SCALING AND THE START-UP PHASE OF SPACE INDUSTRIALIZATION

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Abstract

By terrestrial standards very little mass is needed to construct the space portion of a 10,000 megawatt (10 GW) power system. Use of lunar materials makes it reasonable to consider alternatives to silicon solar cells for conversion of sunlight to electricity and thereby avoid present major problems associated with solar cell production. Machinery needed on the moon to excavate lunar materials and deliver them to a transport system, to beneficiate lunar materials, to produce glasses and ceramics from lunar materials and to chemically process lunar materials into their major oxides and elements are minor mass fractions of the total mass of equipment needed in space to produce an SPS. In addition the processing equipment can throughput several hundred times their own mass each year with very little requirement for makeup mass from earth.

Space Power System Masses Compared to Terrestrial Units

Space solar power stations appear to be ideal candidates for initial products of an early space industry because of their expected high intrinsic value (200 - 400 $/kg) and the vast potential terrestrial market the order of one trillion dollars over the next thirty years. It is now clear that space power stations can be constructed of approximately 90% lunar derived materials even without redesign of the terrestrially based models.[1] With redesign this fraction might be increased somewhat and more importantly the fabrication processes might be substantially simplified.

It is important to pursue the subject of the scale of the SPS as a candidate for construction in space because it provides a dramatic model by which to appreciate how efficiently mass can be used in space and on earth to convert solar energy into electricity. Figure 1 is a scaled sketch of the Grand Coulee Dam in Washington state. Grand Coulee Dam is of interest because it is the largest single producer of electrical power in the United States. Its maximum electrical output will be 9,200,000 kilowatts (9.2 GW) or approximately 10% less than the projected ground output of an SPS. The metropolitan area of Houston consumes 10 GW. Grand Coulee was, and still is, a very large structure with a length of 1.3 km, a height of 0.1 km and a mass of approximately 40,000,000 tons (T). It was planned during the 1920's and constructed in the 1930's. It was clearly a sophisticated engineering challenge. Incidentally, Grand Coulee is powered by solar energy with rain water being the transducer of solar energy to mechanical energy. The energy collector area of Grand Coulee is the drainage basin for the eastern portion of the Columbia River and is approximately 300,000 km^2.[3]

Compared to Grand Coulee little mass is required in space for solar collectors and transmitting antennas to construct an SPS. The concrete mass equivalent (5 T/m^3) of an SPS would be contained in the small, elongated box of concrete along the top left hand portion of the dam. The 10 by 10 by 200 meter section of concrete has a mass of 100,000 T or the same as one SPS. Alternatively, 100,000 T is a 3 meter thick slide across the dam. SPS is an extremely efficient mechanism for the collection of and conversion of solar energy to electricity.

The ground receiving array can be divided into two parts — the sophisticated and expensive electronics for power reception and the support structures of the electronic elements.[4] The sophisticated components have a total mass of approximately 4,500 T and occupy a volume of equivalent mass of concrete of 10 by 10 by 9 meters. The mass of ground antenna supports is large. Recent estimates indicate 2,000,000 tons of concrete pedestals which correspond to 5% of the mass of Grand Coulee. However, there is a very significant difference in that the support structure for the receiving antennas is constructable as many small individual units of concrete and/or metal stands rather than a monolithic structure such as the containment vessel of a nuclear power plant.

Space power systems appear very attractive on a mass standpoint in comparison to nuclear and coal fired plants of similar electrical output. A 10 GW nuclear plant will have an overall mass of the order of 8,000,000 T including foundations, radiation shield, reactors, generators, and ancillary equipment.

A coal fired plant composed of 20 units of 0.5 GW output would have a mass the order of 2,000,000 T or approximately the mass of the support structure of the receiving antenna for a space power system. However, the coal fired plant must burn approximately 35,000,000 T of coal each year. Thus, one 10 GW coal station must transport the mass equivalent of Grand Coulee Dam each year. Presently, the U. S. consumes 16 Grand Coulee's of coal each year. In order to increase the national energy dependence on coal to 40% by the year 2000, we must invest approximately 80 B$ in new mines and transportation systems. We would then be burning approximately 60 Grand Coulee's of coal annually.[5]

Viewed in comparison to Grand Coulee Dam, one begins to be impressed not with the large physical area or size of an SPS (5 by 20 by 0.1 kilometers) but rather, with the fantastically efficient use of matter that an SPS affords in gathering energy and converting it for use on earth or in space. Far less matter must be manipulated, restructured and emplaced in space to produce useful power on the ground than any other power scheme proposed to date. This includes projected terrestrial solar power arrays which must be 6 to 15 times as large in area due to night and cloud cover to collect the same average energy flux and which must be more massive per unit of area to withstand the gravity and environmental conditions of earth. Finally, it is not unreasonable to expect further advances in the transmission of power to the ground to substantially reduce the size and costs of the receiving systems. Viewed in another way one realizes that Grand Coulee contains sufficient mass-equivalent to construct 400 to 500 SPS units. This quantity of electric energy could satisfy all United States power demands well into the next century.

Attention must also be given to overall system scales which must be created and operated if SPS is to be deployed from the earth versus constructed from lunar materials. A feeling for the relative sizes is also contained in Fig. 1. Proposals exist for fully reusable two-stage boosters to be used to ship semi-finished or feedstock materials from earth to low earth orbit to manufacture an SPS unit.[4,6] If these boosters utilize hydrogen and oxygen for propellants, then theoretically the exhaust product could be pure water. The quantity of water exhausted from the launches of all the heavy lift launch vehicles (HLLV) to transport 100,000 T to low earth orbit is indicated in Fig. I-3 as effluent from Grand Coulee Dam. The effluent could form a body of water 10 meters deep by 300 meters wide by 660 meters long. Theoretical designs are available of boosters which are scaled to accommodate this quantity of liquid propellant usage over the course of 250 flights. Other boosters which utilize hydrocarbons and liquid oxygen would have an effluent approximately four times as massive. Bulk liquid handling technology is available to handle this magnitude of propellant. It is used commonly on earth with petroleum at many ports. However, the terrestrial systems are large by traditional aerospace standards and these new launch vehicles must operate in the severe environment of the launch from earth to low earth orbit and return safely many times with minimum refurbishment required between launches. Inert mass of the two-stage fully reusable booster would be the order of 1,000 T. The first stage would have an inert mass of approximately 800 T; the second stage 400 T. The second stage would lift a payload to orbit of 400 T. Half of the fuel in each flight would be used simply to boost the inert mass of the second stage into orbit.

If hydrogen and oxygen were burned stoichiometrically in fuel cells on the moon and used to eject with 60% efficiency 100,000 T into space by means of an electromagnetic mass driver then only 13,000 T of water would be produced which corresponds to 0.7% of the water effluent of the terrestrial boosters. It is not being suggested here that hydrogen and oxygen be used with fuel cells on the moon to produce power to launch payloads in space. Our objective is to illustrate the great difference in the practical scales of propellant and materials handling, at least a factor of 150, which can be expected between utilizing lunar versus only terrestrial materials to construct an SPS or other large space structures. In point of fact, it is anticipated that solar energy will be utilized to power the lunar mass driver and that considerable use will be made of the earliest solar cell production of a space manufacturing facility to increase the ejection capacity of a lunar supply base.[15]

Raw Materials Scale

Figure 2 gives a more detailed depiction of the scale of the raw materials handling and the distribution of processed materials for one 10 GW SPS. We assume for this figure that highland soil essentially equivalent to the whole rock composition of highland rocks is available at the mining site. The major mineral will be plagioclase. The minor mineral will be ilmenite mixed with opaque glasses.[7,8] The oxide compositions of these constituents are approximated as: plagioclase (SiO_2 - 45% by weight, Al_2O_3 - 35%, CaO - 20%) and for the opaques (Al_2O_3 - 20%, TiO_2 - 30%, FeO - 40% and MgO - 10%). It is assumed that magnetic, electric and physical separation techniques have been applied to the soils to produce a 90% plagioclase and 10% residue of opaques and ilmenite for the mineral fractions and which composes approximately 65% of the soil. The remaining 35% is the glass fraction which is used to make native glass components of the SPS. The compositions are in general agreement with modal analyses of the soils returned from the Apollo 17 site.[9]

A total of 215,900 tons of selected lunar material must be transported off the moon and thermally and chemically processed to form 90% of a space power station.[2] Depending on the exact highland landing site it will be necessary to beneficiate up to approximately twice this much soil to produce the ratios of native glass, opaque minerals and plagioclase. It is reasonable to assume that the soil has a bulk density of 2 tons/M^3. Thus, we must be prepared to beneficiate 431,800 tons of soil or 216,000 M^3. This corresponds to a 10 M deep square of soil which is 103 M on a side. If the ultimate objective is to supply materials for the construction of one 10 GW SPS per year, then the excavation and beneficiation rates are the order of 740 tons per day (24 hours) on an 80% operations level or 31 tons per hour. This is a moderate excavation rate by terrestrial standards if the 1/6 gravity of the moon is taken into account. It is advantageous to start with a small operation on the moon and build up to this excavation rate.

Lunar Base

The magnitude of equipment which must be employed on the moon in the initial gathering and processing of lunar material is depicted in Fig. 3. It is highly desirable to minimize the mass of equipment necessary to start operations in space and to make maximum use of space materials to build up further capabilities. The rationale and design of the base was developed during the 1977 Summer Study on space industrialization conducted at the NASA Ames Research Center.[15a] Initial mass on the moon of the base would be approximately 800 tons. Approximately 4000 tons of landers, fuels and payload would have to be ejected from low earth orbit to the moon to land the base. We estimate that 20 - 30 people could install the base in four to six months and ten people could operate it. It would begin ejecting 30,000 tons/year of bulk lunar soil and grow in launch capacity to 0.6 Megton/year (≈3 SPS) over five years. Growth would be provided by the addition of solar cells, habitats and mining equipment.

The initial mining operations would be very small by terrestrial standards. The first excavation is a few meters deep and less than 50 meters in width. It is being worked by a single backhoe which is a small and versatile piece of excavation equipment which can be operated in a semiautomatic mode and monitored from earth. It is estimated that under nominal conditions only one front-end loader (25 T mass) with 12.5 tons of payload will be required to excavate and haul all the soil to a transportation point for ejection from the moon. This assumes the use of beneficiation at the site of the excavation. Approximately 80 MW-hr/yr will be required to operate the equipment. Subsequent introduction of 10 T or 50 T (payload) haulers will increase haulage and efficiency. Few personnel on the moon will be associated with operation of the equipment. Less than one manyear of maintenance per year should be required.[10,14]

The four partially covered tanks are the liquid hydrogen sections of shuttle belly tanks converted to use as habitats, maintenance facility, mass driver loading facility and soil packaging facility. Each tank is approximately 24 meters long.

Under nominal conditions with at-the-mine beneficiation less than 300 tons of mining equipment would be required on the moon over 30 years to deliver 16 million tons of ore to the launcher. Pending the performance of engineering tests of various separation techniques in a quantitative manner on available lunar soils we can only estimate the mass of apparatus required. The calculations of Inculet [11] are modified for the assumptions of 80% duty cycles, an annual mining rate of 432,000 T rather than one magaton and the need for only one stage of beneficiation. Under these assumptions two beneficiation units would be required. A total mass the order of 40 tons and power of 14 kilowatts during operation or approximately 98 MW-hr/yr would be required. These beneficiation techniques should be highly automated and require only maintenance support from lunar personnel. It may well be that the use of physical and magnetic separation processes will require even less power and mass than estimated here. Nondestructive tests on lunar soils can provide far more accurate knowledge of efficiencies.

One cannot send the combination of minerals from the moon which would exactly fulfill the elemental requirements for the construction of an SPS. We assume that the proper mix of native glass to silicon tonnage can be established by the low energy beneficiation processes on the lunar surface. However, the need for silicon to use in solar cells forces one to export from the moon more oxygen, aluminum, calcium, titanium and magnesium than are required by the SPS. It is apparent that the absolute value of this excess is artificial. Substitution of materials will allow the use of aluminum, titanium and magnesium in the construction of SPS units as structural elements and the use of calcium as an electrical conductor under some conditions.[12] In addition, the by-products of the refining process are far from useless in space. All these excess elements can be employed in support of non-SPS functions to great advantage. For example, the oxygen can be used in propulsion and life support; aluminum, iron, calcium, titanium and magnesium can be used in the construction of bootstrapped facilities, spacecraft and other devices for use in space such as radio telescopes, communications equipment and as inputs to products to be used on earth.

Three different materials processing challenges are presented by the major blocks of Fig. 2. These are glass and ceramics production of 34,700 tons/year (or 120 tons per day at 80% utilization), total chemical processing of the lunar soils to separated oxides and separated elements of 181,200 tons/year (or 620 tons/day at 80% utilization) and the preparation of 14,950 tons/year of semiconductor-grade silicon. We will address only the first two problems. However, it is possible that the chemical processing scheme proposed in the following section may be capable of providing the silicon of the required purity level of use in solar cell manufacturing without further secondary refining.[13]

Chemical Processing Facility

Considerable detailed analysis has gone into the conceptual development of a chemical processing facility which could accept any of the major lunar minerals (pyroxenes, plagioclase, olivine or ilmenite with some modifications) and produce virtually complete separation of the oxides or the elements of the minerals.[13,14,15,16] The system presented here [13] is designed to utilize process steps which are or have been employed in production plants, in prototype industrial operations or depend on well established principles of chemical engineering. Much emphasis has been placed on minimizing process temperatures, using low pressure aqueous solutions (avoid the use of high pressure gases), minimizing the loss of process chemicals which must be imported from earth and maximizing the use of lunar materials in both the process chemistry and in the construction of the facility. *It is especially important that the facility can be scaled in output versus size over a wide range of input flow rates.* This means that small benchtop units can be quickly developed, modified for use in Spacelab and deployed on the moon and in orbit as both test articles and productive units.

Figure 4 shows the approximate appearance of the first industrial scale unit appropriate to the start of SPS production. The plant is optimized to process anorthosite (90% pure) at the rate of 30,000 tons/year. A 30 MW solar-power array dominates the picture. It is octahedral, approximately 500 meters on a side, and masses 120 tons. This particular processing facility should have a rather surprisingly low mass. The processing units will mass 105 tons, initial reagent inventory 65 tons, and the solar cells 120 tons. These masses could be placed in orbit by 10 to 15 Shuttle flights. Another 10 to 15 Shuttle flights could deploy the 260 tons for the habitat and fabrication units used primarily during development. The bag of soil entering the plant has a mass of 2,000 tons.

The oxide separation stage shown in the foreground and the electrolytic separation facility in the background use as initial working fluids approximately 65 tons of hydrogen, fluorine and a small amount of sodium to provide a portion of the working fluids for the liquid-phase hydrolysis scheme used in the plant. Additional oxygen and sodium are extracted from the initial runs of lunar soil to provide the full 340 tons of water, hydrogen fluoride and sodium hydroxide necessary for full-scale plant operation. Thus, we see that use of lunar materials minimizes the amount of material that must be shipped from earth to start large scale production. In this plant the makeup loss of hydrogen fluoride would probably constitute the major terrestrial input and is expected to be less than 30 tons per year for 30,000 tons/year output of processed materials. In other words, the facility is estimated to process 1000 times the makeup loss. This may well be improved by further use of lunar materials. If the Shuttle is used to bring the hydrogen fluoride to space then this would contribute 70¢/kg to the processing costs at 20 M$ per Shuttle flight.

It is estimated that as lunar derived iron becomes available it will be possible to construct plants such as this primarily out of lunar materials and that less than 100 tons of equipment need be imported from earth. It should be noted in Fig. 2 that the "excess materials" needed to construct an SPS contain on the order of 600 tons of iron and that six plants of the above capacity could process in one year the 180,000 tons of lunar materials necessary to fabricate 90% of an SPS. The potential of the bootstrapping approach now becomes apparent. Once the skill is established to create and operate the first prototype scale of a space processing facility (30,000 tons/year) then the subsequent five units needed for full production can be brought into production with less than 15 to 20 additional Shuttle flights. This is very powerful leverage. The challenge is to develop the fabrication techniques for working in space.

Glass and Ceramic Production

There is no doubt that a wide range of glasses and ceramics can be produced from lunar materials.[15c,15b,17,18] Glasses and ceramics occur naturally on the moon and have been produced from oxide compositions that are identical to natural bulk compositions of the lunar soils.[17] Duplicated compositions include those at the Apollo 11 (mare, high titanium), Apollo 12 (mare, low titanium), Apollo 16 (highland) soils (see Mackenzie - these proceedings). Glass and ceramic production can benefit from mineral separation as well as from the availability of refined silica and silicon fractions of the lunar soil.

One can be certain that the production of clear window glass, refractory and chemically inert containers, fiberglass wool, reinforced fiberglass strands and ropes, and light pipe fibers is possible. Light pipe fibers for use in communications systems on the earth and in space are especially interesting because they presently cost on the order of 100,000 $/kg for the glass element. Blocks of totally anhydrous lunar glass could be returned to earth for fiber production. Special notice is taken of the use of solar energy and the possibility of glass production by sintering of amorphous powders.

The Lunar and Planetary Institute conducted a workshop on 14-17 April 1979 (proceedings in progress) entitled "Glass and Ceramics Industries in Space Based on Lunar Materials."[19] There were participants from industrial, governmental and university laboratories who are active in the production of and research on glass and ceramics. A suitable point of focus for the meeting was to estimate the equipment and people that would have to be placed on the moon in order to use local lunar materials in order to create a facility for the production of 35,000 tons per year (100 tons/day) of glass products. Major products were to be those needed by the SPS. The products included foamed structural elements, fiberglass and fiberglass with metallic coatings for use in composite structures and in contaminating atmospheres, and substrate glass used for solar cell support. In addition, the plant was to allow for the use of magnetic beneficiation of the feedstock and limited production of iron and oxygen by electrolysis of a portion of the glass melt in a secondary reactor. The oxygen was to be used in foaming, other process uses, and for life support. One major determination of the group was that the technology does exist to produce useful products for these applications from the native glass components and minerals of the lunar highlands. In addition, it is reasonable to expect that a wide range of glasses can be produced (clear glass to very dark glass) with only beneficiated lunar constituates. The anhydrous nature of the lunar glasses would make them superior in mechanical properties and more stable in their other properties than glasses made of terrestrial oxides.

Figure 5 is a preliminary schematic of the proposed glass processing facility. The facility was assumed to be on the moon or in a one-sixth pseudo gravity environment in space. If the plant were in space only the beneficiated ores would be sent from the moon. Lunar soil is introduced (<500 tons/day) into a conveyor system that moves the soil under a powerful permanent magnet. The magnetic component is attracted to the magnet and held against a second conveyor that transports the magnetic fraction (approximately 1 to 5% by weight) to a small melting and electrolysis pot. Free iron and oxygen are collected and the residue is saved for further use as a mixer or disposed of. The other stream of material is introduced into a modifier or blender to adjust the composition and then introduced into the melt tank. On earth a melt tank capable of handling 100 tons/day would be approximately 3.3 by 3.3 by 33 meters in internal volume and have alumina (Al_2O_3) walls approximately 2/3 to 1 meter in thickness and have a mass the order of 1000 tons. Heating is 90% by direct solar.

Table 1 summarizes the estimates of the masses of critical components that would have to be imported from earth in order to construct a plant on the lunar surface in one year. The primary challenge is to provide the alumina bricks which make up the glass melting tank. For this there must be a small chemical processing plant that can produce the alumina at a rate of approximately 1000 tons/year or a total input on the order of three times that rate. The plant would be that previously described and would be approximately 10% the size of the space unit. Cost estimates must be very vague due to the preliminary nature of this analysis. However, if the equipment masses cost on the order of 20,000 $/kg (this excludes the habitats development), then approximately three billion dollars would be required to design and emplace and operate the system. It was felt that the Shuttle was a far more difficult research and development challenge.

Items 1 (chemical plant) and 6 (machine shop) were extremely important to the bootstrapping operation. It was argued that given sources of iron (item 8) and aluminum (or titanium) a semi-automated machine shop could produce the bulk of mechanical items necessary to build up the glass plant and greatly increase the capacity of the excavation fleet and magnetic beneficiation system in one year.

Glass and ceramic production involves many empirical control factors which must be resolved experimentally. This is especially true when ambient conditions are changed from atmospheric pressure to vacuum and in some cases from terrestrial to one-sixth or zero gravity. Availability of the extensive data on lunar soils make it entirely reasonable to begin a series of terrestrial and Spacelab experiments to establish general procedures for the production of a wide range of glass and ceramic products. Terrestrial experiments can very quickly establish the needed key experiments to be performed early in zero-gravity to allow final design of lunar and space production equipment.

A technique developed at Los Alamos Scientific Laboratories (LASL) might be of use in forming habitats, tunnels, pipelines or conduits directly in the regolith and greatly reduce the mass necessary from earth to establish habitats and facilities. Over 1 kilometer of glass lined pipes have been formed directly in basaltic rock by pressing a white hot molybdenum tip into the rocks and soils.[20] The system can be scaled up to large size and heat is generated either by electricity or solar energy. The moon is more suited than the earth to this process due to the lack of water or atmosphere. Following melting the lunar soil could be formed into very thick glass lined walls which could be relatively easy to seal against leaks (if necessary) and would be extremely strong. Figure 6 is a picture of a short tunnel formed in a sandy soil as part of the LASL "Subterrene* Program." The individual glass pipes are approximately 10 cm in diameter and are fused together. In lunar operations a much larger diameter tool would be used which would produce a continuous tunnel.[21]

It was noted by several of the workshop participants that the soil of the moon, in place, is an exceedingly good thermal insulator. It may well be that power for a lunar base can be supplied by turbines in which the working fluid is heated by heat stored in a pool of molten lunar soil. The soil melts to a lava with a rather low viscosity. Solar concentrators could be used during the lunar day to elevate the lava to approximately 2000°K and then heat could be extracted and the pool allowed to cool to 1500°K over the lunar night. Adequate power to operate a lunar base could be provided by a pool of lava the order of 60 meters in diameter. Most of the system components could be manufactured on the moon.

Near-Term Bootstrapping

It is completely clear that the use of lunar materials will greatly reduce the size of transportation systems that are required to provide the materials inputs to an SPS program. At the level of several hundred thousands of tons of materials a year the savings can be enormous. In fact, if the lunar option is used then the major expense and pacing activity is the research and development tasks that must be done to design and activate the production facilities (Fig. 7, Ref. 2). The dilemma is that the size of the production facilities and propellants (130,000 tons) are of the same order of magnitude as a single SPS (Fig. 8, Ref. 2).

The challenge is to determine how to use the vast (100 B$) and available aerospace research and development base developed over the last 20 years to get back to the moon and use bootstrapping with lunar materials to decrease the costs of construction activities. These early small scale operations will serve to remove the uncertainties of having to extrapolate estimates of our true capabilities in space over several orders of magnitude. As a specific example, we know how to build rocket engines which can be powered by liquid oxygen and hydrogen. The development and operation of such systems between the lunar surface and lunar orbit would be relatively cheap to accomplish (<1 B$ - Ref. 22). Such systems could put the tonnages into space necessary to construct major facilities. However, at this point in time it is necessary to plan to bring from earth the required hydrogen which severely degrades the cost advantage. An alternative rocket system which could use lunar oxygen and calcium or aluminum would be a major development challenge (>5 B$), would have less specific impulse than H_2/O_2 systems, and would require the early installation on the moon of a capability to process 400,000 tons per year of lunar soil to make the reactants. There has been much interest in the possibility of enhanced concentrations of hydrogen in the polar regions of the moon.[23] If this is the case then bootstrapping can be used from the very first in the creation of a major industrial capability in space and on the moon. This fact can be determined at a moderate cost by remote observations by a lunar polar orbiting satellite. Several advantages would result. The Shuttle and lunar rockets could provide all the transport needs; construction systems could grow in size steadily as experience was gained, rather than having to be planned from the first for maximum size and then executed in one step, and major production experience could be acquired on the moon initially where the working materials are more readily available.

Figure 9 provides a generalized schematic diagram of the development and flow of mass, people and capital in a space industry. Space industries will have a greater incentive to conserve working fluids and recycle all process and production mass than does terrestrial industry. Pollution control will not simply be a virtue but a necessity. In Fig. 9 the lower case letters correspond to the total extraterrestrial and terrestrial masses, in kilograms extracted from the lunar (or asteroidal) surface (m'), transported into space (m) from the moon (or asteroid). The earth/space export ratio is (d_e). The mass is either lost (l), processed (d_s, d) or exported to make other productive facilities in space (e_p), support space activities (e_o) or exported to earth (e_e) as products.[24] These quantities can change with time as indicated by the "dot" derivative. The mass flow of personnel to and from space is given by p and p' respectively. Terrestrial dollar values are associated with the transport of people (T($/kg)), demandite fractions necessary from earth (D_e($/kg)), the capital invested in the goods (C_e($/kg)) and the value of the imported goods (E_e($/kg)). There will be costs in space associated with the gathering (M'($/kg)), transport (M($/kg)), first processing (P($/kg)), internal production of goods in space (D($/kg)) and maintenance of life-support loops (R($/kg)). Attention will always be focused on decreasing the cost of obtaining a mix of elements which can supply the material needs of the space economy. This average mix might be called "Demandite" in analogy to its use to describe the analogous quantity in the terrestrial economy.[25] This formulation emphasizes the fact that space industry will be a producer of "new wealth".[26,29]

The first step, the original deposition on the moon of masses totaling m_o(kg) deserves very special attention. As we saw earlier, it is not unreasonable to expect that the early mass will grow additional productive capacity at a rate equal to 100 times itself in the first year if the need to send more mass into space can be minimized (i.e., minimize d_e(kg/kg)). If this can be done then the capital cost of the original investment can be minimized. O'Neill[27,28] first drew attention to the possibility of bootstrapping a generalized economy in space on the materials available to us. The studies by O'Leary and others[15d,e,f] have demonstrated that relatively small machines can retrieve to the vicinity of the earth very large quantities of materials to use in space operations. There is clearly much room for advancement in minimizing the first step. The legacies of the Apollo program are two-fold: we have detailed knowledge of a vast subset of the available lunar resources; we have the skills to perform successfully lunar and cis-lunar operations which could be 10 to 20 times larger in people and machinery than was the Apollo program.[30] The power of the space Shuttle is that it will let us accomplish these more extensive and permanent lunar operations at considerably less cost than Apollo.

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Table 1:

A. BOOTSTRAP EQUIPMENT REQUIRED FROM EARTH

	Item	Mass Tons
1.	Small chemical plant to produce SiO_2 (a) plant (b) fluids	50
2.	Equipment for forming refractories	10
3.	Heating equipment and molybdenum electrodes	24
4.	Forming equipment for pipes, blocks, etc.	5
5.	Forming equipment for glass rope	5
6.	Machine shop	50
7.	Volatiles separator	2
8.	Magnetic separator	2
9.	Control equipment .	2
10.	Habitats (3)	150
	Total	350 tons

B. PERSONNEL REQUIRED BY FUNCTIONS
(Two shifts)

	Item	People
1.	Ore separation	2
2.	Chemical plant	10
3.	Construct and operate (a) glass tank (b) rope production, (c) glass blocks, and (d) volatile separator	20
4.	Materials handling and maintenance	8
	Total	40

Figures:

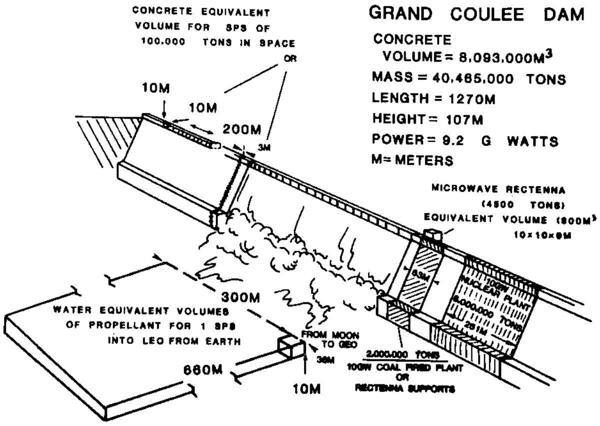

Figure 1

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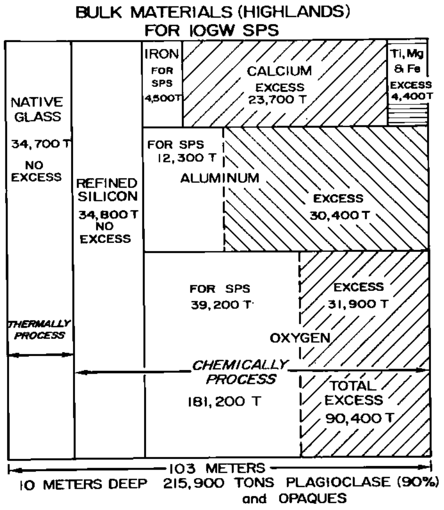
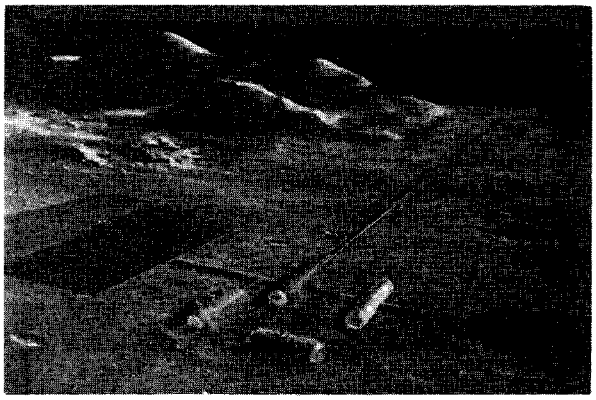


Figure 2



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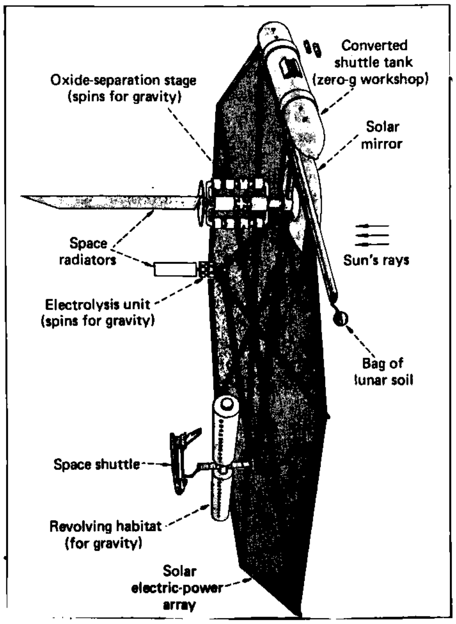

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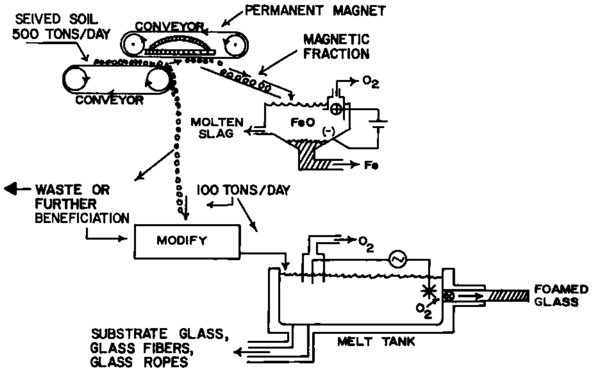

Figure 5

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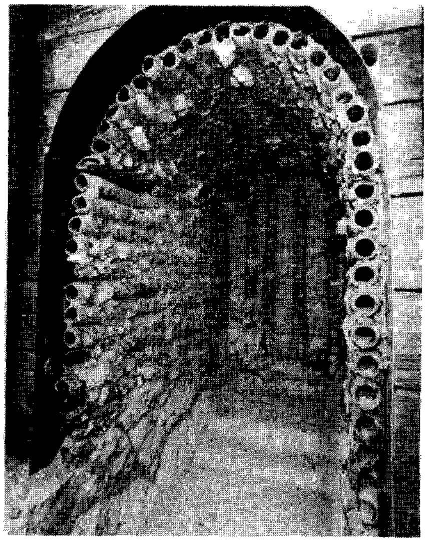

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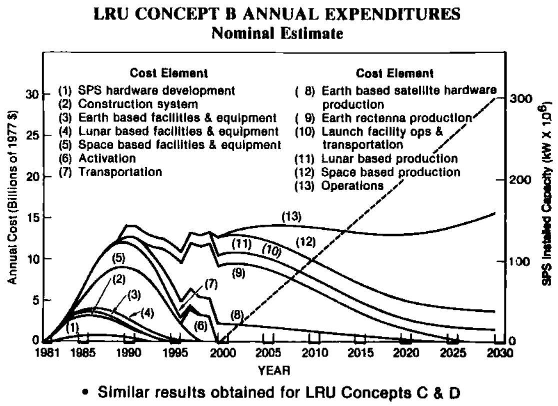

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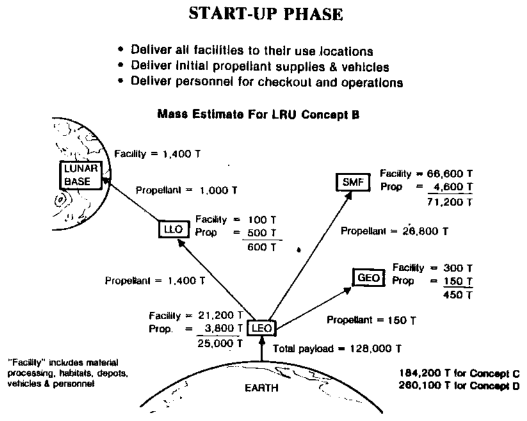

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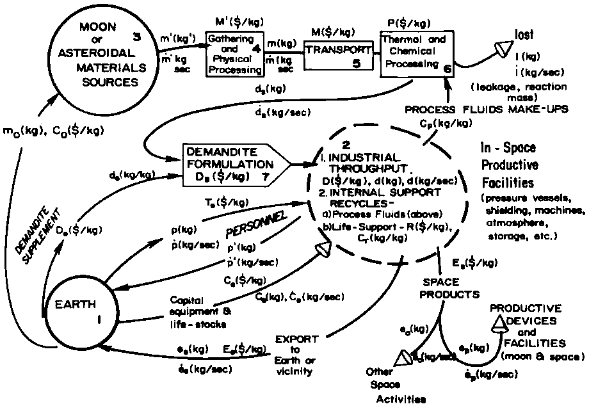

Figure 9 (Ref. 14)

Q. When considering scaling it is necessary to look at two kinds of technology: the moving of large quantities of materials, and sophisticated processes such as the manufacture of solar cells. We must not forget the sophisticated technology. How can you advocate this approach until you have found a cheaper way to do the sophisticated technology?

A. You can't really claim that a steam turbine is sophisticated. We've been building them for 50 years with very little improvement in performance. There would be a very small, if any, mass disadvantage incurred by using steam turbines instead of solar cells.

Q. Both Boeing and Rockwell, particularly Boeing, have studied this question and relegated the thermal energy conversion system to a lower priority because of complex requirements and the large number of moving parts.

A. The primary reason for these decisions was not system complexity, but the radiators. The picture changes if the radiators consist of inexpensive thin metal shells containing the majority of their mass in the form of plain lunar dirt. If these concepts turn out to be practical, their cost is lower than that of the concrete in Grand Coulee Dam, and they comprise better than half the mass of the power supply.

Comment: Both Rockwell and Boeing considered only high-performance turbine systems because of the mass limitation inherent in Earth-launched systems. If that mass limitation is removed, it's possible to consider a low temperature radiator which might be made of aluminum. Changing the philosophy of the basic argument to one in which the cost of mass is not exorbitant permits the use of simple systems, and such simple systems certainly <u>can</u> be built with today's technology.