APPENDIX B-5

TRANSPORTATION AND OPERATIONS ASPECTS OF SPACE ENERGY SYSTEMS

Gordon R. Woodcock

The three energy systems were examined to understand the need for and importance of space transportation and operations.

Lunar Helium-3:   Although the helium-3 resource on the Moon is enormous compared to its availability on Earth, it is quite rare in terms of its concentration of a few parts per billion in the lunar regolith.   Consequently, the main space transportation challenge is the delivery of mining and extraction equipment. Return of extracted helium-3 to Earth is trivial by comparison.   Our analysis showed that conservative extrapolations of today's space transportation systems, and use of lunar-derived hydrogen and oxygen propellants obtained as a byproduct of helium-3 production, lead to projected transport costs to the Moon below the upper economic limit of $3000/kg.

Helium-3 production is clearly the easiest of the three concepts to demonstrate (from the space transportation and operations point of view).   Such demonstration, consisting of the experimental extraction of a few kg. of helium-3 over a year or more time, is compatible with the activities of an early lunar base.

Solar Power Satellite: This concept enjoys the soundest overall technical foundation.   Every technical aspect of the SPS concept has been demonstrated on a practical scale; there is little doubt that an SPS, if constructed, would work, i.e., transmit useful energy to Earth. The challenge of the SPS is to produce hardware for very large space systems at costs commensurate with today's commercial industrial practice, and transport the hardware to geosynchronous orbit and assemble it there at similarly low costs.   Even if most of the SPS hardware is produced on the Moon, as here proposed, the transportation rate, at least 10,000 metric tons per year to low Earth orbit, is more than an order of magnitude greater than present-day traffic (a few hundred tons per year). Relatively sophisticated transportation infrastructures are needed to obtain low-cost delivery from the Moon and from Earth and to support production operations on the Moon and assembly and checkout operations in geosynchronous orbit.

Transportation cost extrapolations, using reasonable economy-of-scale factors, project economically feasible overall transportation and operations costs for the lunar-derived SPS option.

The physics of microwave power beaming demand a relatively large-scale demonstration project. From the transportation standpoint, the demonstration is about twice as demanding in terms of total Earth launch as constructing a model lunar base: roughly 40 launches of a representative heavy-lift vehicle. A demonstrator SPS using laser power transmission could be much smaller, but with the expected relatively low efficiency of a laser power beam, would be less likely to demonstrate the potential for economic energy supply.

Lunar Power System: The space transportation and operations requirements for this energy concept are poorly understood because the concept has been less studied than the others. It is argued by the advocates that this concept can be almost entirely bootstrapped on the Moon from lunar materials. This is at least plausible, but there are important gaps in knowledge. First, the microwave power transmission performance requirements are at least an order of magnitude more severe than for the SPS, and the SPS itself requires unprecedented performance, about 20 db more gain than the Arecibo space astronomy antenna. Secondly, lunar surface operations are required on a very large scale and are very poorly understood at present. On the basis of present knowledge, the space transportation requirements for the LPS appear more modest than for SPS. However, we do not really understand the lunar surface operations requirement, and this could reverse the comparison.

It is important to recognize that if the LPS works, there is a qualitative economic difference compared to the other systems. This is that a given investment in space transportation and operations leads to a given capability for increasing the rate of power system installation, while in the case of the other systems, the investment leads to a given rate of installation.

The LPS appears to be the most difficult to demonstrate because of the physics of microwave optics and the relatively great (10 x GEO) transmission distance involved. This observation is very preliminary because our understanding of this concept is very preliminary.

PURPOSE OF ANALYSIS

A brief comparative analysis was made for three concepts of supplying large-scale electrical energy to Earth from space. The concepts were (1) mining helium-3 on the Moon and returning it to Earth; (2) constructing solar power satellites in geosynchronous orbit from lunar materials (the energy is beamed by microwave to receivers on Earth); (3) constructing power collection and beaming systems on the Moon itself and transmitting the energy to Earth by microwave. This analysis concerned mainly space transportation and operations, but each of the systems is briefly characterized in the following material to provide a basis for space transportation and operations analysis.
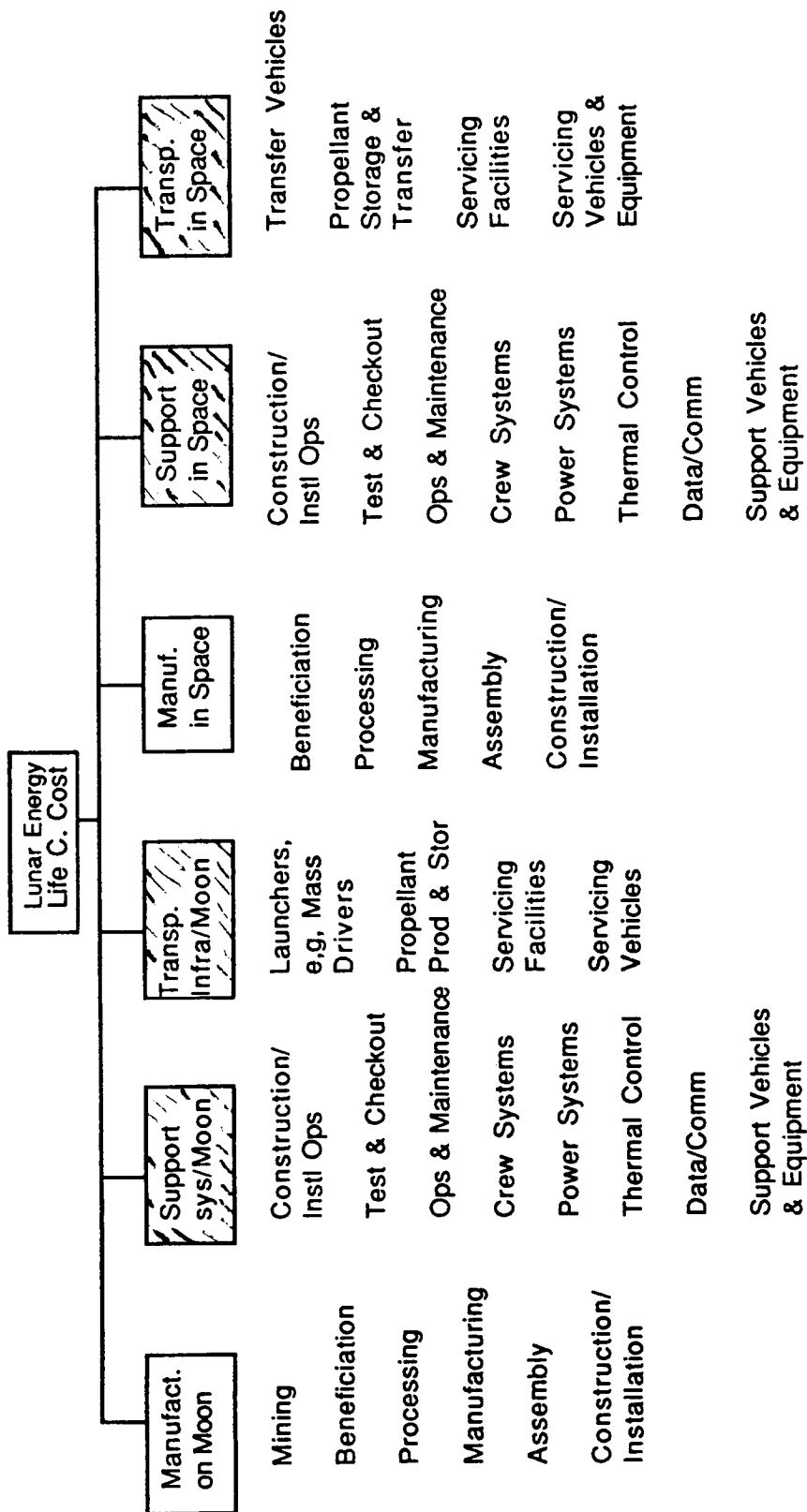
Purpose of Analysis

Roughly Normalize the Space Transportation and
Operations Requirements of the Three
Energy Options.

Develop Rough-order-of-magnitude
Transportation and Operations Costs.

Compare the Demonstration Requirements of the
Three Options re Space Transportation and
Operations.

Lunar Energy Life Cycle Cost Work Breakdown Structure

The facing page illustrates a complete work breakdown structure for the space segments of lunar energy systems. This study concerned portions of the shaded elements.

Lunar Energy Life C. Cost

Manufact. on Moon
- Mining
- Beneficiation
- Processing
- Manufacturing
- Assembly
- Construction/Installation

Support sys/Moon
- Construction/Instl Ops
- Test & Checkout
- Ops & Maintenance
- Crew Systems
- Power Systems
- Thermal Control
- Data/Comm
- Support Vehicles & Equipment

Transp. Infra/Moon
- Launchers, e.g, Mass Drivers
- Propellant Prod & Stor
- Servicing Facilities
- Servicing Vehicles

Manuf. in Space
- Beneficiation
- Processing
- Manufacturing
- Assembly
- Construction/Installation

Support in Space
- Construction/Instl Ops
- Test & Checkout
- Ops & Maintenance
- Crew Systems
- Power Systems
- Thermal Control
- Data/Comm
- Support Vehicles & Equipment

Transp. in Space
- Transfer Vehicles
- Propellant Storage & Transfer
- Servicing Facilities
- Servicing Vehicles & Equipment

Lunar Helium-3 Concept

The approach to acquisition of helium-3 from the Moon is diagrammed here. The principal space transportation and operations requirement is to deliver, set up, and operate the extraction systems (mining, beneficiation, volatiles extraction, helium-3 separation) on the Moon. Regolith is mined, beneficiated to select the grain size range most productive of volatiles, and heated to drive off the volatiles. Process heat will be derived from solar conentration; other process energy will be electrical. Beneficiation and volatile extraction may be done locally by the mining machines, or in a central processing plant, or partly by each. Volatiles other than helium-3 will be separated and stored for industrial use, e.g. as rocket propellant. Separated helium-3 can be returned to Earth on crew return flights. One metric ton per year of helium-3 will generate 10,000 megawatts of electricity continuously.
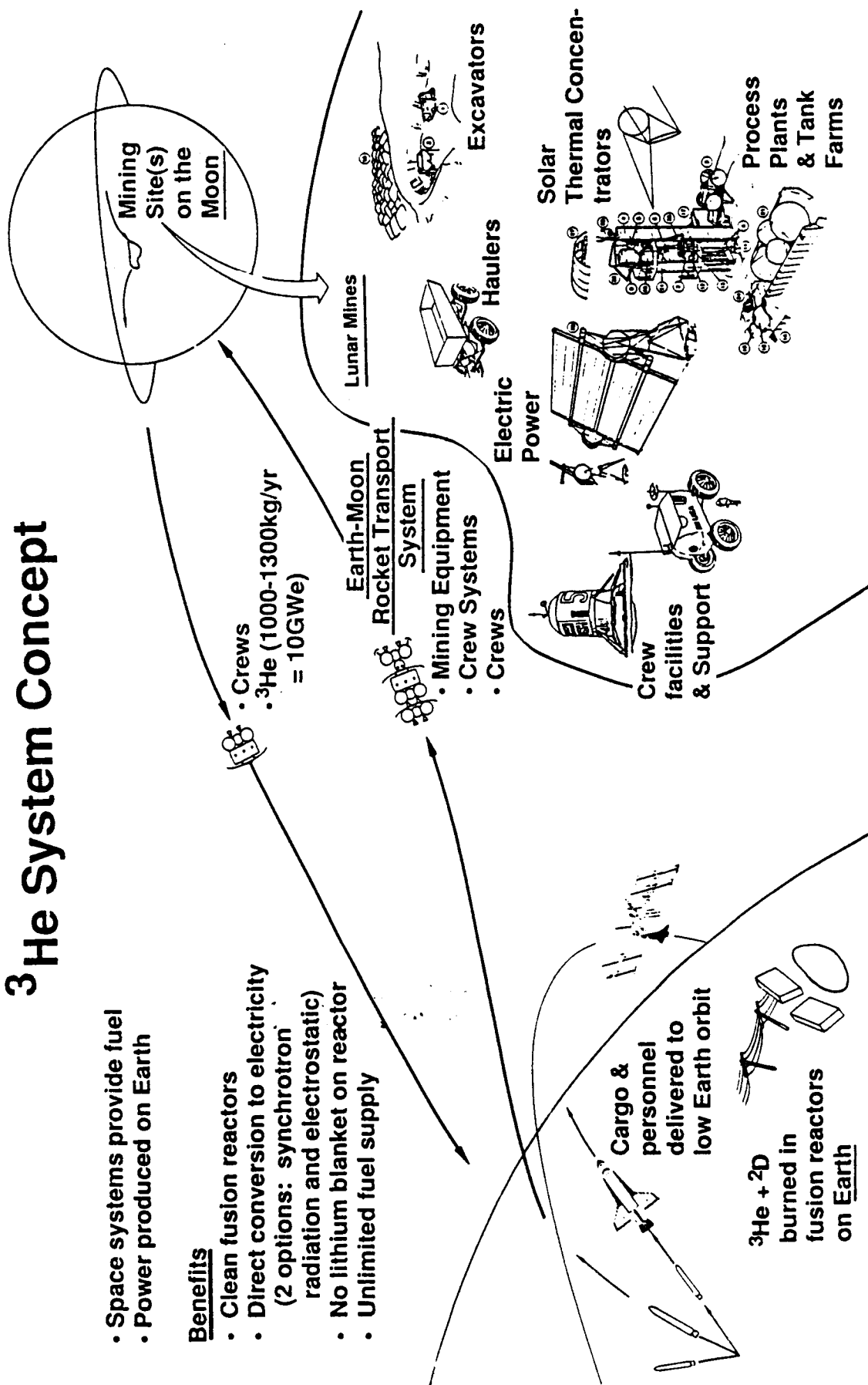
³He System Concept

Benefits

- Space systems provide fuel
- Power produced on Earth

- Clean fusion reactors
- Direct conversion to electricity
  (2 options: synchrotron
  radiation and electrostatic)
- No lithium blanket on reactor
- Unlimited fuel supply

Mining Site(s) on the Moon

Excavators

Lunar Mines

Haulers

Solar Thermal Concen-trators

Process Plants & Tank Farms

Electric Power

- Crews
- ³He (1000-1300kg/yr = 10GWe)

Earth-Moon Rocket Transport System

- Mining Equipment
- Crew Systems
- Crews

Crew facilities & Support

Cargo & personnel delivered to low Earth orbit

³He + ²D burned in fusion reactors on Earth

G890111

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All of the systems were sized at an energy production rate of 10,000 megawatts (10GW) net delivered on Earth for comparison purposes. This does not imply that 10 GW is an appropriate size for a generating system; indeed these systems have significant differences in unit size capability.

The quantity of helium-3 required is a straightforward energy calculation. The key is that one atom of helium-3 (3 amu), reacting with a deuterium atom, releases 18.3 MeV of energy. 50% conversion efficiency is a reasonable expectation; direct conversion from energetic charged particles to electricity is a possibility, and conversion of synchroton radiation from the plasma to electricity by a rectifying antenna is also possible.

Calculation based on the known concentration of helium-3 in lunar regolith yields the excavation rate. Conceptual designs for mining machines and processing equipment were developed by the University of Wisconsin. The number of miners is based on the UW design. Each miner and the associated processing equipment, according to their conceptual design, adds up to 45 metric tons. This sets the space transportation requirement for delivery to the Moon.

Power requirements are an issue. Most of the power needed is thermal power; significant additional power is needed for refrigeration since the separation of helium-3 from helium-4 occurs at cryogenic temperature. Thermal power can be delivered by solar concentrators or possibly by nuclear reactors. The thermal power delivery temperature is about $600^\circ C$; a 200 MW_{th} reactor might be less massive than solar concentrators, and would allow day and night operation of the processing plants.

Helium-3 System Sizing

Helium-3 Quantity for 10 GWe

(100% conv.)

$$10 \text{ GW-yr} \times \frac{8760 \text{ E6 kWh}}{\text{GW-yr}} \times \frac{3.6\text{E6 j}}{\text{kWh}} \times \frac{1 \text{ kg conv to energy}}{8.9875 \text{ E16 j}} \times \frac{931 \text{ MeV/amu}}{18.3 \text{ MeV/3 amu}} = 535 \text{ kg He3 at}$$
$$(e = mc2) \qquad (fusion) \qquad 100\% \text{ plant eff'y}$$

[About 1 ton at 50 % efficienty.]

Mining System

Usable Helium-3 concentration 8.4 parts per billion (of regolith excavated)

Regolith excavated = 1 ton/7E-9 = 145 million tons; processed after beneficiation = 120 m. tons.

One miner estimated to excavate 10 million tons/yr; need 20 miners.

Byproducts: H_2 6100kg/kg ^{3}He; H_2O 3300 kg/kg;

Surface Power

$$\blacktriangleright 120 \text{ E9 kg} \times 600C \times 0.1 \text{ sp. ht.} \times 0.2 \text{ recup factor} \times \frac{4186 \text{ j/Kcal}}{3.6 \text{ E6 j/kWh} \times 8.76 \text{ E6 kWh/MW-yr}} = 190 \text{ MW}$$

250 + megawatts with reasonable efficiency factors.

What we know:

o ^{3}He reduces fusion reactor radiation contamination & other radiation problems by a factor of 50.

o There are almost unlimited quantities of ^{3}He on the Moon (at low conentrations).

o Use of byproducts in the transporation system can reduce costs to the target range.

o ^{3}He is worth 1 to 2 million dollars per kilogram as a fusion fuel.

Comparison of Transportation Options

Transportation cost to the Moon for mining and processing equipment may be significantly ameliorated by using the hydrogen and oxygen byproduct of helium-3 extraction for operation of the space transfer vehicle (STV) fleet. The facing page shows the results of a simple network analysis for several options of lunar propellant use. If all space transfer propellant must be launched from Earth, the total Earth launch requirement is about eight times the net payload delivered to the Moon. This assumes use of aerobraking for return to low Earth orbit; without aerobraking the ratio of masses is much worse. For this baseline estimate, we assumed aerobrake mass of 15% of the payload (recovered hardware plus any mission payload) of the aerobrake.

If lunar oxygen is supplied to the lunar descent/ascent vehicle (STV operations are assumed to use the lunar orbit rendezvous - LOR - mode), the Earth launch requirement is reduced by about 32% at the cost of 1427 tons per year lunar oxygen production. If lunar oxygen is also carried to lunar orbit by the lander/ascent vehicle and there supplied to the Earth/Moon transfer stage, so that it gets all its oxygen from the Moon, the Earth launch requirement actually goes up, and a very large lunar oxygen production is required. If the aerobrake mass can be reduced to 10%, a slight payoff is realized in that the Earth launch requirement beocmes slightly less than that for the case of supplying lunar oxygen only to the lander/ascent stage.

If lunar hydrogen is also available, as is expected for the helium-3 mining case, the Earth launch requirement is dramatically reduced and the lunar oxygen production requirement is much less than needed for the oxygen-only case. Tradeoff analyses indicated that use of lunar-produced hydrogen and oxygen yields the least overall transportation cost, provided that the lunar propellants are byproducts of helium-3 production.
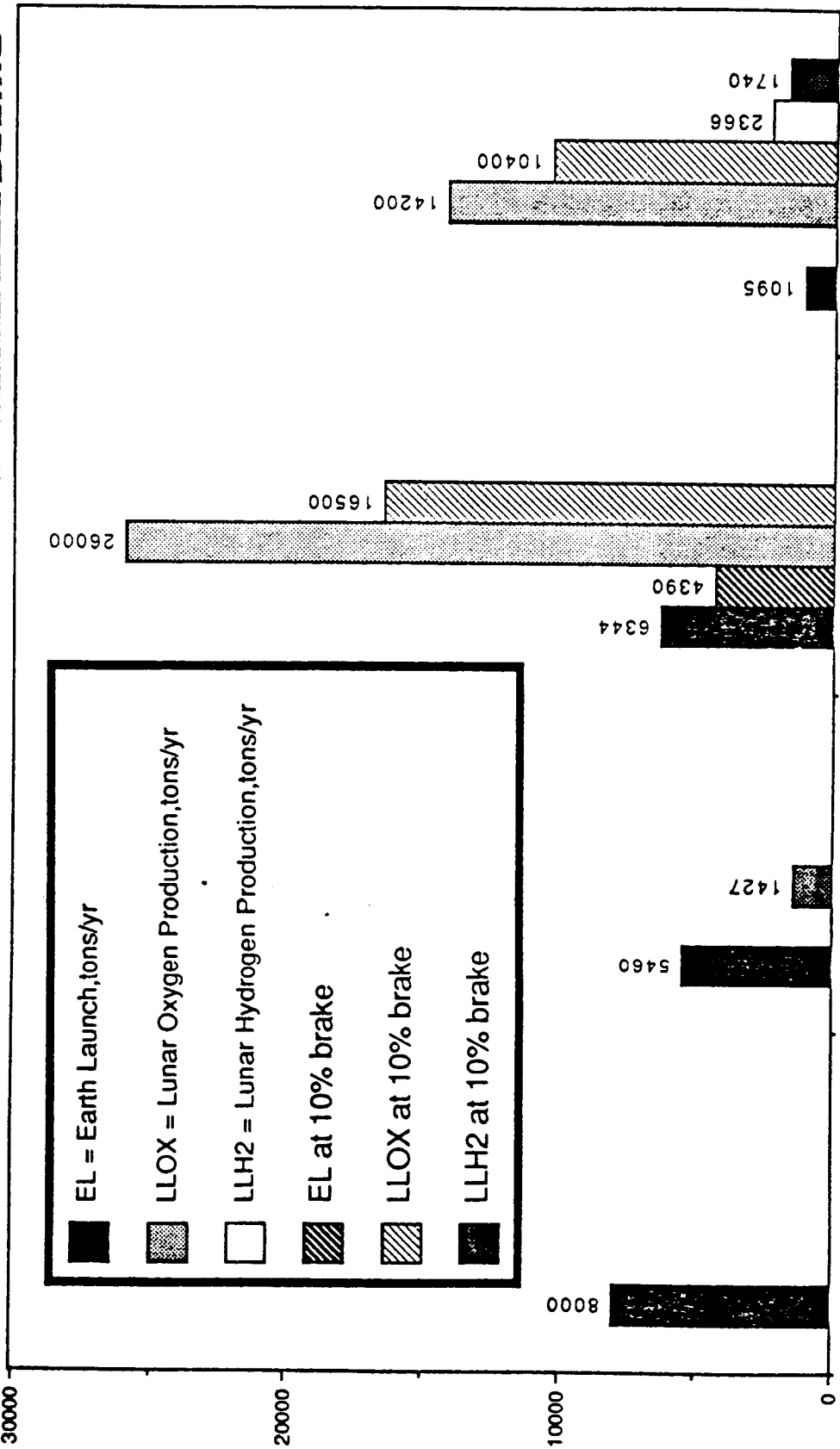
Comparison of Transportation Options

Launch & Propellant Requirements in Tons

To Place 1000T/yr on Lunar Surface

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ADVANCED CIVIL SPACE SYSTEMS

Legend:
- ■ EL = Earth Launch,tons/yr
- ▦ LLOX = Lunar Oxygen Production,tons/yr
- □ LLH2 = Lunar Hydrogen Production,tons/yr
- ▨ EL at 10% brake
- ▧ LLOX at 10% brake
- ■ LLH2 at 10% brake

All Earth Launch: 8000

Lunar Oxygen in Lander/Ascent: 5460, 1427

Lunar Oxygen in All STV Stages: 6344, 4390, 26000, 16500

Lunar Oxygen and Hydrogen in all STV: 1095, 14200, 10400, 2366, 1740

Axis: 0, 10000, 20000, 30000

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The transportation network analysis alluded to above included calculation of vehicle and fleet sizes. These results were used to estimate an overall lunar transportation cost. The cost analysis summarized on the facing page used a commercial approach, including a reasonable return on investment in the luanr STV fleet and a short (5 year) writeoff period. Earth launch costs were based on an expected capability of a Shuttle-C adapted to this mission, including a recoverable propulsion/avionics module. Projected Earth launch costs for an Advanced Launch System (ALS) are about half the figure quoted here.

The target launch cost to make lunar helium-3 commercially economic, assuming the University of Wisconsin mass figures for mining and processing equipment, is about $3000/kg. As indicated, a relatively unsophisticated system is projected to achieve acceptable cost. A reasonable attempt to optimize the system, e.g. by incorporating an ALS, would bring the projected costs down to the $2000 - $2500 range.

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Total Lunar Transportation Cost

Transport Case 4 - Lunar hydrogen and oxygen byproduct used for all STV operations.

Earth launch 1095 tonnes per year.

Lunar STV fleet average unit cost $670 million; six vehicles.

Annual cost = unit investment @ 15% ROI/5 years + 10% annual spares & ops = 40%/yr.

Lunar fleet cost = 40% x $670 million X 6 vehicles = $1608/kg.

Launch cost = 1095 tonnes x $1425/kg = $1560/kg.

Total $3168/kg.

Note: This is not an optimized system. It indicates that costs in the target range are achievable with modest improvements on present-day space transportation systems.

We would expect an optimized system to deliver somewhat, but not dramatically, lower costs.

Helium-3: What We Know

Quite a lot is known about the helium-3 concept. The resource estimates are based on measured quantities of helium-3 in lunar samples returned to Earth during the Apollo program. Although the concentration is very low, the total resource is enormous.

The importance of Helium-3, as described in Appendix B2, is based on estimates of the simplification to fusion reactors (e.g. elimination of the lithium blanket) that it offers, and the increased lifetime that results from the fifty-fold reduction in neutron flux. The result is an estimated economic value of helium-3 on Earth of $1000/gram. The estimate is quite conservative in that these simplifications and increases in life and availability may mean the difference between economic and uneconomic fusion reactors.

Processes for extraction and separation of helium-3 are well-known. We may, of course, find better processes.

The real space transportation issue is delivery of the mining and processing equipment to the Moon. Return of the helium-3 is a relatively trivial issue. Straightforward evolution of present-day space transportation technology can bring costs into the acceptable range; new inventions are not required. A key to the acceptable costs is the use of the hydrogen and oxygen byproducts of helium-3 production as rocket propellant.

Helium-3: What We Know

- Recoverable Helium-3 resource on the Moon is huge.

- Helium-3 as fusion fuel has potential value on the order of $1000/gram.

- Helium-3 can be extracted from regolith by bulk heating.

- Processes for separation of helium-3 from the (much greater) volume of other volatiles are well known.

- The space transportation cost issue is delivery of mining and processing equipment to the Moon (not return of helium-3).

- Hydrogen and oxygen propellants for operation of the space transfer vehicle fleet can be produced as a byproduct of helium-3 production.

- Space transportation cost estimates indicate economically acceptable costs, based on University of Wisconsin estimates for mass of mining and processing equipment.

Since the principal economic issue associated with lunar helium-3 is the space transport cost for delivery of mining and extraction equipment to the Moon, the mass of this equipment is a critical issue. The definitions that presently exist are very preliminary conceptual designs. A much more detailed definition is needed, including many trade studies. Some or even much of the mass of equipment might be lunar-produced from indigenous resources, reducing the transportation burden.

Fusion reactor costs, and the benefits in reactor investment and operation costs (and also potential benefits in plant availability) need better definition, so that we can attach a more confident value to the cost benefits of helium-3. Optimistic estimates of the value of helium-3 might place its value as high as $2000/gram.

Lunar Helium-3 Issues

Definition of mining and extraction system.

Mass delivered to Moon is a critical financial factor.
Optimum extraction means (present baseline is thermal bulk heating of regolith;
   options include grinding and reagent methods).
Power delivery - thermal power should come from direct concentration of solar energy;
   electrical systems would be too massive.
Centralized vs. distributed processing trade.
Cost of lunar installations.

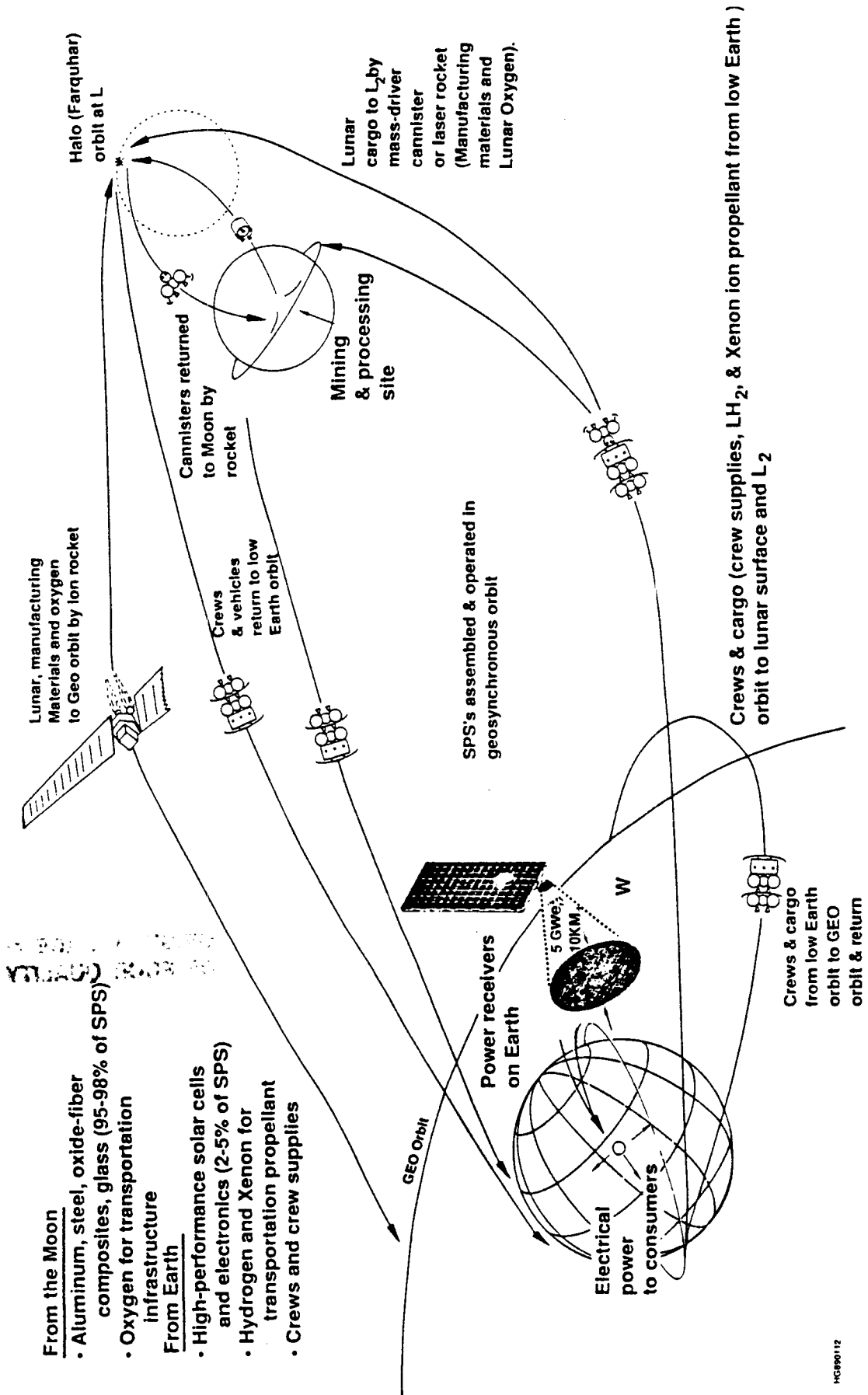Cost benefits of helium-3 versus tritium   (value of helium-3)

Fusion rector costs

Solar power satellites were studied in considerable depth about ten years ago. Those studies considered mainly a scenario in which all of the satellite hardware would be delivered to geosynchronous orbit from Earth. Significant issues were raised as to the very low space transportation costs projected by the studies. If the transport costs were as high as suggested by the critics, the SPS system would be economically infeasible.

Certain contemporary studies recommended that most of the mass, 95% or more, of an SPS could be produced from lunar materials. Space transportation costs from the Moon to geosynchronous orbit were argued to be far less than from the Earth's surface. A representative transportation scheme is illustrated on the facing page. The lunar libration point L2 would ba a major staging base or node. Lunar-produced cargo would be launched to L2 by electromagnetic catapult (mass driver). Transportation from L2 to geosynchronous orbit and return would employ solar electric propulsion. In the scenario illustrated, hydrogen propellant for cryogenic rockets and inert gas propellant for electric propulsion systems is supplied from Earth. We conducted trades to optimize the transportation system, leading to the concept shown.

Operations Concept for Manufacture of SPSs From Lunar Resources

From the Moon
- Aluminum, steel, oxide-fiber composites, glass (95-98% of SPS)
- Oxygen for transportation infrastructure

From Earth
- High-performance solar cells and electronics (2-5% of SPS)
- Hydrogen and Xenon for transportation propellant
- Crews and crew supplies

Lunar, manufacturing Materials and oxygen to Geo orbit by Ion rocket

Cannisters returned to Moon by rocket

Crews & vehicles return to low Earth orbit

Mining & processing site

Halo (Farquhar) orbit at L

Lunar cargo to L_2 by mass-driver cannister or laser rocket (Manufacturing materials and Lunar Oxygen).

Crews & cargo (crew supplies, LH_2, & Xenon ion propellant from low Earth) orbit to lunar surface and L_2

SPS's assembled & operated in geosynchronous orbit

GEO Orbit

Power receivers on Earth

5 Gwe, 10KM

W

Electrical power to consumers

Crews & cargo from low Earth orbit to GEO orbit & return

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Solar Power Satellite System Sizing

Solar power satellites optimize to very large unit size, because of the physics of power beaming. The wavelength selected by the SPS systems studies was 12 cm. (2.45 GHz) in the industrial microwave band. An alternate industrial band is available at about 5.6 GHz. It is projected to have somewhat less efficiency, and greater losses associated with severe weather. A 5-GHz system would, however, optimize at 1 - 2 GWe.

Thermal limits of one kind or another result in power density limits at both the transmitter and receiver. Plugging these limits into system optimizations is the mechanism that determines optimum unit size.

The facing page provides rough estimating rules for the mass of solar collectors and power transmitters.

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Solar Power Satellite System Sizing

Solar power satellite in GEO orbit

D1 typ 1 km

D2 typ. 12 km

Power receiving station on Earth

Aperture product: $D1D2 = 2klH$ (coherent microwave physics)
$l = 12.24$ cm $= 1.224 \times 10^{-4}$ km (2.45 GHz industrial band)
k typically 1.4
H typically 37,000 (GEO distance)
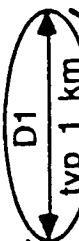D1D2 typically 12.7

XMTR peak pwr lim 20 kW/sq m.
(magnetrons; thermal)
5 kW/sq m (solid state; thermal)

Typical avg/peak ratio 40%

Array sizing

$$A = \frac{\text{delivered power}}{(\text{solar input})(\text{collection eff.})(\text{link ef}}$$

$$\text{typ. } A = \frac{5 \text{ million kWe}}{(1.353 \text{ kW/sqm})(0.15)(0.65)}$$

$= 37$ million sq m, e.g. 4 x 10 km

typ. m = 8 to 10 tons/megawatt

2800 T/km² aperture + 8 T/MWe (Net, Earth)
Receiver peak limit 25 - 50 mw/sq cm
(250 - 500 W/sq m), set by ionosphere
heating.   Typ. avg/peak ratio 20%

Microwave power beaming has been thoroughly demonstrated in laboratory and field tests. Laboratory tests many years ago demonstrated end-to-end electrical power to electrical power efficiencies greater than 50%. Field tests at JPL in 1975 demonstrated receiver efficiencies of about 85%. DC to RF conversion approaching 90% has been demonstrated using magnetrons in laboratory setups; klystrons have reached 70%. Correlations between theory and experiment for power beaming are well understood.

Conversion of sunlight to electricity by photovoltaics is well-understood. While selection of the preferred photovoltaic system would require a substantial amount of work, several options exist today with performance superior to that assumed by the SPS systems studies of 1976-1981. These systems studies, adjusted to allow for recent technology advances, provide a sound mass and performance data base.

Use of lunar materials offers a significant reduction in transportation costs for the emplacement of SPSs in geosynchronous orbit. Most of the raw materials needed to fabricate SPSs are available on the Moon. A few years ago, it was feared that increased in-space fabrication costs would offset the transportation savings, but advances in automation and robotics, applicable to space assembly, alleviate that concern.

Large-scale use of lunar materials will reduce needed Earth launch rates by at least a factor of ten compared with construction of SPSs entirely from Earth-derived materials. This substantially eliminates the environmental concerns associated with extremely high launch rates.

Solar Power Satellite - What We Know

Efficient power transfer proven in laboratory and field experiments.

Magnetrons identified as most effective microwave power transmitters.

Performance of space photovoltaics well understood and proven.

Extensive design studies by joint DOE-NASA program provide sound mass and performance data base.

Raw materials for fabrication of 95% - 98% of an SPS are available on the Moon.

Space transportation cost analysis show potential for significant cost savings through use of lunar materials.

Use of lunar materials would reduce Earth launch requirements by factor of 10 compared to earlier studies, substantially eliminating environmental concerns of high launch rates.
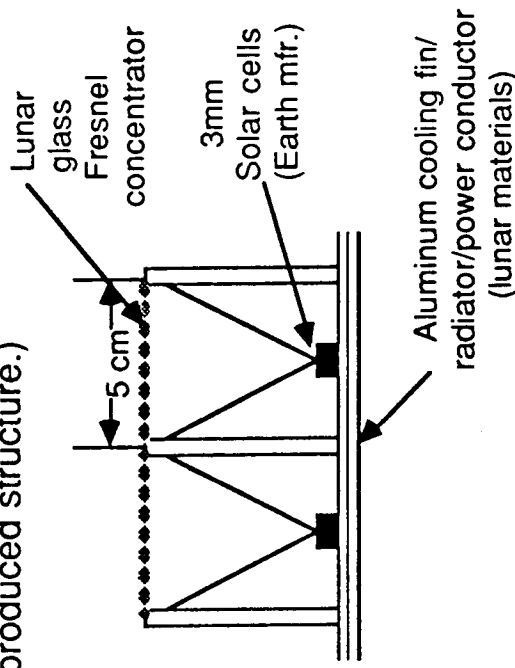
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SPS Issues

The most important SPS issues deriving from the lunar production scenario are described on the facing page.

The most promising design strategy appears to be use of high-performance photovoltaics with high concentration of sunlight. This strategy could permit operation of the photovoltaic system at efficiency approaching 30%. Almost all of the mass of material is in the concentration, structural support, and power conductor systems. Even if the photovoltaics are produced on Earth, the lunar material contribution to the SPS can exceed 95% mass.

Lunar and space manufacturing and assembly systems need definition. Contemporary thinking about space assembly systems would lead to (1) use of the SPS as its own assembly platform, eliminating the need for a large and expensive assembly facility, and (2) heavy reliance on automation and robotics assembly operations, reducing the human crew at the geosynchronous assembly station from hundreds to a few. If these potential advances can be realized, the cost for assembly operations can be controlled to a modest figure that is a small part of the overall SPS cost.

SPS Issues

- Best High-efficiency, high concentration collector design compatible with lunar materials and space manufacture (Design strategy : Earth-produced high-performance, high-concentration solar cells in lunar-produced structure.)

  - Definition and cost of lunar mining and manufacturing systems

- Definition and cost of space manufacturing and assembly systems

- Definition and cost of economically optimal space transportation and operations systems (Strawman system ROM cost about $12 billion/10GWe SPS capacity emplaced at GEO)

Lunar glass Fresnel concentrator

3mm Solar cells (Earth mfr.)

Aluminum cooling fin/ radiator/power conductor (lunar materials)

5 cm

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Evolution of Lunar Power System (LPS)

The lunar power system concept is an approach to minimizing space transportation requirements for space-collected power beamed to Earth. The space power collectors and beaming systems are constructed on the Moon itself, mainly of lunar materials. Large phased-array antennas constructed on the Moon produce near-field microwave beams focused on power receivers (rectennas) on Earth. Because of the great range (385,000 km) it is necessary to use a large transmitter aperture and near-field focusing to obtain reasonable receiver apertures on Earth.
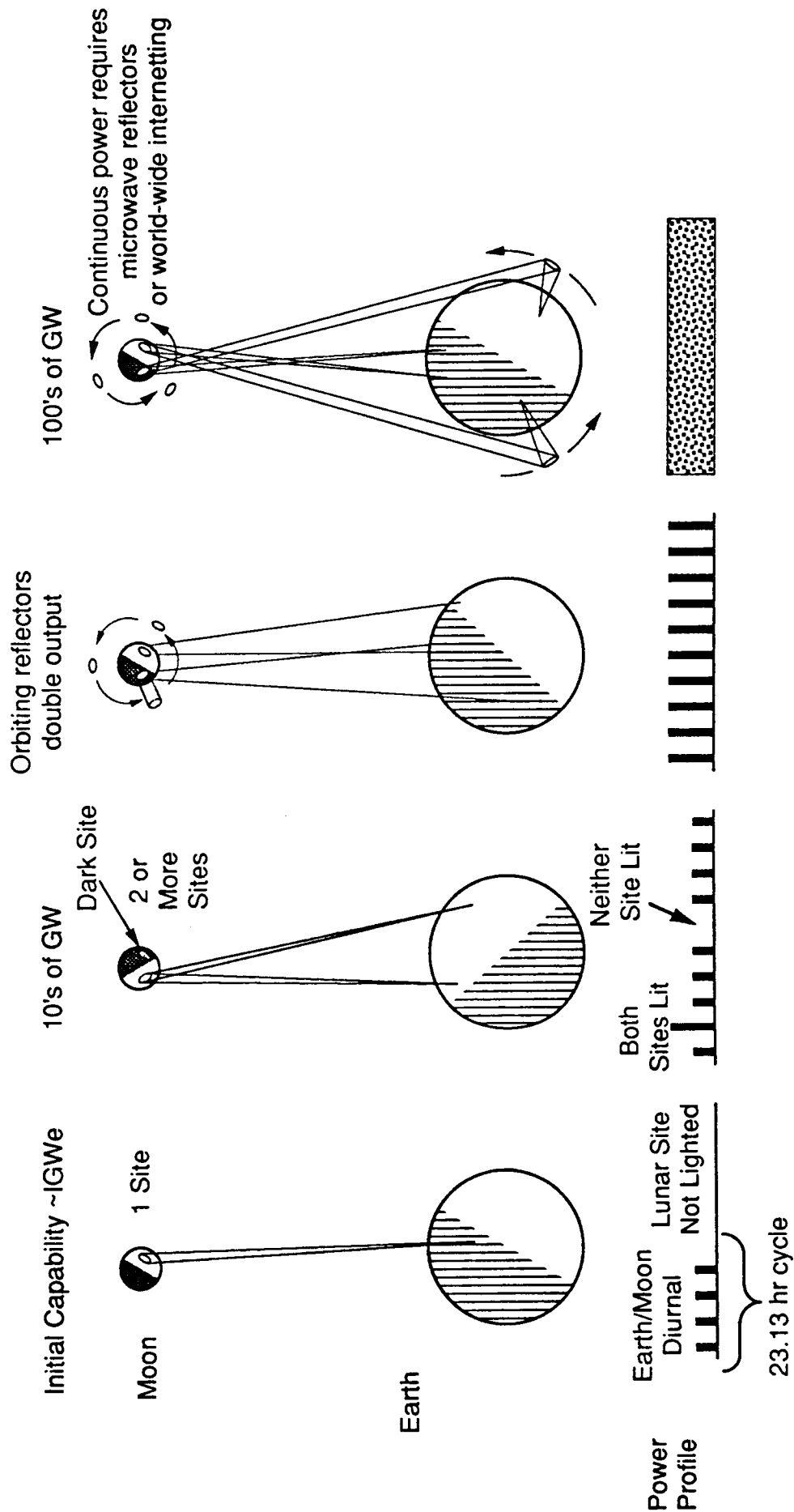
Since the Moon always keeps one face towards Earth, a transmitter on the near side can always transmit to Earth. However, the Earth rotates relative to the Moon, so that unlike the geosynchronous SPS, a lunar power transmitter cannot always transmit to the same site on Earth. The LPS, then, is inherently a global system. Also, since the Moon rotates relative to the Sun, any single site on the Moon will be sunlit for about 14 (Earth) days and dark for about 14. Power availability can be increased, but not made continuous, by locating a second power station near the opposite limb of the Moon.

Basic to the LPS concept is multi-beaming, so that one 50,000 megawatt power transmitter site on the Moon would feed numerous power receivers on Earth. This avoids any one receiver site being of excessive unit size. A phased-array antenna can generate multiple beams by synthesizing what amounts to an interference pattern.

A system of orbiting optical reflectors that would illuminate otherwise dark power sites on the lunar surface could enable continuous transmission to Earth. Lunar beamed power would still be available to any particular Earth site only when that site faced the Moon. A second system of orbiting microwave reflectors could provide continuous power to Earth receiving sites.

The lunar power system is seen to be inherently a global system, and one that is truly efficient only on a very large scale.

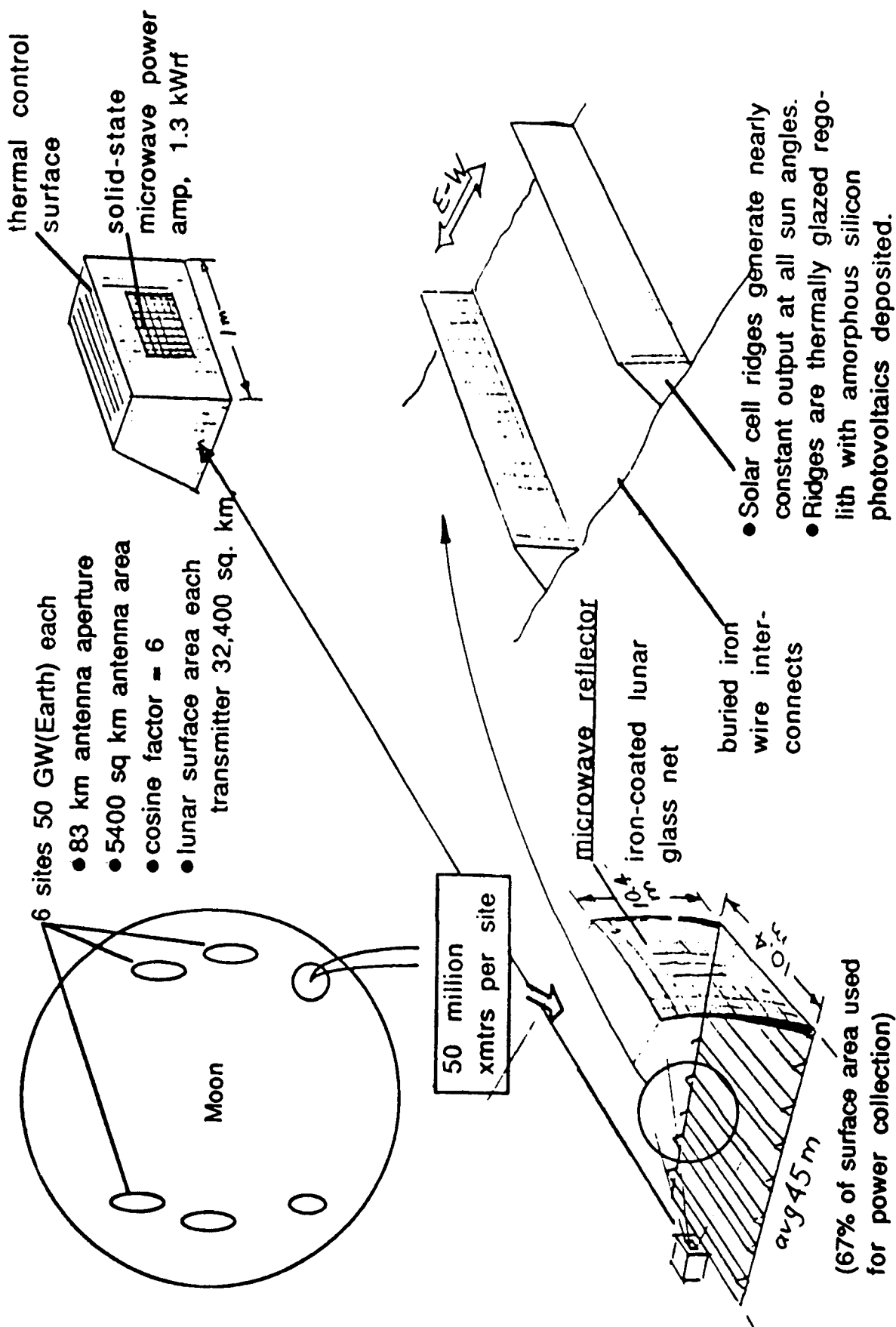# Evolution of Lunar Power System to Continuous Baseload Power Requires Auxiliary Reflectors at Earth and Moon

Initial Capability ~1GWe

1 Site

Moon

Earth

Power Profile

Earth/Moon Diurnal — Lunar Site Not Lighted

23.13 hr cycle

10's of GW

Orbiting reflectors double output

100's of GW

Continuous power requires microwave reflectors or world-wide internetting

Dark Site

2 or More Sites

Neither Site Lit

Both Sites Lit

Lunar Power System Concept

A look at the actual power installations on the Moon reveals millions of modular microwave power transmitters at each of several sites. Each modular transmitter consists of a solar cell collection field, geometrically arranged to have nearly constant power output as the Sun slowly crosses the lunar sky; a microwave power generator and phase control system, and a reflector antenna. All of the power collection, conversion, and transmission equipment is presumed to be lunar-manufactured except for microwave generators and phase control electronics.

The field of transmitter antenna reflectors would appear as a filled aperture as viewed from Earth.

Lunar Power System Concept

thermal control surface

solid-state microwave power amp, 1.3 kWrf

1 m

6 sites 50 GW(Earth) each
- 83 km antenna aperture
- 5400 sq km antenna area
- cosine factor = 6
- lunar surface area each transmitter 32,400 sq. km

Moon

50 million xmtrs per site

E-W

- Solar cell ridges generate nearly constant output at all sun angles.
- Ridges are thermally glazed regolith with amorphous silicon photovoltaics deposited.

microwave reflector
iron-coated lunar glass net

buried iron wire interconnects

10^4 m

avg 45 m

(67% of surface area used for power collection)

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Iron and glass are readily producible on the Moon. While amorphous silicon solar cells will be more difficult to produce, silicon is very plentiful on the Moon. Microwave power generators will probably use gallium arsenide and be produced on Earth, as will the power and phase control electronics.

Distributed array power beaming appears feasible. There are concerns as to the efficiency of distributed antennas which are not on a contiguous plane, and very high phase control precision is needed to produce the near-field beam focused on Earth at a range of 385,000 km (about 3 billion wavelengths).

Relatively modest minimum power levels are feasible (if any power level is feasible). Since a low power density antenna does not require a structure to support it (it is on the surface of the Moon), the cost penalties attendant to low power density space antennas do not apply.

Finally, the LPS is inherently a global, large-scale system. It cannot deliver baseload power except with optical reflectors orbiting the Moon to provide continuous solar illumination, and cannot deliver baseload power to any particular region unless systems are globally interconnected.

Lunar Power System - What We Know

Construction materials needed are available on the Moon.

Theory supports concept of distributed phased array power beaming antenna (performance analysis needed).

Smallest feasible power size is on the order of 1 GWe. Low power density antenna does not incur cost penalties that would occur if one had to build a structure to support it.

System augmentation, by reflectors orbiting both the Moon and Earth, needed to deliver baseload power.

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LPS Installation Operations Sizing

The scale of operations for the LPS is truly enormous, and not well understood. What is involved in making ten transmitter unit installations per minute is a big question. Preparation of 25 square meters per second of lunar surface area is a huge operations rate. If the 20-mile freeway spur between I-65 and Huntsville, Alabama could be built at that rate, it could be finished in two days instead of the anticipated three years. While freeway construction seems much more complex than the lunar operations for LPS, such comparisons certainly give one pause.

LPS Installation Operations Sizing

10 GWe/yr = 5 million transmitter units/yr, 10 per minute.

Regolith moved/shaped: 2340 sq km per year, to 30 cm average depth, = 1.4E9 tons/yr,
    = 140 machines at 1E7 tons/yr each.

Prepared area (glazed, solar cells) = 793 sq km/yr = 25 sq m/sec.

Thermal power for glazing = 25 sq m x 0.001 m x 2000 kg/sq m x 0.1 sp ht x 4186 j/Kcal
    = 21 E6 j/sec, 21 megawatts, 150 kW/machine

With 140 machines, each one does 100 sites/day.

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The lunar power system transmitter requires very high phase control performance even compared to the SPS. While the SPS is a planar-wave far-field transmitter, the LPS must generate a set of concave (focused) near-field waves of much greater precision. Detailed performance analyses for the transmitter systems are needed to establish the transmitter unit design and determine reflector requirements. The transmitter phased array can partially correct for inaccuracies in the reflector, but only to the extent that such inaccuracies do not cause multiple ray paths.

The lunar surfacing job to be done and the solar cell deposition machine need better definition to scope the difficulty of the operations tasks. Finally, an analysis of the integration of LPS power into Earth power grids and the distribution of LPS power on Earth needs to be done to establish the generating capacity displacement capability of LPS. (This means, "how much generating capacity (if any) of another type can one kilowatt of LPS power replace?" The answer is very important to determining the value in dollars per kilowatt for LPS generating capacity.)

Lunar Power System Issues

Technology and design requirements on lunar power transmitter antenna for high-efficiency multi-beam power transfer:

   Transmitter unit design
   Reflector - shaping and accuracy requirements

Extent of lunar "surfacing" job; depth of regolith to be moved/smoothed.

Definition of solar cell deposition machine.

Scope and scale of lunar surface operations.

Integration into power grids; power distribution on Earth.

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Basic Statistics of the Energy Options

The lunar operations scales of the three concepts are very different. The SPS involves much smaller lunar operations than the other options, but requires much greater space transportation infrastructure, and for efficient large-scale delivery of lunar materials to space (the other options do not require this), needs development of a mass driver and a multi-megawatt solar (or nuclear) electric propulsion system. This chart emphasizes differences in lunar operations; space transportation needs are compared later.

The nature of the operations for these systems is somewhat different. A given scale of operations for the helium-3 system delivers a certain quantity of mining operations equipment to the Moon each year; this equipment increases the production rate for helium-3 fuel, and correspondingly increases the supportable generating capacity on Earth. The SPS is very similar; a given scale of operations leads to a given construction rate, and hence a given rate of increase in generating capacity on Earth. In both cases, one should presume a certain requirement for operations and maintenance of capacity, and this would increase as the generating capacity is increased. With a fixed space operations capability level, the O&M requirement would increase with capacity and would eventually saturate the fixed space operations capability, displacing the ability to further increase generating capacity.

In the LPS scenario, a given scale of space transportation operations delivers equipment to the Moon capable of a given costruction rate. Thus continued operation of the space transportation system leads to an ever-increasing construction rate, rather than maintaining a constant construction rate as is the case with the other scenarios. This is a powerful advantage if it is valid.

There are two caveats in this: (1) the LPS construction rate may be controlled mainly by lunar surface operations that require support from Earth; and (2) the LPS construction rate may be controlled by construction of orbiting reflectors or other support systems that require continuing space transportation operations. Neither of these caveats is understood; analysis and simulations are needed.

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Basic Statistics of the Energy Options

Producing 10 GWe per Year

	Lunar Helium 3: (10 GWe Generating Cap)	SPS at GEO (10 GWe Inst'd per year)	Lunar Power System (10 GWe Inst'd per year)
Tons/Yr of Regolith	200 million (to get 1.3 tons Helium-3)	2 million	1400 million
Processing Depth	1 meter	1 meter	30 cm*
Area/Yr	200 square km	1 square km	2340 square km (actually used, 60% of site)
# of Mining Machines	20	2 (plus spares)	140
Processing Plants	Volatiles separation and liquefaction	Aluminum 40,000 T Glass 40,000 T Oxygen 25,000 T Misc. 10,000 T	Silicon Iron Glass (surface glazing is part of "miner".)
Lunar Surface Power	250 + MW	500 MW	400 MW
Mass Drivers	(none)	3 at 100 kg/min.	(none)

*Criswell assumes 2.7 cm avg depth

"Mining" Comparison

Helium - 3	SPS	LPS
Excavate regolith, 200 million tons/yr, 200 sq km at 1 meter depth	Excavate regolith, 2 million tons/yr, 1 square km per year at 2 meters	Excavate/move/shape regolith, 1400 million tons/yr at 30 cm depth*, 2340 sq km
Heat to drive off volatiles	Beneficiate for aluminum, glass, oxygen, & other production.	Beneficiate for glass & silicon production
Pressurize & collect volatiles	40,000 T Aluminum 40,000 T Glass 25,000 T Oxygen 10,000 T Other	Extract native iron
		Glaze surface
Note		Deposit silicon solar cells & interconnect
Process energy, if supplied by fuel cells, would consume about 65,000 kg/d O2 & H2.	Operate mass driver to launch lunar-produced products to L2.	Lay wire

Note: Dr. Criswell's papers assume 2.7 cm depth; the greater depth estimate comes from Boeing studies of lunar surface operations.
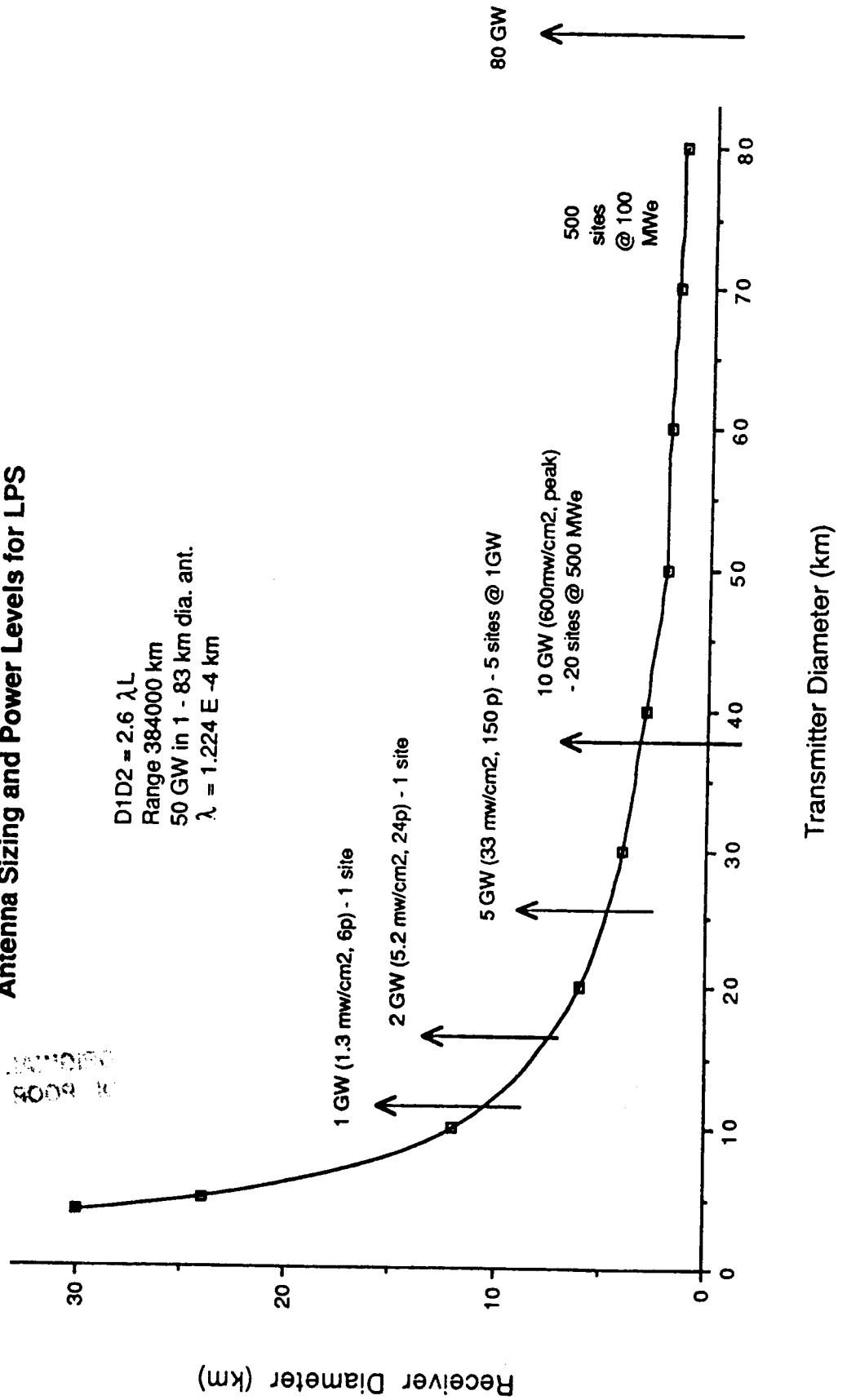
The facing page shows receiver antenna sizing and power levels reached as an LPS transmitter grows in size at constant transmitter power density. When the transmitter reaches 10 km diameter, its output is about 1 GW_e Earth equivalent, and it is capable of focusing a beam to about 10 km diameter with an average power density of 1.3 milliwatts/cm^2, with peak receiver density of 6 mW/cm^2. Similar results are shown for other transmitter sizes and powers. When the transmitter reaches about 25 km diameter, it generates 5 GW_e with a potential peak power density of 150 mW/cm^2. Since the acceptable peak value is thought to be about 30 mW/cm^2, at this point the transmitter needs to generate at least 5 beams to reduce the power density at each receiver site. As the transmitter continues to grow in size, the power per receiver site and the antenna size at the receiver sites decreases and the number of sites increases.

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Antenna Sizing and Power Levels for LPS

D1D2 = 2.6 λL
Range 384000 km
50 GW in 1 - 83 km dia. ant.
λ = 1.224 E -4 km

1 GW (1.3 mw/cm2, 6p) - 1 site

2 GW (5.2 mw/cm2, 24p) - 1 site

5 GW (33 mw/cm2, 150 p) - 5 sites @ 1GW

10 GW (600mw/cm2, peak)
- 20 sites @ 500 MWe

500 sites @ 100 MWe

80 GW

Transmitter Diameter (km)

Receiver Diameter (km)

The top issues for each concept are stated here. In the helium-3 case the top issue for space operations is clearly the definition of the mining and extraction system and its mass and cost. One might argue that the feasibility of helium-3 fusion reactors is the top issue, but this is not a space operations issue.

For SPS, a further definition of the processing, logistics, and manufacturing systems for lunar-derived SPS production is the issue. Logistics is better understood than the other factors. We need to know precisely what is being produced on the Moon, how it is packaged and shipped to geosynchronous orbit, and how the assembly process is to operate. Earlier SPS scenarios assumed only final assembly at the GEO site, while the lunar scenario will require much parts fabrication and assembly, in view of the small mass capability per launch of the mass driver. Contemporary/future automation and robotics capabilities need to be included.

The issues concerning the LPS were mainly discussed in the text for the prior chart. The entire lunar surface operations system needs a careful preliminary definition and assessment.

Concerns/Top Issues

Helium 3:
- Mining System Definition
- Power rqts and Power Delivery System $\left.\right\}$ 45 tons may be much too low
  (Electric systems $\approx$ 20T/MWe = 200 T/miner)

SPS :
- Processing/logistics/Mfr. system to deliver lunar-derived SPS components and/or raw materials to GEO

LPS:
- Scale of surface operations
- Mass of material to be produced
  (major issues are antenna reflectors and depth of regolith to be moved/processed)
- Definition of machine that deposits solar cells

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Representative demonstration steps for the options are described here, using analogies to the commonly described demonstration steps for the fusion program. Clearly, in the later phases, as is true for the fusion program, demonstration of a capability to supply energy at an acceptable cost is a key part of the demonstration process.

Representative Demonstration Steps

	Helium-3	SPS	LPS
"Scientific Break-even"	Show that there is Helium-3 on the Moon (accomplished)	Demonstrate efficient power beaming (accomplished)	Demonstrate efficient power beaming (accomplished)
"Ignition"	Demonstrate extraction by practical engineering process	Demonstrate phase control over GEO distance	Analytically validate antenna design & demonstrate phase control over lunar distance
"Engineering Test Reactor"	Demonstrate critical features of processing on the Moon	Demonstrate critical features of lunar materials processing - mat'ls production - transport, e.g. mass driver	Demonstrate critical features of lunar operations - mat'ls processing - solar cell deposition - antenna fabrication
"Prototype"	Deliver useful power	Deliver useful power	Deliver useful power

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Plausible Prototype Plant Scales

Prototyping scales are presented here. Clearly, the helium-3 system is the easiest to prototype (from the point of view of space operations; makes no judgement as to the difficulty of demonstrating fusion reactors) since initial recovery and return to Earth of modest quantities of helium-3 is compatible with a few heavy-lift launch vehicle (HLV) flights and with an early lunar base.

The other concepts are driven to larger scales by the physics of microwave power beaming. The SPS is easier than the LPS, and could be demonstrated by a pilot-plant SPS derived entirely from Earth. If the demonstration is derived from Earth, certain key technical demonstrations remain, including lunar processing and mass driver operations.

Plausible Prototype Plant Scales

Helium-3	SPS	LPS
Deliver one prototype miner with power supply and pilot volatiles plant	Produce 500 MWe pilot plant [7000 T at GEO]	Produce 1 GWe pilot plant (10 km dia site & 10 km Earth receiver)
1 MWe power on lunar surface + 10 MWth for miner	Operate pilot plants for aluminum, oxygen and glass on lunar surface	5 - 10 mining & construction machines
Return Helium-3 to Earth: 10 kg 3 times/yr	5 MWe power on lunar surface	Circa 2000 T Earth-mfr. hdwe Microwave amps Power processors Electronics Thermal control hdwe Silicon refinery
Roughly 4 HLV flights at 140 T; feasible with early lunar base	1 mass driver on lunar surface	Few MWe power
	Robotics suite to GEO	Roughly 80 HLV flights; advanced lunar base (number could be reduced with in-situ propellant production)
	1 SEPS	
	Roughly 40 HLV flights; advanced lunar base (100 HLVs all Earth produced)	

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Strongest Features of Each

Helium-3: Compatibility of demonstration with early lunar base.

SPS: Confidence in the technology (of the basic SPS; not necessarily of producing SPSs from lunar materials).

LPS: Potential leverage for total energy production for a given space infrastructure investment.

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Phase A Definition Needs

The issues raised earlier in this presentation lead to the Phase A definition
needs described here. These are important for higher confidence in certain
technical feasibility issues, and in economic characteristics of the systems.

Phase A Definition Needs

Helium-3: Mining and processing systems including support systems/equipment. (Adequate definition of crew systems exists.)

SPS: Processing, logistics, and manufacturing systems required to produce SPSs from lunar materials. (Adequate definition of SPS itself exists.)

LPS: Antenna system & its performance; mobile processing machines; overall operations; power grid internetting.

Note: These can be modest efforts if they focus only on key issues.

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