ELECTRICAL POWER INTEGRATION FOR LUNAR OPERATIONS

Gordon Woodcock
Boeing Defense and Space Group

Abstract

Electrical power for future lunar operations is expected to range from a few kilowatts for an early human outpost to many megawatts for industrial operations in the 21st century. All electrical power must be imported -- as chemical, solar, nuclear, or directed energy. The slow rotation of the Moon and consequent long lunar night impose severe mass penalties on solar systems needing night delivery from storage. The cost of power depends on the cost of the power system, the cost of its transportation to the Moon, operating cost, and, of course, the life of the power system. The economic feasibility of some proposed lunar ventures depends in part on the cost of power. This paper explores power integration issues, and costs and affordability in the context of the following representative lunar ventures:

1. Early human outpost (10 kWe)
2. Early permanent lunar base, including experimental ISMU activities (100 kWe)
3. Lunar oxygen production serving an evolved lunar base (500 kWe)
4. Lunar base production of specialized high-value products for use on Earth (5 kWe)
5. Lunar mining and production of helium-3 (500 kWe)

The schema of the paper is to project likely costs of power alternatives (including integration factors) in these power ranges, to select the most economic, to determine power cost contribution to the product or activities, to estimate whether the power cost is economically acceptable, and, finally, to offer suggestions for reaching acceptability where cost problems exist.

LUNAR ELECTRIC POWER INTEGRATION

Introduction: Sources and Uses of Power on the Moon

Past lunar missions have used battery power (the Apollo Lunar Module), solar power (Surveyor), and RTG power (the ALSEP instruments left on the lunar surface by Apollo). Future missions, as indicated in *Figure 1*, may use all of these and in addition nuclear and beamed power, the latter transmitted by microwave or laser. Laser beaming can achieve narrow enough beams to transmit power from Earth; microwave transmission would be limited to the L1 point (about 55,000 km. towards the Earth from the near side of the Moon), or closer. Uses of power on the Moon include life support for people, operation of scientific instruments and equipment, infrastructure including habitats, transportation, communications, and other subsystems. Several industrial uses have been proposed, from making oxygen for lunar transportation systems to production of energy or energy supplies for Earth. The lunar module produced and used about 1 kW electric power. Future uses, in the far future, could go to thousands of megawatts.

Figures 2 and *3* summarize ranges of power consumption for the uses cited in *Figure 1*.

Life Support systems use power to recycle and purify water, to regenerate oxygen after it has oxidized food to H_2O and CO_2, to provide thermal control to the crew cabin and circulate air, to process wastes, and to control the cabin atmosphere and remove trace contaminants. Future lunar crew missions will use partially or fully closed systems. Partially closed systems recycle water. Regeneration of oxygen for a "fully closed" system roughly doubles the power requirement. A life support system is not entirely closed unless it also regenerates food. Since plant photosynthesis is not energy efficient, regeneration of food with man-made energy through artificial lights is power intensive. Food regeneration also requires extra pressurized volume. Natural sunlight is available on the Moon during the lunar day. The problem is that the lunar day and night are each about 14 Earth days long. Plants are likely to die, or at least not be productive, if deprived of light during the lunar night. Therefore, some artificial light will be required and must be produced during the lunar night when sunlight is not available for power generation. How much artificial light is needed, or should optimally be provided, is the subject of current research and is not presently known. Saving power tends to increase volume since plants grow more slowly with less total light per unit time. A "best guess" for bioregenerative life support today would be about 6 kWe per person.

Most **science** missions require relatively little power. Large-scale drilling projects might require up to tens of kW but would be intermittent in nature. Telescopes need less than one to a few kW. Science projects demanding high power can be imagined but none are presently in NASA's planning.

Infrastructure refers to all the other systems and subsystems, in addition to ECLS, required on the Moon to keep a base operational. The 5 kWe initial value provides for basic data processing, controls and displays, and communications. As more crew are added power increases for lights, crew systems such as galleys and toilets, additional data processing and displays, airlock operations, and other miscellaneous uses.

Initial lunar **surface transportation** will have at least one pressurized rover and later operations may have up to several unpressurized and pressurized rovers. Mining and construction operations can range from small experimental systems to large industrial systems. A 12-person base will probably have enough crew labor available to support only very modest mining and construction operations such as production of lunar oxygen for the lunar space transportation system.

The bottom of *Figure 2* presents a typical calculation. The first line is 5 for initial infrastructure, 2 + 1 life support and infrastructure per person, 25 for science, 5 for unpressurized rovers and 10 for two pressurized rovers. The bioregenerative example uses 6 kWe per person for life support.

Figure 3 describes **industrial** uses. A typical 12-person base might produce 50 t. oxygen per year, for 1.5 million kWh per year, an average of 171 kWe. Particular specialized products have not been identified. The extremely high vacuum and dry environment on the Moon could, for example, lead to specialized opto-electronic products. Depending on the processing required, the energy cost per unit mass can be high. Production would likely be quite small. At 1 t. of specialized products per year, for example, and 267,000 kWh per ton, the power is about 30 kWe.

Scenarios for energy supply to Earth involve processing of large amounts of materials and need large amounts of power, up to hundreds of megawatts or more. These scenarios have severe limits on affordability and must consider energy payback. Laser power transmission from the Earth to the Moon, while an attractive option for lunar power levels up to a few megawatts, may prove so inefficient as to be not viable for Earth energy scenarios. This depends on the energy consumption on the Moon needed to produce a given amount of Earth energy, a value for which only very poor estimates exist. Clearly, it does not make sense to supply energy to Earth with a system that consumes more energy on Earth than it produces.

Costs and Economic Considerations

Supply of electric power on the Moon can best be evaluated on the basis of cost of the power produced, and whether the cost can be reasonably borne by the planned uses. A major component of the cost of any lunar power system is the amortization of the cost of delivering the power system or its constituents from Earth.

Figure 4 illustrates representative cost estimates for lunar cargo transportation from Earth. A large heavy-lift vehicle (HLV) of the type contemplated for early use in the SEI program is estimated to have a delivery cost to low Earth orbit of about $2500/lb. (We use cost per pound here because it is the most commonly quoted value. $2500/lb is $5.5 million per metric ton.) If conventional cryogenic rocket propulsion is used for delivery from low Earth orbit to the Moon, the cost multiplier is about eight, mainly because the payload delivered to the lunar surface is about 1/6 the payload to low Earth orbit. The cost estimate shown here considers a small amount for operations costs. This presumes that operations for HLV launches are conducted by crews that will perform other duties when not working the infrequent HLV launches. If crews are dedicated or if launch preparation and mission operations become elaborate, the operations cost contribution could easily be several times the estimate shown.

At higher launch rates hardware production costs as well as operations benefit from economies of scale. When lunar transportation operations mature and become routine it will be economical to use a smaller, frequently launched HLV with reusable lunar in-space transportation hardware and Earth orbit operations for re-use turnaround. Finally as launch rates exceed a few tens, partially to fully reusable launchers become economic. Shown here is a reusable booster, reusable core stage propulsion/avionics module, expendable core tank design approach identified as optimal for launch rates in the 100 to 200 range by several studies including the Space Transportation Architecture Study (STAS) conducted a few years ago for the Air Force. Transport costs to the Moon are further reduced by advanced reusable cargo delivery systems such as the electric propulsion lunar transfer vehicle referenced in the *Figure*. The power cost estimates to follow used the transportation cost values (20,000, 2500, 1500, and 400 dollars per pound) shown in this *Figure* as appropriate to the lunar activity level considered.

Cost Estimates for Lunar Power

Given estimates for transportation cost it is possible to estimate the cost of lunar power alternatives in a manner similar to estimating the cost of power from utility powerplants. *Figure 5* presents such estimates for a wide range of power sources and lunar scenarios. All of these estimates are for cost and do not include profit. Since most of the investment in the power plant is at the beginning of life and the power is delivered over a period of years, it is necessary to include a cost of money which in all cases was set at 10% per annum. In each case the transportation cost was selected based on the power output considered and the presumed level of lunar transportation activity appropriate to that power output.

It is perhaps important to comment further on the cost of money. Cost of money is calculated the same way as return on investment. ROI is often quoted as a total return including cost of money plus additional profits. Cost of money is usually quoted as the return available on low-risk investments. This is the interest rate paid for borrowed funds by a secure borrower, and of course also the interest rate an investor can obtain without taking appreciable risk. Private investors will demand a much higher return on a risky project. A cost of money equal to the interest rate the government normally pays should be assessed against a project funded by the U. S. government. If a utility company were to make the investment in a lunar power system, it would demand a much higher rate of return than is usual for the relatively safer investment in an Earth-based power plant. The 10% used here is somewhat high for government-paid interest and somewhat low for the return that would likely be sought by a utility.

The Apollo lunar module was battery powered. The cost of its electric power was something like the \$200,000/kWh quoted here. Since the lunar module delivered less than 100 kWh during its lunar surface mission, the resulting \$20 million cost for power on the Moon was a small fraction of the total cost of an Apollo flight. Fuel cells provide about an order of magnitude greater power density (per unit mass) and therefore yield an order of magnitude lower cost. Nuclear power plants by comparison have enormous power density. Even a small nuclear plant can deliver power on the Moon a thousand times cheaper than batteries.

As nuclear power plant size increases and transportation cost comes down with the much greater scale of lunar operations appropriate to the higher power levels, nuclear power cost estimates come down to a few dollars per kWh. The lowest nuclear values shown are within a factor of 100 of utility power on Earth. The cost of the largest nuclear plant shown includes a hefty charge for on-site construction on the Moon. This is an exceedingly uncertain cost since the amount of construction is not known (concepts are not well enough defined to make rational estimates) and the cost of the components of a lunar construction operation, such as labor costs, are also not known. The cost of providing fabricated uranium reactor core elements is also shown, to indicate that it is a modest fraction of the estimated total nuclear power cost. Fusion fuels (deuterium and helium-3) are available on the Moon. The extraction cost is poorly defined. Solar electric costs are estimated lower than nuclear cost if the solar power is used only during the lunar day when the sun shines, and several times higher if night-time storage must be provided for continuous loads. This is an important factor to be considered by a potential power user, especially before large-scale continuous lunar power systems are emplaced: a day-only power user may get off considerably cheaper.

It has been observed that a large-scale continuous solar power system could be installed at either of the lunar poles. The Moon's polar axis is inclined only about 1 degree to the ecliptic. Consequently, a ring-wall solar array installed around a lunar pole would be continuously illuminated with the effective illumination area 1/# times the cylindrical array area. A transmission line would need to be installed to the points of use but at high enough power consumption levels, if the transmission line could be made from lunar materials, the cost could be very competitive.

The final set of estimates is for laser beam power projected to the Moon from beaming stations on Earth. This source of power is estimated to be cost competitive with nuclear systems in the range about 100 kWe to 10 MWe, with uncertainties in costs for both sources of power much too large to ascertain a winner. At power levels 100 MWe or above, the economies of scale for large nuclear plants presently show a preference for nuclear power. Laser power beaming, however, is in its infancy and major improvements in system efficiencies or new laser technologies could change this result.

Figure 6 illustrates that the problem of large-scale lunar industrialization is much broader than just electric power. The figure is a mass distribution estimate, developed by an input/output analysis, for a lunar industrial plant capable of Producing 40,000 metric tons of metals and lunar glass fiber structural materials per year. The total estimate for the plant mass was also about 40,000 t., a product-to-mass ratio of one. This, by the way, puts it in the competitive range. The point is that for this lunar plant, with total mass like that of an aircraft carrier, the 100 MWe power plant at 10 kg/kWe is a small portion of the total installation. The plant mass included a mass driver (electromagnetic catapult) for launching finished product to a lunar libration point. Most of the power consumption, however, is for reduction of lunar rocks to metals. Large-scale lunar industrialization will require major advances on a broad front of planetary resource utilization and economic space operations.

Affordability of Lunar Power

Figure 7 attempts to put the results obtained here into perspective. On the left are ranges of "reasonable" costs of power for several applications. (The units for each application are different; see curves.) For example, the cost of power to support crew operations can range from a few hundred millions per man-year to as low as a million for large-scale operations. The cost of a man-year on the Moon for Apollo was something like sixty billions. We will not pay such a high price in the future. The projected cost for NASA's proposed First Lunar Outpost is on the order of $3 billion per man-year. This drops to about 200 million for a 12-person permanent base and further to a few millions per man-year for a larger industrial operation. Consequently we set the target value for power cost at a fraction of these figures, a high of about 300 million and a low of 1 million.

The bottom of the chart shows costs for power with ranges for the various technologies from the estimates in this paper. Chemical energy for electric power, for example, is shown as marginally within the top of the range for crew support and too high for the other applications. Solar/RFC hits the middle of the range for crew support; nuclear and (laser) beamed power both extend to the bottom of the crew range.

Cost range rationales for the other applications were as follows: Oxygen shipped from Earth early in lunar operations will cost several times $10,000 per pound. The upper end of the range is set at $10,000. Earlier we indicated a possibility for lunar transportation to drop almost two orders of magnitude by the time of large-scale lunar operations; a corresponding drop in power cost for lunar oxygen is shown. There is no good estimate for special products. I took the view that these would be highly specialized raw materials for which manufacturing processes and properties would benefit from the extreme lunar vacuum and state of desiccation. An appropriate raw materials cost is in the range of a few dollars per gram. Finally, Earth energy (electric; all current lunar energy for Earth scenarios produce electric energy on Earth) presently costs its producers from less than one cent to a few cents per kWh.

All of the prime candidates for lunar power fall somewhere in the competitive range for lunar oxygen and special products. Solar day only is promising for those processes that can afford to operate only during the lunar day. However, the cost of getting only 50% duty from a processing plant must be taken into account in assessing the economics of solar day-only energy. Earth energy supply demands a lunar power cost on the order of $1 per kWh; only nuclear and solar polar options offer potential to reach this range, with very large uncertainties presently attached to solar polar power.

Concluding Remarks

An orderly evolution in lunar power production is indicated; many alternative evolutionary paths are possible with, in most cases, no clear choice among them from today's vantage point. Solar/RFC is a clear choice for early Lunar Outpost operations simply because other alternatives are too expensive (chemical) or not available (nuclear, beamed). Solar day-only may find a niche if the cost penalty for day-only operations is not too high. Nuclear and laser beamed power options are indicated as competitive, with both holding considerable promise for costs one to two orders of magnitude less than solar/RFC at adequately large scales. Solar polar is only practical on a very large energy scale. Its eventual costs will depend heavily on cost outcomes for lunar industrial development since to be practical it must be produced and installed mainly by a lunar industry.

In this paper we have shown that lunar power requirements are attainable and that the cost of power can be commensurate with the costs of the activities supported. It will be necessary to develop nuclear or laser-beamed power for lunar development to go beyond modest permanent science bases. It is clear that electrical power engineering for the Moon can meet the challenges of lunar development.

Lunar Electric Power Integration

Sources (Supplies)

- Chemical
  - Batteries
  - Fuel Cells
- Nuclear
  - Isotopes
  - Fission Reactors
  - Fusion Reactors
- Solar
  - With/Without Storage
- Beamed
  - From L1 Libration Point
  - From Earth

Sinks (Users)

- Life Support
- Science
- Infrastructure
- Surface Transportation
- Industry
  - Oxygen (Propellant)
  - Mining & Manufacturing
  - Specialized Products
  - Lunar Construction
- Energy Scenarios
  - Helium-3
  - SPS
  - LPS

FIGURE 1

ADVANCED CIVIL SPACE SYSTEMS

Use Quantities (Sinks)

BOEING

Life Support	Partially open ~ 1 kWe/person Closed ~ 2 kWe/person Bio Regen Up to 10kWe/person; depends on use of natural light
Science	• Most current concepts are modest = 25kWe or less • One can imagine massive projects, e.g. accelerator around lunar equator
Infrastructure	Roughly 5kWe + 1 to 2 per person
Surface Transportation	Unpressurized rover 1-2 kWe Pressurized, 100km range ~ 10kWe Pressurized, 1000km range ~ 25kWe (Duty cycle 25% or less) Mining/construction a few kWe per vehicle Typical construction 10t/yr-person
For Example:	12-Person base, some science, 100km rover 5 +(2+1) 12+25 + 5+10 =81kWe, closed ECLSS 5 +(6+1) 12+25 + 5+10 =129kWe, Bio-regen Modest construction would add 50 to 200 kWe

FIGURE 2

ADVANCED CIVIL SPACE SYSTEMS

Use Quantities (Sinks) continued

BOEING

Industry

- Oxygen roughly 30,000kWh/ton } Not additive; one may be byproduct of the other
- Metals similar
- Glass & ceramics; cast basalt, etc. ~ 5000 kWh/ton; varies widely
- Miners & haulers don't use much energy compared to processing, unless long distance hauling
- Specialized products highly variable, up to >100,000 kWh/ton

Examples (1) Heat to 2000°C at 10% efficiency; (2) 50ev/molecule @ MW=50 &10% efficiency

(1) 4000 cal/g =17 MJ/kg = 4700kWh/ton

(2) $\frac{50ev}{50amu} * 1.6*10^{-19} \frac{j}{ev} \; \frac{6*10^{26}}{kg}$ amu /10%efficiency $= \frac{9.6*10^{8} \text{ j/kg}}{3.6*10^{6} \text{ j/kWh}}$ = 267kWh/kg

= 267,000 kWh/ton

- May be able to sustain fairly high prices

Energy Scenarios - Supply to Earth

- Run to hundreds of megawatts and up
- Cannot sustain high prices
- Must consider energy payback

FIGURE 3

Lunar Transportation Cost Ranges

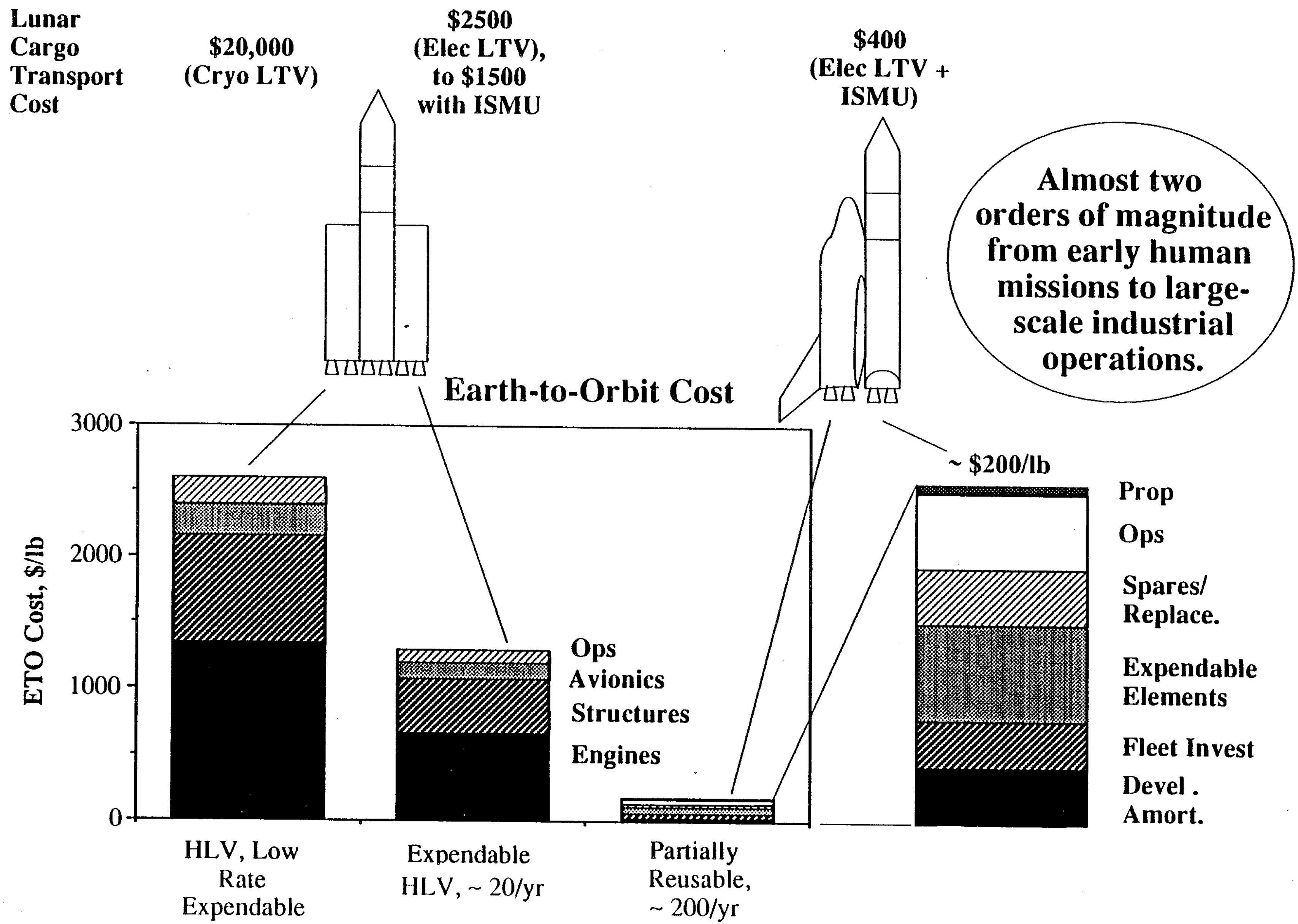


FIGURE 4

FIGURE 5

Power Sources

Type	Performance Notes	Assumed Trans. Cost	Cost Ranges
Chemical			
Batteries	< 0.1 kWh/lb	$20,000/lb	> $200,000/kWh
Fuel Cells	1 KWh/lb	(same)	$20,000/kWh
Nuclear			
SP-100 Class	20t. pre-integrated	$20,000	$250/kWh
(100kWe)	cost $200M.	$ 2,500	$70/kWh
	7-year life		
	10% Cost of Money (COM)		
	No backup		(x2 with backup)
SP-100 with	25t. pre-integrated		
dynamic	cost $500M.	$ 2,500	$60/kWh
conversion	7 year life		
(500kWe)	10% Cost of Money (COM)		
	One backup		
Multi-megawatt	10kg/kWe = 1000 t. (No reserve)		
plant	Cost, $5B-10B		
(100MWe)	Requires lunar construction	$ 1,500	$ 2.00 to $ 2.80
	$4.5 Billion	$ 400	$ 1.70 to $ 2.45
	30 year life		
	10% COM - 40% Reserve		

FIGURE 6

Power Sources

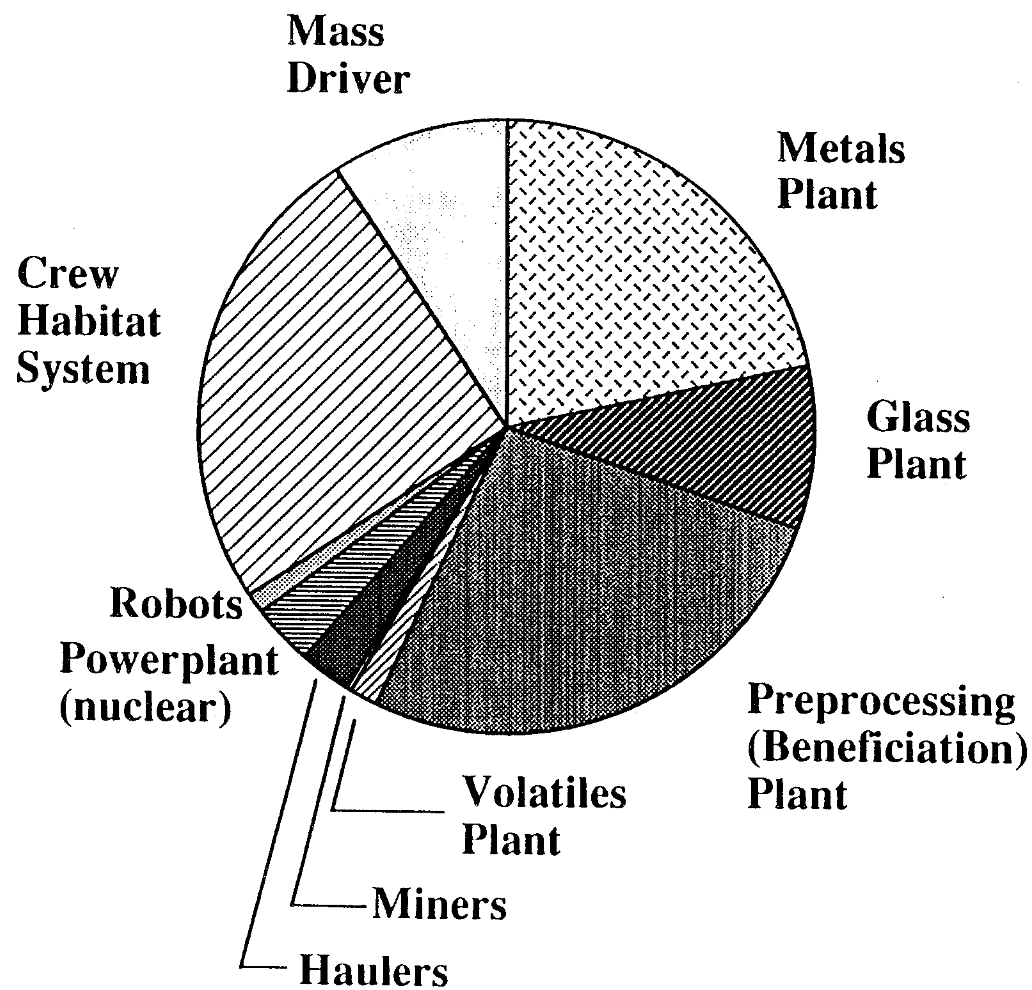
Type	Performance Notes	Assumed Trans. Cost	Cost Ranges
Nuclear Fuel			
Fission	Core 20%U 50% enriched 10% burnup = 1% fissionable 20% conv. effy $200\ MEV * \frac{6 \times 10^{26}\ fissions}{235kg\ \ fissile} \times$ $\frac{1\ kwh}{3.6x10^{6}\ j} \times \frac{1.6 \times 10^{-19}\ j/ev}{kWh/kg}$ = 45000 kWh/kg	$ 20,000	< 50¢/kWh
Fusion	Available on the Moon.		
Solar-Electric	25% array, 1350w/m² solar, 45% duty cycle, 5kg/m² $2000/watt, 30y life, 10% COM	$ 20,000 $ 1,500	$66/kWh $51/kWh (Array cost dominates)
Solar-Electric RFC	Same array, 3kW array/kWe 600kg/kW RFC system 100% duty cycle	$ 20,000 $ 1,500	$470/kWh $175/kWh (Transportation dominates at high cost)

FIGURE 7

Power Sources

Type	Performance Notes	Assumed Trans. Cost	Cost Ranges
Solar Power at Poles (Not including transmission line system) (Transmission line to Equator, est. 50,000t; 500kV @ 200 MWe, 2700km)	25% array 1350 w/m² solar, cylinder aspect (1/π), 5kg/m², 100%d.c., 30 year life 10% COM. $2000 & $20/watt	$ 1500	$71.75 & 2.45/kWh
		$ 400	$70.50 & $1.20
		Lunar built	$70/kWh to 70¢/kWh
Beam Power			
200 kWe	60m dia array @ $700,000/m² (950kWe solar equivalent) =$2B = $200m/yr 4-1.5 MW_L 2% eff. laser @ $100m 30 yr. life 10% COM 2¢/kWe for Earth power 75MWe = $13m/yr	$ 20,000	175/kWh
		$ 2,500	140 (Dominated by array cost)
10 mWe (1 link capacity)	Same array @ $2 billion 46,000kg transport to Moon 12-10 MW_L lasers @ $250m $350 m/yr for electric power	$ 20,000	$ 12.00
		$ 2,500	$ 10.00 (Dominated by laser cost)

Mass Distribution for Large Lunar Industrial Plant



Total Mass ≈ 40,000 t.

FIGURE 8

C-2

Cost of Power on the Moon: Does it Matter?

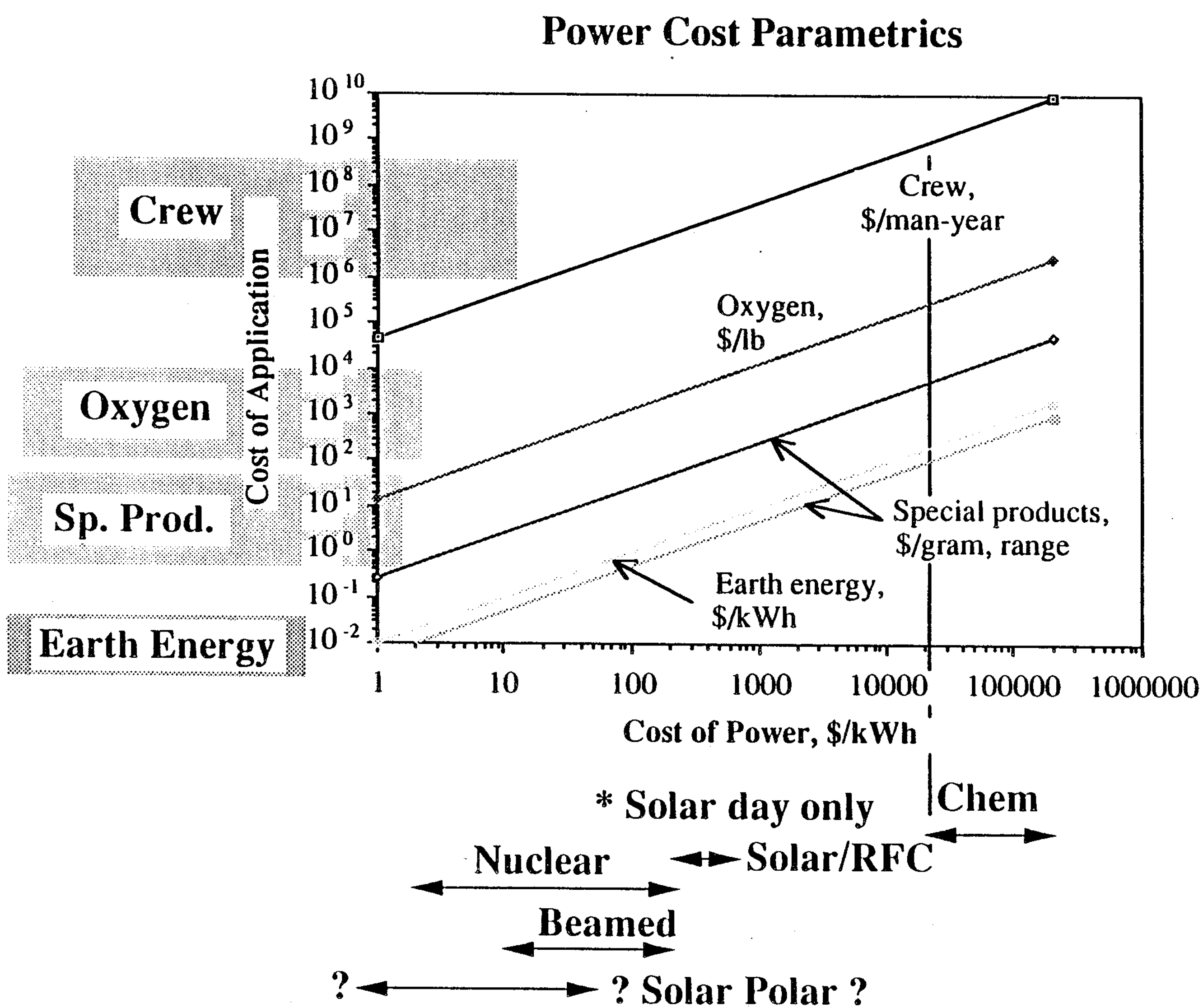


FIGURE 9