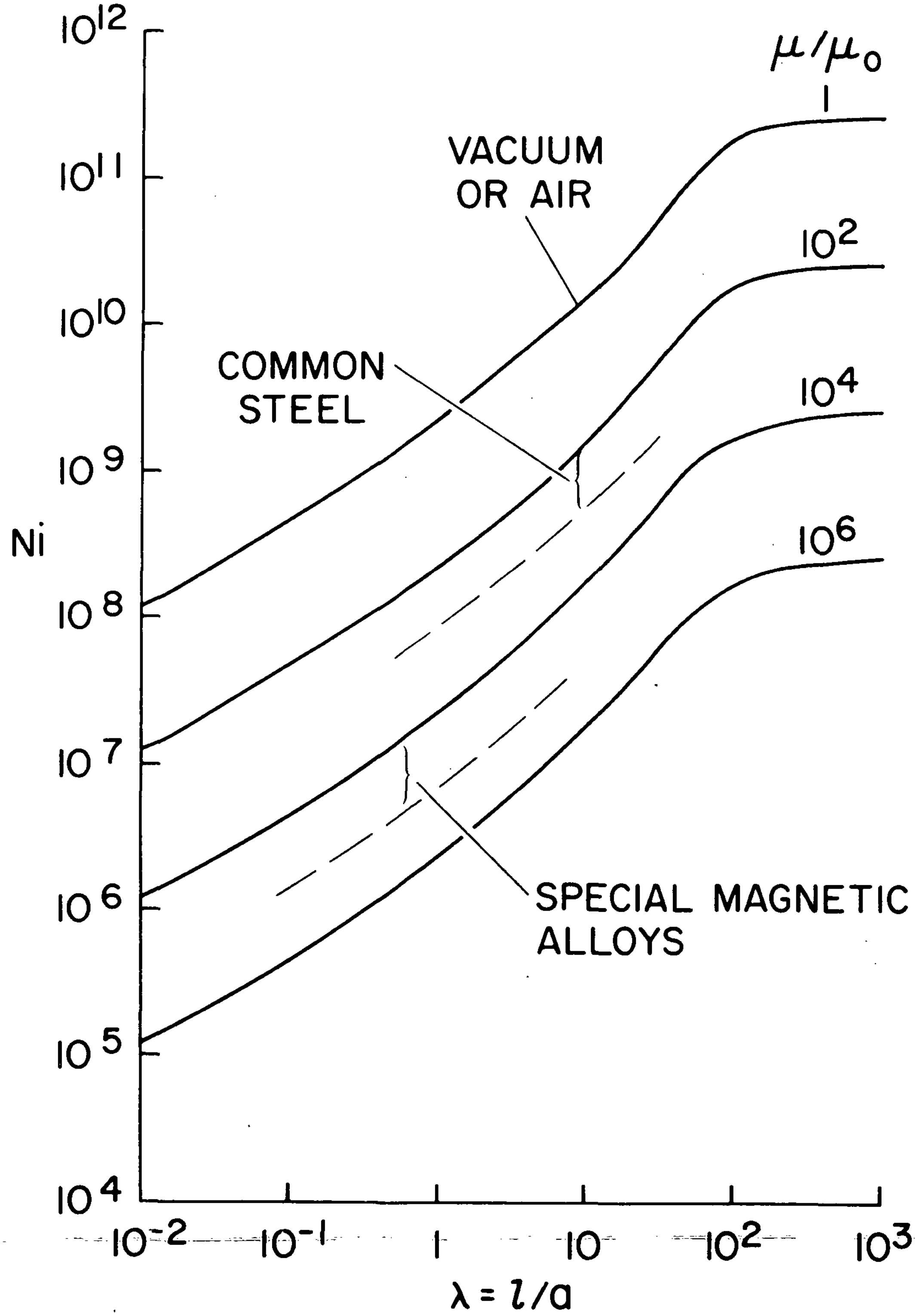


Figure A-7 Sliding Coil Accelerator Sizing.

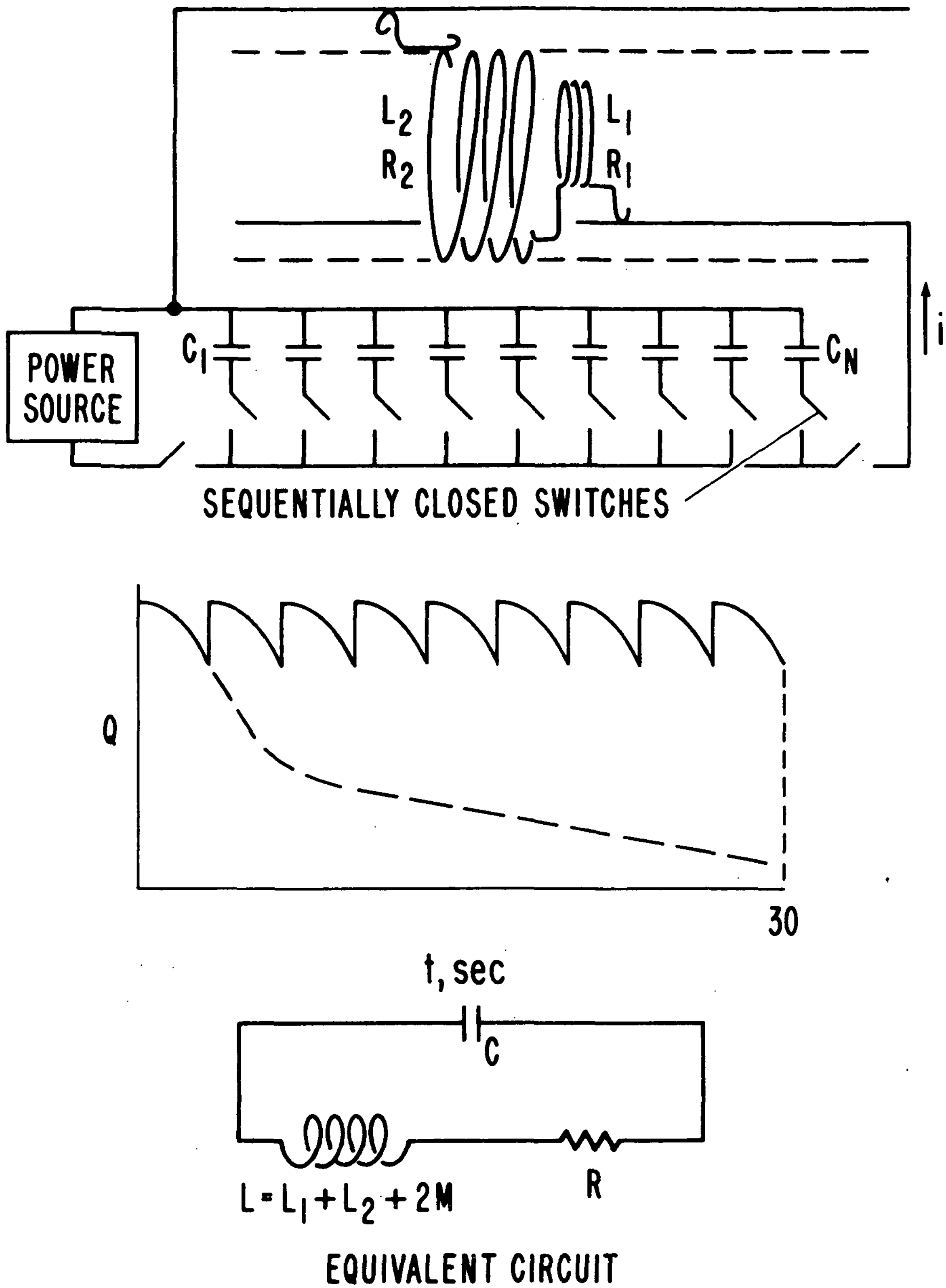


Figure A-8 Sliding Coil Accelerator Schematic.

TABLE A-3 SUMMARY OF COIL CALCULATIONS

Case	Coil Calculation	Coil Mass	Radius a	Outside Diameter
1	$Ni = 10^9$ $r = .0269\ \mu\Omega/(cm^2/cm)$ $a = 1 = b$ $\Delta T = 650^oC$	3.175×10^6 kg	3.89 m	11.58 m
2	$Ni = 10^7$ $r = .0269\ \mu\cdot\Omega/(cm^2/cm)$ $a = 1 = b$ $\Delta T = 760^oC$	500 kg	0.213 m	0.64 m
3	$Ni = 10^8$ $r = .0269\ \mu\ \Omega/cm^2/cm)$ $a = 10b = 10\ 1$ $\Delta T = 483^oC$	2.22×10^5 kg	7.37 m	15.50 m
4	$Ni = 10^7$ $r = .0269\ \mu\ \Omega/(cm^2/cm)$ $a = 10b = 10\ 1$ $\Delta T = 483^oC$	7.03×10^3 kg	2.32 m	4.88 m

the core is improved enough to lower Ni to 10^7. In addition, if the temperature of the copper windings is allowed to increase from -204°C (-400°F) to 538°C (1,000°F), then the mass requirement is reduced to 500 kg (1,100 lb) and the core outside diameter is 0.64 meters (two feet). A more reasonable coil geometry (i.e., thinner cross section) is examined in Cases 3 and 4 of table A-3. This configuration is heavier because the thinness of the coil cross section increases the resistance and consequently the mass. The coil of Case 4 has a reasonable weight, but is again dependent on cyrogenic temperatures.

The final coil design, i.e., the specification of N and i must wait for a definition of the complete electrical circuit.

Power Circuitry

The launch system must be supplied with a quick burst of energy (i.e., for approximately 30 seconds per launch) while, in all likelihood, the power will be generated continuously (as from a nuclear power station). As such, a bank of capacitors or batteries which would be charged slowly and discharged quickly might be appropriate. The schematic of a possible arrangement is given in figure A-8. Other arrangement possibilities are given in reference 22.

The size and number of capacitors is, of course, a function of the other system parameters; inductance and resistance. If Ni for the moving coil is 10^7 amp-turns, and 10^5 turns was selected, then the cross sectional area of each wire would be about 5.42×10^{-3} cm^2 (8.4×10^{-4} in^2) based on the 542 square centimeter (84 square inch) cross section of the coil (approximately 30 gage wire). This wire has a resistance of about 100 Ω per 30 meters (100 feet) or a total resistance of 5×10^6 ohms for 1.525×10^6 meters (6×10^7 inches). The current must be 100 amps to achieve the 10^7 amp-turns which, neglecting back emf, implies a driving voltage of 5×10^7v. Other cases are described in table A-4.

Table A-4 SOME COIL CALCULATIONS

$Ni = 10^7$ amp-turns

$a = 10b = 10$ 1

$\Delta T = 483^oC$

$r = .029\ \mu\ \Omega/(cm^2/cm)$

Based on Case 4 from Table A-4

	N, turns	i, amps	Wire, m	Resist., ohms	Resist. Drop Volt (iR), Volt	Heat (i^2R), watts
A	10^5	10^2	1.525×10^6 (No. 30)	$.5 \times 10^6$	5×10^7	5×10^9
B	10^5	10^2	1.525×10^5 (No. 10)	500	5×10^5	5×10^8
C	10^3	10^4	1.525×10^4 (No. 0)	5	5×10^4	5×10^8
D	1	10^7	Single toroid	5×10^{-7}	5	5×10^7

The stationary coil need not be as heavy as the moving one since each section of the stationary coil will be activated, and hence heated, for only a fraction of the launch time. The analysis does, however, show that high permeability, and hence weight, is not only desirable, it is necessary. The most adroit solution would be the use of high magnetic permeability payloads.

The inductance of the coil with 10^3 turns is:

$$L = \frac{N^2 \mu A}{l} = \frac{(10^3)^2 \ (4\pi \times 10^{-7}) \left[\frac{\pi}{4}\left(\frac{91.5}{.0254}\right)^2\right]}{(9.15/.0254)}$$

$$= 3.5 \times 10^4 \text{ henry}$$

Since the coupling of the coils is strong, say 0.5, the mutual inductance will be high, say 2×10^4 henry. The total inductance of the system, then, is perhaps 10^5 henrys.

In a perfectly damped circuit, $R = 2\sqrt{L/C}$. In this case, then, the capacitance would have to be:

$$C = \frac{4L}{R^2} = \frac{4 \times 10^5}{(2 \times 60)^2} \approx 10^2 \text{ farads}$$

The current in the circuit will decay according to the formula:

$$i = I_m e^{-\frac{Rt}{2L}} \sin 2\pi f_1 t$$

where $I_m = \dfrac{2\pi f_o^2 Q}{f_1}$

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Q = initial capacitor charge in Coulombs.

The current is to first order approximation, found to be:

$i \approx t \quad \text{for } t < 10^4 \text{ sec}$

Despite the size of the components, the circuit current builds up at a uselessly slow rate.

Since it is so difficult to get a current moving in such a circuit, it appears a possible solution would be to short circuit the coil and build the current to I_o in advance of launch. This might be quite feasible using a super-cooled coil. The current in an R-L circuit decays exponentially by the relationship:

$$i = I_o e^{-\frac{Rt}{L}}$$

An external voltage, Vo, would add an additional current, determined only by the circuit resistance, and the total current would subsequently drop until it reached the added current level in accordance with the formula:

$$i = \frac{Vo}{R} - \left(\frac{Vo}{R} - I_o\right) e^{-\frac{Rt}{L}}$$

If L is 10^5, R is 100 Ω, there is an initial current of 10^4 amps and 10^5 volts is applied, then:

$$i = 10^3 + \frac{9 \times 10^3}{e^{10^{-3}t}}, \text{ amps}$$

Expanding $e^{10^{-3}t}$ in an exponential series gives:

$$i = 10^3 + \frac{0.9 \times 10^4}{1 + 10^{-3}\, t}, \text{ amps}$$

If the resistance can be reduced to 10 ohms, then the current will remain at 10^4 amps rather than slowly dropping to 10^3 amps. The energy input during launch is Vit = 30 x 10^9 watt seconds, which is roughly equivalent to the energy requirement for launch.

REFERENCES

1. Finke, Reinald G. and Oliver, Robert C.; "Comparison of Chemical and Nuclear Propulsion for Lunar and Cislunar Transportation Systems;" Institute for Defense Analysis, Science and Technology Division; Contract DAHC 1567 C 0011, Task T-58; October 1970.

2. "Nuclear Flight System Definition Study--Phase II;" Volume 1: Summary, Volume 2: Reusable Nuclear Stage Missions and Operations; and Volume 3: Reusable Nuclear State Concept Design; Lockheed Missiles & Space Company, Sunnyvale, CA; Contract NAS8-24715; May 1, 1970.

3. "Pre-phase A Study for an Analysis of a Reusable Space Tug;" Volume 1: Management Summary; Volume 2: Technical Summary; and Volume 3: Mission and Operations Analysis; North American Rockwell Space Division; Contract NAS9-10925; March 22, 1971.

4. Meyer, H. J. and Minich, J. J.; "Mission Definition, Performance Capability, and Operations Analysis of Chemical Orbit-to-Orbit Shuttle;" The Aerospace Corporation, Systems Engineering Operations, El Segundo, CA; Contract F04701-70-C-0059; December 1970.

5. "Nuclear Flight System Definition Study;" Final Report Volume 1: Summary; McDonnell Douglas Astronautics Company, Western Division, Huntington Beach, CA; Contract NAS8-24714; May 1970.

6. "Improved Lunar Cargo and Personnel Delivery System;" Volume II Study Summary, Final Report; Lockheed Missiles and Space Company, Sunnyvale, CA; Contract NAS8-21006; June 28, 1968.

7. Sugar, R. D. and Winneberger, R. A.; "Mission Analysis of OOS/RNS Operations Between Earth Orbit and Lunar Orbit;" The Aerospace Corporation, El Segundo, CA; Contract F04701-69-C-0066; June 1970.

8. Webb, E. D. and Van Zytveld, P. J.; "Advances in the Analysis of Shuttle Operations Between Earth and Lunar Orbits;" AAS/AIAA Astrodynamics Specialists Conference 1970; Ft. Lauderdale, FL; August 17-19, 1971.

9. Gunther, P.; "Asymptotically Optimum Two-Impulse Transfer from Lunar Orbit;" AIAA Journal, Vol. 4, No. 2; February 1966.

10. Deerwester, Jerry M.; "Plane Change Requirements Associated with Rendezvous in a Lunar Satellite Orbit;" AIAA Journal, Vol. 2, No. 5; May 1964.

11. Sugar, R. D.; "Velocity Requirements for Operations Between the Lunar Surface and a Lunar Orbit Space Station;" The Aerospace Corporation, El Segundo, CA; Contract F-4701-70-C-0059; July 1970.

12. Fishbach, Lawrence H. and Willis, Edward A., Jr.; "Performance Potential of Gas-Core and Fusion Rockets: A Mission Applications Survey;" NASA TMX-67940; Lewis Research Center, Cleveland, OH; November 1971.

13. Latham, Thomas S.; "Summary of the Performance Characteristics of the Nuclear Light Bulk Engine;" AIAA/SAE 7th Propulsion Joint Specialist Conference; Salt Lake City, UT; June 14-18, 1971.

14. Ragsdale, Robert G. and Willis, Edward A., Jr.; "Gas-Core Rocket Reactors - A New Look;" AIAA/SAE 7th Propulsion Joint Specialist Conference; Salt Lake City, UT; June 14-18, 1971.

15. "TRW Space Data," J. B. Kendrick, editor; TRW Systems Group, TRW, Inc; 1967.

16. Laithwaite, E.R. and Nasar, S.A.; " Linear Motion Electrical Machines;" Proceedings of the IEEE, Vol. 58, No. 4; April 1970.

17. Laithwaite, E.R.; "Linear Induction-Motor Propulsion for High-Speed Railways;" Engineers' Digest, Vol. 23, No. 8; August 1962.

18. Ooi, Boon-Teck and White, David C.; "Traction and Normal Forces in the Linear Induction Motor;" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 4; April 1970.

19. Jones, M.F.; "Launching Aircraft Electrically;" Aviation; Oct. 1946.

20. "Final Report Study of Linear Induction Motor and Its Feasibility for High-Speed Ground Transportation;" U.S. Dept. of Transportation Study Contract C-145-66/Neg; Garrett Report 67-1948; June 1967.

21. Shaw, J.M., Sketch, H.J., and Logic, J.M.; "The Theory Design Construction and Testing of an Electric Launcher;" Royal Aircraft Establishment Report AERO-2523, EL-1484; July 1954.

22. Karlheinz, Thom and Norwood, Jr., Joseph; "Theory of an Electromagnetic Mass Accelerator for Achieving Hypervelocities;" NASA TN D-886; June 1961.

23. Snow, Chester; "Formulas for Computing Capacitance and Inductance;" NBS Circular 544; 1954.

24. "Reference Data for Radio Engineers," Fourth Edition; International Telephone and Telegraph Corp.; 1949. (Data from Automatic Electric Co., Chicago.)

25. Sears, F. W.; "Electricity and Magnetism;" Addison Wesley Press, Inc.; 1951.

26. Kantrowitz, Arthur; "Propulsion to Orbit by Ground-Based Lasers;" Aeronautics and Astronautics; May 1972.

27. Rom, Frank E. and Putre, Henry A.; "Laser Propulsion;" NASA TM X-2510; 1972.

28. Cremers, C. J., Birkebak, R. C. and White, J. E.: "Lunar Surface Temperatures at Tranquility Base;" AIAA Paper No. 71-79, AIAA 9th Aerospace Sciences Meeting, New York, NY; January 1971.

29. NASA SP-8013; "Meteoroid Environment Model-1969 (Near Earth to Lunar Surface);" March 1969.

30. "Technological Requirements Common to Manned Planetary Missions--Appendix B--Environments;" North American Rockwell Space Division; Contract NAS2-3918, January 1968.

31. NASA SP- ; "The Interplanetary Meteoroid Environment--1969;" September 1969.

32. Loeffler, I. J., et al; "Meteoroid Protection for Space Radiators;" Progress in Astronautics & Aeronautics, Vol. II; Academic 1972.

33. "Properties and Composition of Lunar Materials: Earth Analogies," Science, 26 June 1970.

34. "Apollo 14 Active Seismic Experiment", Science, 17 March 1972.

35. "Radiological Factors in Manned Space Flight;" NAS-NRC Publication 1487; Washington, D. C.; 1967.

36. "Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems;" Space Science Board, Radiobiological Advisory Panel, Committee on Space Medicine, National Academy of Sciences; Washington, D. C.; 1970.

37. English, Robert A.; "The Lunar Radiation Environment;" Kelsey-Seybold Clinic; Contract NAS9-9965, Report No. 72-4; February 1972.

38. Adams, James and Billingham, John; "Moonlab: A Design for a Semi-permanent Lunar Base;" Proceedings of the Seventh Annual Working Group on Extraterrestrial Resources; Denver, Colorado; June 1969; NASA SP-229.

39. "Lunar Base Emplacement Study for Boeing Company;" Holmes & Narver, Inc.; Report No. HN-176-4007; October 1963.

40. "Project Horizon: A U.S. Army Study for the Establishment of a Lunar Military Outpost;" Phase 1, Vol. 2: Technical Considerations and Plans and; Vol. 4: Technical Services Capabilities and Support; Army Missile Command; Redstone Arsenal, Alabama; June 1959.

41. Grubelich, Gregory and Markow, Edward G.; "Structural Design on Installations on the Moon;" Grumman Aircraft Corp.; April 1968.

42. Johnson, Stewart W.; "Criteria for the Design of Structures for a Permanent Lunar Base;" PhD Thesis, Univ. of Illinois; 1964.

43. Fraser, T. M.; "The Intangibles of Habitability During Long Duration Space Missions;" NASA CR-1084; June 1968.

44. Peele, Robert; Mining Engineers' Handbook, 3rd Edition; 1945.

45. Taggert, Arthur F.; "Handbook of Mineral Dressing Ores and Industrial Minerals;" 6th Printing, John Wiley & Sons; New York; 1956.

46. Boretz, J. E. and Miller, J. L.; "Large Solar Arrays for Multi-Mission Lunar Surface Exploration;" Intersociety Energy Conversion Engineering Conference, 1968; IEEE Transactions on Aerospace and Electrical Systems.

47. Miller, Paul R.; "High Power, Long-Life Electrical Generating Systems for Lunar Base Missions;" from Proceedings of the Seventh Annual Working Group on Extraterrestrial Resources; NASA SP-229; 1969.

48. Gylfe, J. Donald; "Reactor and Shield Subsystems for MORL and Lunar Base Power Plants;" from 1967 Intersociety Energy Conversion Engineering Conference; American Society of Mechanical Engineers; 1967.

49. Glaser, Peter E.; "A New View of Solar Energy;" 1971 Intersociety Energy Conversion Engineering Conference Proceedings; Society of Automotive Engineers.

50. Dallas, Thomas; Diaguila, Anthony J.; and Saltsman, James F.; "Design Studies on the Effect of Orientation, Lunation and Location on the Performance of Lunar Radiators;" NASA TM X-1846; 1969.

51. Greenfield, Harold H.; "Man Rating of Reactor Power Systems for Lunar-Base Missions;" from 1967 Intersociety Energy Conversion Engineering Conference; American Society of Mechanical Engineers.

52. Carruthers, R. and Hancox, R.; "The Economics of Toroidal Fusion Reactors;" from 1971 Intersociety Energy Conversion Engineering Conference; Society of Automotive Engineers.

53. Encyclopedia Americana, Vol. 19; American Corporation; New York; 1970.

54. Encyclopedia Britannica, Vol. 15; Encyclopedia Britannica, Inc.; William Benton Publisher; Chicago, IL, 1966.

55. Joy Manufacturing Company Bulletin M-225.

56. Atlas Conveyor Company Sales Bulletins 150A and 240.

57. Taggert, Arthur F.; Handbook of Mineral Dressing; Wiley & Sons, Inc.; New York, 1956.

58. U. S. Atomic Energy Commission; Los Alamos Scientific Laboratory Press Release; New York Times; December 25, 1971.

59. Carbon Company, Inc.; St. Marys, PA, Sales Literature, 1971.

60. U.S. Bureau of Mines; Rock Fragmentation by Creating a Thermal Inclusion with Dielectric Heating; RI 7424; 1970.

61. Terraspace, Inc.; Design of A Water Cannon for Rock Tunneling Experiments; Final Report; DOT Contract DOT-FR-00017, 1971.

62. Lavoie, Francis J.; "Magnetic Fluids;" Machine Design, Vol 44, No. 13; June 1972.

63. Staff, Bureau of Mines; "Mineral Facts and Problems;" Bureau of Mines Bulletin 650; U.S. Dept. of Interior; 1970 Edition.

64. "Encyclopedia of Chemical Technology;" 2nd Edition, Vol. 12; Iron to Manganese, Interscience Publishers - John Wiley & Sons, 1967.

65. "Battle to Bottle-Up Fusion for Useful Power;" Chemical Week, December 23, 1970.

66. "Fusion Reactors Shaping Up;" Chemical Engineering; April 5, 1971.

67. "Declassification Reveals Progress in Laser Fusion;" Science News, Vol. 101; May 20, 1972.

68. "Lasers Get a Grip on Fusion Power;" Business Week; May 20, 1972.

69. Basov, Nikolai and Krokhin, Oleg; "Laser Light For Fusion Fire;" New Scientist and Science Journal; September 1971.

70. Eastlund, Bernard J. and Gough, William C.; "The Fusion Torch: A New Approach to Pollution and Energy Usage;" Division of Research-U.S. Atomic Energy Committee; Washington, D. C.; November 1969.

71. Werner, R. W., et al; "Engineering and Economic Aspects of Mirror Machine Reactors with Direct Conversion;" Proceedings of the 4th International Conference on Plasma Physics and Controlled Nuclear Fusion Research; International Atomic Energy Agency; Madison, WI; Vol. III; June 1971.

72. Gibson, A.; Hancox, R.; and Bickerton, R. J.; "Economic Feasibility of Stellarator and Tokamak Fusion Reactors;" Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research; International Atomic Energy Agency, Madison, WI; June 1971; Vol III.

73. Forsen, H. K.; "Review of Reactor Systems;" Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research; International Atomic Energy Agency, Madison, WI; June 1971; Vol. III.

74. Soo, S. L.; "Direct Energy Conversion;" Prentice-Hall, Inc.; Englewood Cliffs, NJ; 1968.

75. Kubsachewski, O. and Evans, E.; "Metallurgical Thermochemistry;" Pergamon Press, Inc., NY; Third Edition; 1958.

76. Goldsmith, Alexander; Waterman, Thomas E.; Hirschorn, Harry J.; "Handbook of Thermophysical Properties of Solid Materials;" The MacMillan Company, NY; 1961; Vol. 3.

77. Sosman, Robert B.; "The Phases of Silica;" Rutgers University Press, New Brunswick, NJ; 1965.