EXCAVATION COSTS FOR LUNAR MATERIALS

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Abstract

A lunar strip mining system is presented which is capable of excavating and transporting 3 million metric tons of ore per year to a central processing plant on the moon's surface. The mining system would grow from a single front-end loader in the first year, to a fleet of ten haulers in the 30th year. The cumulative mass of equipment transported from the earth to the moon by the 30th year would range from 160 to 780 tons, depending on the assumptions and conditions. The net energy required per year would grow from an initial 8 MW-hr to a range of 160 to 930 MW-hr by the 30th year, again depending on the assumptions. Lunar personnel requirements would consist of a single individual, whose primary function would be to perform maintenance. All of the mining equipment would either operate automatically or by remote control from earth. The projected cost for the lunar mining system is approximately $12 to $37 per ton of ore over the life of the mine. Consequently, the cost of the mining system is an important part of the overall economics of exploiting lunar resources.

Introduction

The National Aeronautics and Space Administration and the Department of Energy are currently studying the feasibility of an energy system based on solar power satellites. These satellites would be in geosynchronous orbit and would consist of huge arrays of solar cells which would generate electricity directly from sunlight. The electricity would then be converted into a microwave beam for transmission to earth, where it would be reconverted to electricity. Each satellite would produce approximately 10 GW of power.

The amount of mass required for such a satellite system is enormous compared to earlier space programs. Each satellite would have a mass of approximately 100,000 tons and more than 100 satellites would be constructed. There are three possible sources of materials for construction of the satellites: the earth, the moon, or a passing asteroid which would be captured and placed in earth orbit. All three sources are currently being studied.

Investigations of the samples returned from the moon during the Apollo program have demonstrated that, after beneficiation, the top few meters of lunar soil contain almost all of the basic raw materials needed to construct the solar power satellites, especially aluminum, silicon, and oxygen. This paper describes a strip mining system which could be used to excavate the ore and transport it to a central processing plant on the lunar surface.

The mining system would consist of a front-end loader and a fleet of haulers. This system was chosen over other methods primarily for two reasons: flexibility and maintenance.

Flexibility:	This system can easily expand to accommodate the desired quantity of ore. In addition, if various sources of materials must be exploited, then the equipment can simply be re-directed to the different mine locations as required.
Maintenance:	With this system, all of the pieces of equipment can be returned to the plant and maintenance can be performed in an enclosed shelter in a shirt-sleeve environment. This is a critical requirement.

Mining Plan

Mining Rate

A Satellite Manufacturing Facility (SMF) has been proposed to assemble the solar power satellites in earth-orbit. The SMF, as presently conceived, would require a feedstock of approximately 600,000 tons per year of beneficiated lunar ore. This beneficiated ore is expected to represent 20% of the total lunar ore mined. Thus a gross mining rate of 3,000,000 tons/yr will be required to supply the SMF. All of the lunar ore will be strip mined from the lunar surface without requiring any overburden removal.

The current scenario presumes that this gross mining rate would be achieved in the fifth year of lunar operations, growing from an initial rate of 30,000 T/yr. The mining rate and the cumulative ore mined over the 30-year life of the mine is presented in Table 1. This same information is shown graphically in Fig. 1 for the first few years of the operation. Although this scenario requires the mining rate to increase by a factor of one hundred over a period of five years, in fact the quantity of ore is not large by terrestrial standards and can be easily accomplished in the allotted time.

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TABLE 1.
LUNAR MINING PLAN

Mining Year	Gross Mining Rate (T/yr)	Net Ore To SMF (T/yr)	Cumulative Ore Mined (T)	Cumulative Ore to SMF (T)
1	30,000	30,000*	30,000	30,000
2	150,000	30,000	180,000	60,000
3	600,000	120,000	780,000	180,000
4	1,500,000	300,000	2,280,000	480,000
5	3,000,000	600,000	5,280,000	1,080,000
7	3,000,000	600,000	11,300,000	2,280,000
10	3,000,000	600,000	20,300,000	4,080,000
15	3,000,000	600,000	35,500,000	7,080,000
20	3,000,000	600,000	50,300,000	10,100,000
25	3,000,000	600,000	65,300,000	13,100,000
30	3,000,000	600,000	80,300,000	16,100,000

*No beneficiation during first year

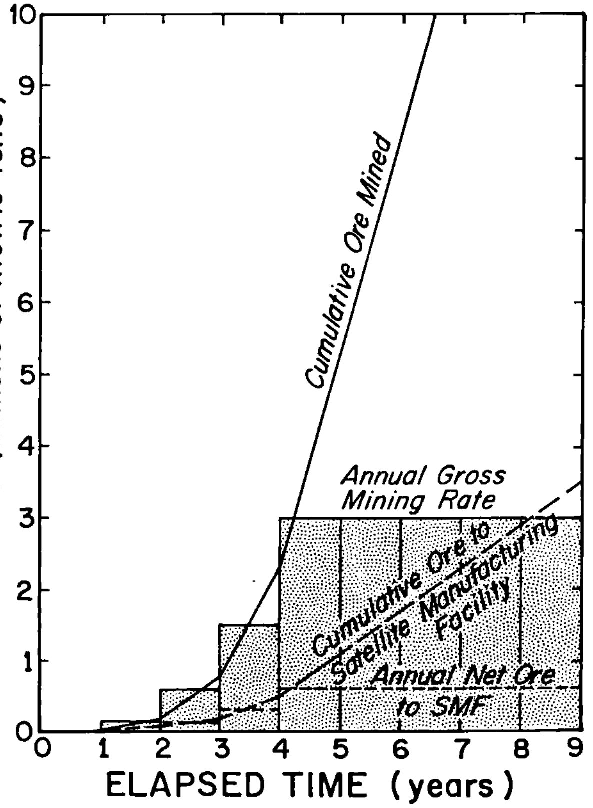
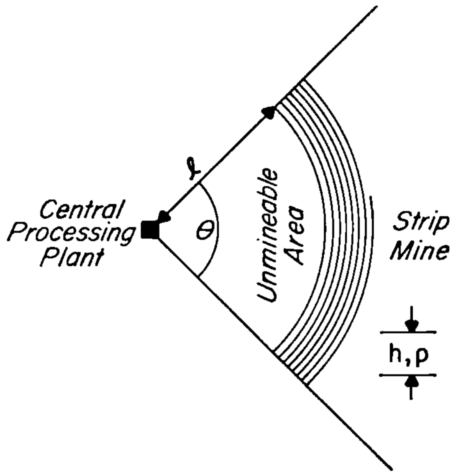


Fig. 1 Lunar Mining Plan



ℓ : Radial Distance from Plant to Mine over Unmineable Area

θ : Mine Angle

h : Thickness of Mineable Ore

ρ : Bulk Density of Ore

Fig. 2 Mine Lay Out

Mine Geometry

Of course, the location of the lunar plant and mine have not been determined yet. For purposes of this study, a hypothetical mine layout has been assumed, as shown in Fig. 2.

The lunar soil is assumed to be unmineable for a radial distance of 2 km from the plant. Beyond that point is the mine, subtending an angle of $\pi/2$ radians. The thickness of the mineable ore is taken as 2 m, which is a rather arbitrary assumption; future exploration will likely yield a greater depth.

The bulk of the ore is taken to be 1.8 T/m^3. This is considered to be a very reasonable estimate, and is based on many direct measurements.(1)

Early Years of Mining

During the first two years of the mine, all of the ore will be excavated and transported to the plant by a front-end loader. Using a front-end loader to transport the ore a distance of more than 2 km would not normally be considered a very efficient method. However, a single front-end loader is the least amount of equipment needed to start ore flowing into the plant. Furthermore, the amount of ore is not large during the first two years, and can easily be handled by a front-end loader.

Starting in the third year, haulers would be brought to the moon for transporting the ore from the mine to the plant. The front-end loader would remain in the mine and load the haulers.

As presently envisioned, electrostatic beneficiation of the ore would begin in the second year of mining. Other investigators are studying whether or not this beneficiation could be performed concurrently at the mine. Even if it could, it has been assumed in this paper that the beneficiation module would remain at the plant during the second year. It would then be moved to the mine with the front-end loader in the third year.

Number of Haulers and Excavators

General Expression

The following expression has been derived for determining the number of haulers, N, required at any time during the life of the mine:

$$N = \frac{M'f}{TmAE}\left[\frac{w\left(4\ell^2 + \frac{8M}{B\theta h\rho} \text{ x } 10^{-6}\right)^{1/2}}{Sv_{max}} + \frac{1}{3600}\left(\frac{Mt_e s}{F\rho qe} + t_{s\ell} + t'_{\ell} + t_d + t'_u\right)\right] \ldots\ldots(1)$$

Each of these factors is defined in Table 2. A range of values for each factor has been selected which reflects ideal, nominal, and unfavorable conditions. In this way, the minimum, most likely, and maximum number of haulers can be calculated. These values are also summarized in Table 2.

TABLE 2.

FACTORS USED TO CALCULATE NUMBER OF HAULERS REQUIRED FOR MINING PLAN

Factor	Symbol	Units		Conditions		
				Ideal	Nominal	Unfavorable
Gross mining rate	M'	T/yr		See Table 1		
Fraction of ore returned to plant	f	--	Case 1*	0.2	0.2	0.2
			Case 2	1.0	1.0	1.0
Time available to mine per year	T	hr		8766	4185	3987
Payload of each Hauler	m	T		Varies from 5 to 200		
Availability of Equipment	A	--		0.8	0.95	0.85
Efficiency of Equipment	E	--		1.0	0.83	0.67
Wander Factor	w	--		1.0	1.1	1.15
Radial Distance from plant to Mine	ℓ	km		2	2	2
Cumulative ore mined	M	T		See Table 1		
Mineability factor	B	--		1.0	0.98	0.95
Mine angle	θ	radians		$\pi/2$	$\pi/2$	$\pi/2$
Depth of mineable ore	h	m		2	2	2
Bulk Density of Ore	ρ	T/m^3		1.8	1.8	1.8
Maximum Speed of Hauler	v_{max}	kph		68	33	23
Speed Factor	S	--		0.9	0.85	0.7
Grade	Δ	--		0	±0.03	±0.05
Rolling Resistance	μ	--		0.02	0.05	0.07
Cycle time for front-end loader	t_e	s		30	45	60
Swell factor	s	--		1.0	1.15	1.3
Bucket fill factor	F	--		1.0	0.95	0.9
Spotting time to Load	t_{sl}	5		0	10	20
Re-load time at Plant	t'_l	s	Case 1	0	0	0
			Case 2	10	20	30
Dump time	t_d	s		15	25	40
Unload time at Mine	t'_u	s	Case 1	0	0	0
			Case 2	15	25	40

* Case 1: With concurrent electrostatic beneficiation
Case 2: Without concurrent electrostatic beneficiation

The most important factors in this expression are:

- Gross mining rate (M')
- Distance from plant to mine (ℓ)
- Fraction of ore transported to plant (f)
- Time available to mine per lunar day (T)
- Payload of each hauler (m)
- Maximum speed of hauler (v_{max})

Of these, the single most important factor is the fraction of ore transported to the plant. If electrostatic beneficiation can be performed at the mine, then as much as 80% of the ore will remain in the mine area and only 20% will require transport to the plant. This factor has such an enormous influence that two cases have been considered: with and without concurrent electrostatic beneficiation.

Number of Haulers Required

By substituting the appropriate factors from Table 2 into Equ. (1), the number of haulers required, N, can be calculated for any case and condition. This has been done and is summarized in Table 3.

As can be seen in Table 3, the payload of each hauler is significantly less for Case 1 than for Case 2. As noted above, electrostatic beneficiation at the mine has an enormous influence on the ore transport system.

Examining Table 3 further, it can be seen that for any given hauler payload, the number of haulers required under ideal conditions is typically about one-tenth of that required under unfavorable conditions. This large range is primarily due to two factors: (1) the time available to mine; and (2) the speed of each hauler. Under ideal conditions, it has been assumed that mining can occur during lunar day and night, and that the haul road is level and well-compacted. As a result, the time available for mining is more than double and the speed of each hauler is nearly quadruple the respective parameters under unfavorable conditions.

Ideal conditions define the absolute minimum number of haulers required to transport the lunar ore, and as such, are rather unrealistic. At the other extreme, unfavorable conditions define the maximum number of haulers required if everything is adverse: reduced time available for mining, steep grades and loose soil, poor equipment efficiency, and extra time required for loading and unloading.

TABLE 3. NUMBER OF HAULERS REQUIRED

	Case 1. With Concurrent Electrostatic Beneficiation						Case 2. Without Concurrent Electrostatic Beneficiation								
Mining	m=10			m=20			m=50			m=100			m=200		
Year	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U
3	1	1	2	1	1	1	1	1	3	1	1	2	1	1	1
4	1	3	6	1	2	3	1	3	6	1	2	3	1	1	2
5	1	5	12	1	3	6	2	5	12	1	3	6	1	2	3
7	2	6	13	1	3	7	2	6	14	1	3	7	1	2	4
10	2	6	15	1	3	8	2	7	16	1	4	8	1	2	4
15	2	7	18	1	4	9	2	8	19	1	4	10	1	2	5
20	2	8	21	1	4	11	2	9	21	1	5	11	1	3	6
25	2	9	23	1	5	12	2	9	23	1	5	12	1	3	6
30	2	10	25	1	5	13	2	10	25	1	5	13	1	3	7

m: Payload of Each Hauler (Tons)
I: Ideal Conditions
N: Nominal Conditions
U: Unfavorable Conditions

Consequently, for planning purposes, nominal conditions have been assumed. Referring to Table 3, a hauler payload of 10 tons with concurrent electrostatic beneficiation results in a reasonable fleet size, even after 30 years. Similarly, a hauler payload of 50 tons is appropriate without concurrent electrostatic beneficiation. The growth in the number of haulers for these two cases over the life of the mine is shown in Fig. 3. In both cases, the initial requirement for haulers is small. However, the fleet increases rapidly to five haulers in the fifth year. The growth slows down then, and a maximum fleet of 10 haulers is required by the 30th year.

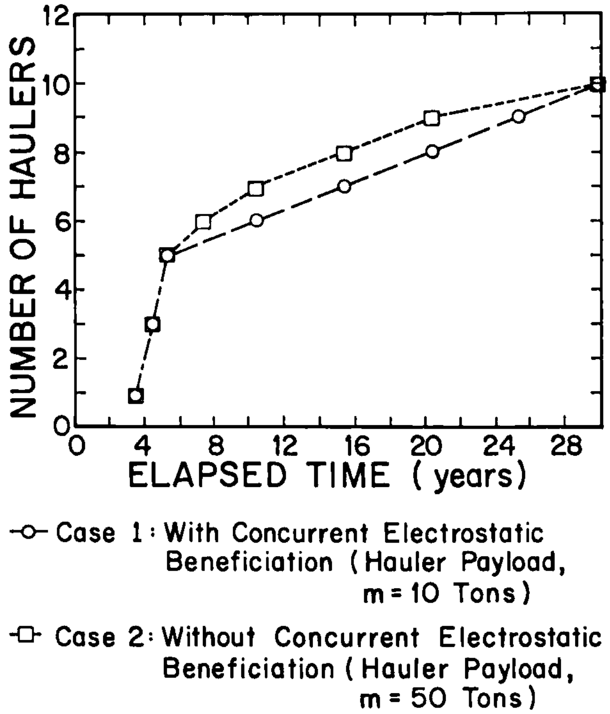


Fig. 3 Number of Haulers Required Under Nominal Conditions

Hauler-Excavator Match

It has been presumed that it will require four passes by the front-end loader to fill the hauler. The bucket capacity, q_e, has been calculated to be:

	Ideal	Nominal	Unfavorable
q_e =	$6.9m^3$	$8.4m^3$	$10.0m^3$

This is not a wide variation, and for convenience, the bucket capacity will be taken as $10.0m^3$. Allowing for swell, the mass per bucketful would be 12.5 tons. This applies to both Case 1 and Case 2, since the total amount of ore mined is the same whether or not concurrent electrostatic beneficiation can be performed.

Mass of Mining Equipment

Mass of Haulers

A plot of empty vehicle mass, m_h, versus payload, m, for a variety of terrestrial haulers is presented in Fig. 4. As can be seen, there are numerous haulers available which have a payload of 10 to 50 tons. In fact, the largest commercially available hauler has a capacity of nearly 320 tons. Note also that the points in Fig. 4 tend to fall along a straight line; the ratio of payload to vehicle mass, m/m_h, is approximately 1.3 over a wide range.

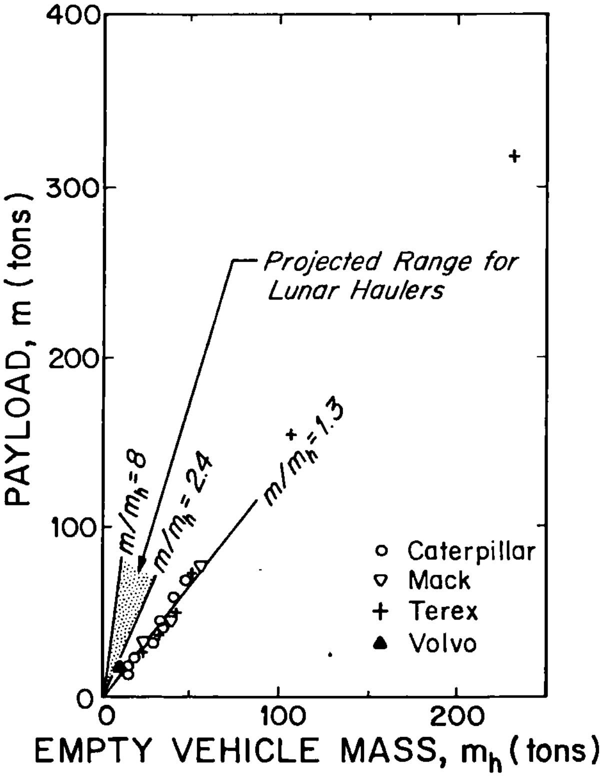


Fig. 4 Mass of Terrestrial Haulers

Most of the mass of the hauler is devoted to structural support of the payload. Because of the reduced lunar gravity, an equivalent mass payload on the moon would impose one-sixth as much structural load as on earth. Consequently, as a first approximation, it should be possible to design lunar haulers with one-sixth as much mass, or $m/m_h = 8$.

By comparison, the Lunar Roving Vehicle (LRV) of the Apollo project had a ratio of $m/m_h = 2.4$(2). The LRV obviously falls at the low end of the scale, with an empty vehicle mass of only about 0.2 tons.

These two ratios have been assumed to be upper and lower bounds. The mass of each lunar hauler can then be estimated to fall in the following ranges:

Case	Payload	Vehicle Mass
1	10 T	1.2 to 4.2 T
2	50 T	6.2 to 20.8T

Mass of Front-end Loader

Unlike the haulers, the mass of a front-end loader is independent of the gravity field. This is because the vehicle mass is used as a counter-balance to prevent it from tipping over when the bucket is loaded and extended. Thus, without greatly changing the geometry of the vehicle (and thereby reducing its maneuverability), the mass of the lunar front-end loader would be essentially the same as its terrestrial counterpart.

A plot of tipping mass versus empty vehicle mass for a variety of terrestrial front-end loaders is presented in Fig. 5.

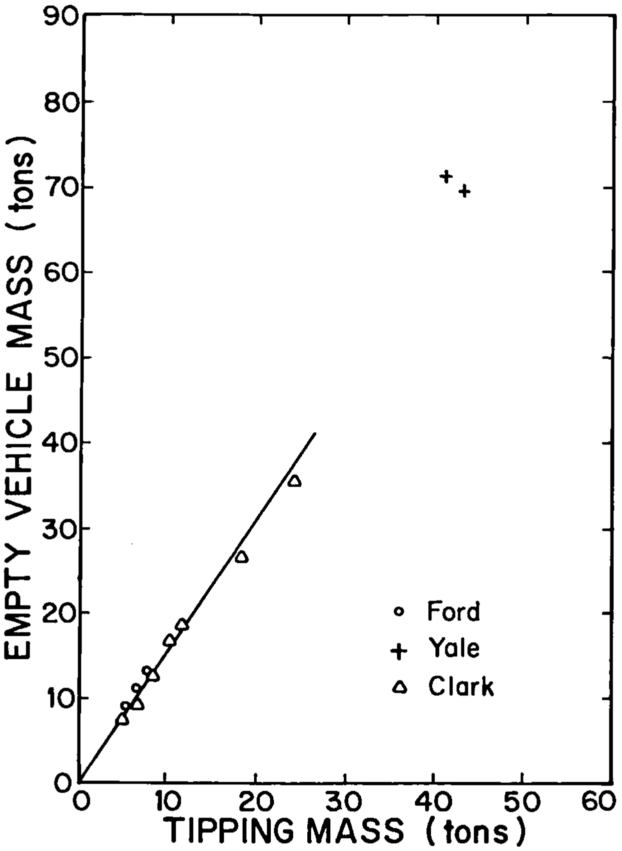
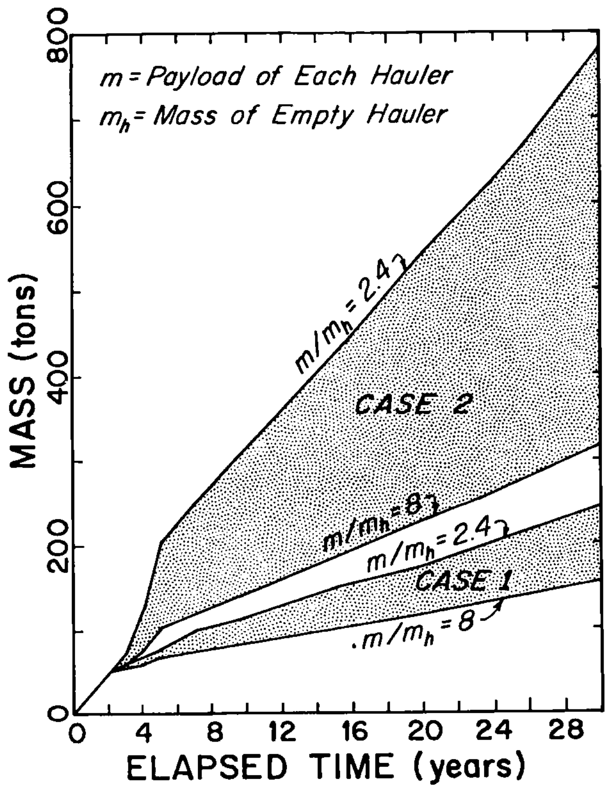


Fig. 5 Mass of Terrestrial Front-End Loaders

As with the haulers, the points tend to fall along a straight line. It is the usual terrestrial practice to multiply the bucket load by a factor of 2.0 to determine a safe tipping mass(3). The lunar equipment will presumably incorporate automatic sensing systems to prevent tipping over, and a factor of safety of 1.2 should be adequate. Thus, using a bucket load of 12.5 tons, a tipping mass of 15T is used to enter Fig. 5, from whence a vehicle mass of 23.5T is found.

Cumulative Mass of Mining Equipment

The cumulative mass of the mining equipment, including an allowance for back-up vehicles and spare parts, has been evaluated and is presented in Fig. 6.



Including Back-Up Vehicles and Spare Parts

Nominal Conditions

Case 1: With Concurrent Electrostatic Beneficiation (m = 10 Tons)

Case 2: Without Concurrent Electrostatic Beneficiation (m = 50 Tons)

Fig. 6 Cumulative Mass of Mining Equipment

In the first two years of the mine, only front-end loaders, plus spare parts, are transported to the moon. Thus, in either Case 1 or Case 2, a mass of 26T must be shipped the first year, and an additional 26T the second year. Beyond that point, the cumulative masses for the two cases diverge owing to the heavier haulers required for Case 2. By the 30th year, the cumulative mass can range from a minimum of 160 to 240 tons for Case 1, to 320 to 780 tons for Case 2.

Energy Required For Mining System

Hauler Transport

The energy required to excavate the lunar ore at the mine is trivial compared to the energy required to transport it from the mine to the plant. Consequently, the excavation energy has been neglected in the analysis that follows.

The net energy (i.e., neglecting losses due to energy storage or conversion) required for a single hauler to transport a load of ore to the plant and return to the mine is given by:

$$E = (0.139)\ w\left(4\ell^2 + \frac{8M}{B\theta hp} \times 10^{-6}\right)^{\frac{1}{2}} a m_h \left[\left(1 + \frac{m}{m_h}\right)(\mu + \Delta) + \left(1 + \frac{(f-0.2)m}{m_h}\right)(\mu - \Delta)\right] \quad \text{..........} \quad (2)$$

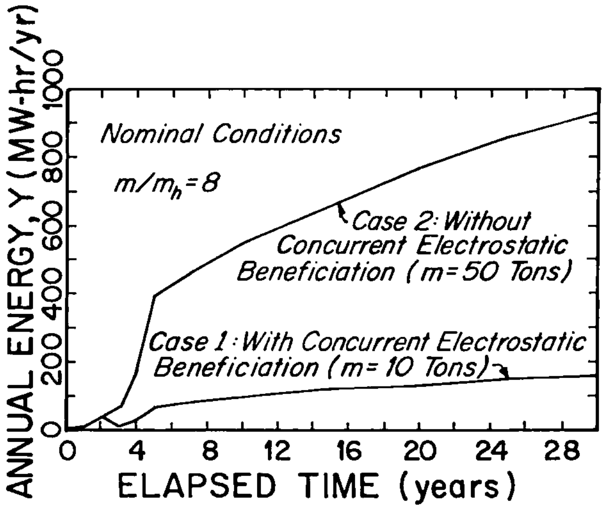
where, E = net energy per load (kW-hr/load)
a = acceleration of lunar gravity = 1.63 m/s^2
and all of the other terms have previously been defined.

The net energy required for any given mining year, Y, is then approximately given by:

$$Y = E\,\frac{M'f}{m} \quad \text{.....................} \quad (3)$$

Once again, by substituting all of the appropriate factors into Equations (2) and (3), the net energy required for the mining system can be calculated. This has been done and is presented in Fig. 7. The energy required in the first two years is the same for Case 1 or Case 2, because a front-end loader is used to transport the ore in both cases. After that, the energy required for Case 2 is considerably greater, owing to the use of larger haulers and the necessity to transport waste back to the mine.

Note that for Case 1, the energy requirements actually decrease during the third and fourth years. This is because beneficiation at the mine commences with the third year, and the fact that the haulers are much more efficient for transportation than the front-end loader.



m = Payload of Each Hauler
m_h = Mass of Empty Hauler

Fig. 7 Net Energy Required for Mining System

The large differences between ideal and unfavorable conditions are primarily due to the differences in rolling resistance plus grade: unfavorable conditions assume a total resistance of 12%, whereas ideal conditions assume 2%, or a ratio of six.

For the third and subsequent mining years, the net energy requirements presented in Fig. 7 have been calculated assuming a payload to hauler mass ratio of $m/m_h = 8$. A ratio of $m/m_h = 2.4$ would require approximately 30% more energy.

Personnel

Lunar-Based Personnel

In the previous sections, the amount of mass and energy required to operate the lunar strip mining system has been discussed in detail. In this section, the personnel requirements are considered. Of these three factors, personnel is by far the most important and challenging. It is extremely expensive to transport people to the moon and to supply them with the basic requirements of life. Consequently, it is imperative that the number of people required to operate the mining system be kept to an absolute minimum. It is believed that the entire system can be operated by one person on the moon, with support and assistance from earth, of course. Obviously, this one individual would have to be rotated back to earth, similar to the other personnel at the plant.

The primary function of this person would be to perform maintenance on the mining equipment during lunar night. During lunar day, he would be available for monitoring the mining activities and trouble-shooting if required. All of the equipment would either be automatic or remote-controlled, and thus, no other personnel would be required to operate the mining system.

Automatic Haulers

The haulers can undoubtedly be designed to operate in an automatic mode, only requiring occasional re-programming. Prior to mining, orbital photographs would document the topography in great detail. A family of haul roads would be selected and stored in each hauler's on-board computer memory. Using inertial guidance, radar, laser ranging, electronic guideposts, satellite tracking, or a combination thereof, the hauler could navigate back and forth from the mine according to a programmed sequence. Earth-based personnel would monitor the performance of the haulers and would have the capability to switch to remote control if necessary. The haulers could also be either remotely or manually controlled on the lunar surface.

Such a system should be readily attainable with present technology. In fact a child's toy is presently being sold which will follow a simple programmed path.

Remote Controlled Front-End Loader

There are many variables associated with excavation and it is doubtful that the front-end loader could operate automatically. However, it should be possible to remotely control it from earth. The front-end loader would be equipped with television cameras and various sensors to monitor its performance and location. This data would be displayed to an earth-based technician who would control the operations. As with the haulers, the front-end loader could also be either remotely or manually controlled on the lunar surface.

Again, the technology already exists for designing such a system. On a small scale, remote-controlled excavation on the moon and Mars have already been accomplished in the Surveyor and Viking programs. On earth, large draglines have been equipped with digital displays so that the operator can better monitor his own performance. Because of safety requirements, simple remote-controlled equipment has been designed for use in underground mines on earth. One study by a terrestrial equipment manufacturer suggests that in the future, most soil-moving and surface mining projects will be performed by remote control, again because of increasing safety standards(4)

Cost

In the preceding sections, three important cost components of the lunar mining system have been identified: mass, energy and personnel. An approximate estimate of the cost can be made using the following assumptions:

- The cost to transport mass from the earth to the lunar surface will be $2K/kg.
- The cost of energy supplied on the moon will be 5¢/kW-hr.
- Personnel on the moon will require 10 kg/day of consummables transported from earth. At $2K/kg, this amounts to $20K/day to support one person on the moon.

To these three cost components, a fourth component must be added: the cost of money. To simplify the analysis, constant dollars have been used, i.e., zero inflation. Hence, an interest rate of 3% has been used in the calculations.

Using these parameters, it is then a straightforward exercise to calculate the total cost of the lunar mining system. Under nominal conditions, the total cost over the 30-year life of the mine varies from a minimum of nearly $1B (Case 1, $m/m_h = 8$) to a maximum of almost $3B (Case 2, $m/m_h = 2.4$). Thus, the effect of the larger haulers, which are required in Case 2 to transport unbeneficiated ore, is to triple the total cost. In either case, the cost for transport of mass to the moon is the single largest component, representing 60 to 90% of the total. Personnel is the second most important, representing 10 to 40% of the total. The cost for energy is negligible, amounting to less than 1%.

In terms of the total ore mined, the cost amounts to $12 to $37 per ton over the life of the mine, which is high by terrestrial standards. Furthermore, in terms of the beneficiated ore, the cost jumps by a factor of five to $60 to $185 per ton. Thus, the cost of the mining system is an important part of the overall economics of exploiting lunar resources. It is believed that technological advances can reduce these costs significantly. Additional research and studies need to be performed.

Conclusions

This study has demonstrated the feasibility of a lunar mining system utilizing a remote-controlled front-end loader and a fleet of automatic haulers. One person would be required on the moon to monitor operations and to perform maintenance during lunar night. Cost estimates range from $1B to $3B to excavate a total of 16 million metric tons of ore over the 30-year life of the mine.

Acknowledgements

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References

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Q. If the hauler is controlled from Earth, will there be any problem associated with the three-second time lag between observation of video signals and the actual feedback?

A. That's not really a problem; most of it will be automatic and sequenced. There will be very little human control.

Q. What type of fuel sources will be used for the vehicle?

A. There are several possible energy sources; e.g., spinning flywheels or batteries.

Q. Why do you restrict operations to the lunar day?

A. There is a problem with having the equipment operate both day and night. You can design equipment to work during either day or night, but it is difficult to design equipment to take both temperature extremes. The ideal conditions, of course, would be to work both day and night.

Q. Wouldn't the drag-line and conveyor combination belt be simpler and cheaper?

A. Not necessarily, because you have a lot of front-end mass and extensive set-up that has to be accomplished. I chose this system because it would be very easy to off-load a front-end loader and immediately start to move the lunar material to the processing plant. The amount of material to be moved is not large by terrestrial standards.