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NONTERRESTRIAL MATERIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS

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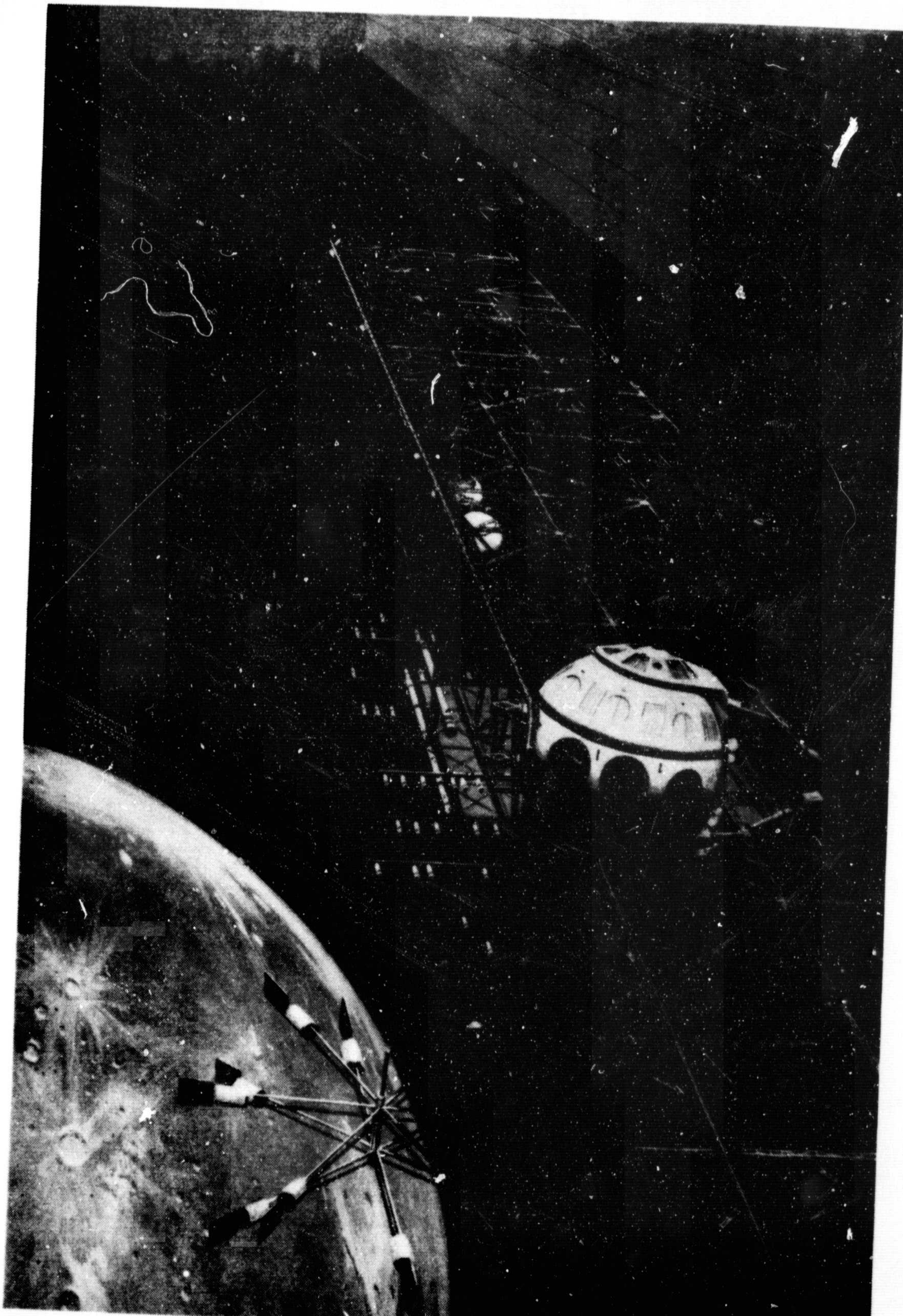

FOREWORD

This report is based on systems study efforts that are being sponsored by the National Aeronautics and Space Administration. The objective and purpose of these studies are to identify new systems and techniques that may provide planning recommendations for research and advancement of technology.

NASA has no current plans to pursue a development program on the processing and utilization of extraterrestrial materials.

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NONTERRESTRIAL MATERIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS

SUMMARY

Present and past space system studies involve the definition of major future large space systems in the area of communication, energy and others for which the material must be transported from the ground into space for construction and assembly. The studies indicate the major cost impact of transporting these required large quantities of material from Earth and the potential environmental impact of large numbers of heavy lift vehicle launches through the Earth's atmosphere.

A number of NASA sponsored summer studies and independent university efforts indicated the possibility that large space system material delivery and construction from lunar sources may be of a potential economic and environmental advantage. This is based primarily on the fact that the energy required to transport lunar material into space is only approximately 4.5 percent of the energy required for transportation from Earth. Presently this potential is under investigation to provide NASA with supplemental information required to arrive at optimum large space system options and programs, for the time period around the turn of the century. This report attempts to provide pertinent and readily usable information on the extraterrestrial processing of materials and manufacturing of components and elements of these planned large space systems from pre-processed lunar materials which are made available at a processing and manufacturing site in space. The scenary for this envisioned activity consists of a number of major elements located at specific places in space and on the lunar surface. A lunar surface mining operation provides the required quantities of lunar material in a pre-processed condition to a space manufacturing facility which may be located at a number of possible areas in space. These delivered materials consist primarily of oxygen, silicon, aluminum, iron, magnesium and calcium locked into a great variety of complex compounds.

The activities at the space manufacturing facility consist of final processing of the incoming pre-processed material to commercial grade raw material and of performing a series of large scale manufacturing processes which would include the following products: large structures to support energy generating

and large communication systems in space, large area solar cell blankets, radio frequency generators, and electrical equipment. These processing and manufacturing facilities are highly automated and are sized for annual outputs of at least 10^5 metric tons of products. Required facilities, equipment, machinery, energy and manpower are defined and a first cut of the cost and benefits is provided.

Included in the discussion are various critical system elements and their respective required technology advancements. Economic boundary conditions are established to evaluate economic goals for space processing and manufacturing.

I. INTRODUCTION

A. Background

Many past and present studies conducted by the National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center (MSFC) in Huntsville, Alabama, and specific experiments conducted in space during the last decade have provided considerable evidence that the processing of certain materials in the environment of space may become a major, profitable industrial activity in the future. Based on this experience preparations are underway by NASA, various industries and governments here and abroad for a wide range of material processing activities to be carried out on the Space Shuttle during the next 10 years [1]. From this we hope to proceed toward a large scale industrialization of space with a profitable return on any investment.

Three major areas have been defined [2, 3] where space industrialization could respond to major human needs: new services, new products, and new sources of energy. To provide these, NASA in addition to studying and experimenting with material processes in space, is expecting to be able to manufacture and assemble the large structures in space that are required to support large future communications antennas, production facilities, and space power systems. MSFC operates already an automated machine which produces structural beams as a prelude to space-based construction activities.

All materials needed in future space industrial activities in material processing and construction are presently planned to be shipped into space from Earth. Two lines of reasoning indicate an alternative to this mode of operation. First, one can expect that the costs of extracting essential materials from progressively lower grade ores may rise dramatically in the future so that at some point the decreasing cost of access to space would make available the practically infinite resources of the solar system, specifically of the Moon. Second, all terrestrial materials have to be lifted into space against the strong gravitational force of the Earth, resulting in high energy requirements with associated high costs of transportation. In the last few years, a number of NASA sponsored and independent studies at universities and in industry [4-6] have concluded that the Moon could be a readily available source of industrial raw materials. Particularly the low gravitational attraction of the Moon, which is only approximately 17 percent of that of the Earth, would require a transportation energy consumption of only between 4 and 8 percent to carry material from the Moon into space as compared with the Earth. Therefore, these studies concluded that it may be economically advantageous to do materials processing and product manufacturing in space by utilizing lunar materials rather than terrestrial ones.

In 1978 NASA began a limited effort to thoroughly explore the option of lunar materials utilization for the in-space production of large future space systems. While the NASA/Johnson Space Center in Houston, Texas, investigates the lunar materials extraction techniques and the pre-processing required before shipment into space [7], MSFC studies the required final materials processing in space and the production techniques for the numerous elements and components of large space systems from lunar material [8]. This presentation is intended to give the first results of this latter effort: the processing and manufacturing of large space systems from lunar material.

B. A Space Industrial Scenario

The following scenario is intended to put the subject of a large scale space manufacturing and processing facility into the context of an overall integrated operation.

To determine the feasibility, the technological problems, and the profitability of a large industrial production facility and operation in space based on lunar materials utilization, the desired products and their material requirements must first be defined. These are then compared with the material availability on the Moon. The flow of material from the Moon to the space manufacturing facility and of the products to their destination determine the transportation requirements and the size of the lunar and space manufacturing facility.

1. <u>The Primary Product</u>. The economy of lunar material extraction is highly dependent upon the total quantity of material required over an assumed facility life time of 30 years.

Studies [7, 8] have concluded that a minimum of between 1 and 3 million metric tons of lunar material are required to start providing a return on the investment. The only presently envisioned large space system which would fulfill this requirement is the Satellite Power System (SPS) (Fig. 1) which has been under NASA study for approximately 6 years. This system has a potential to provide a major fraction of the U.S. electric power early in the next century. Therefore, our scenario will be based on an assumed SPS program over 30 years with the construction of one 10-GW satellite per year. The construction materials requirements for one satellite are shown in Table 1.

TABLE 1. SATELLITE POWER SYSTEMS MANUFACTURING MATERIAL REQUIREMENTS

Construction Materials (Earth Resources)	Satellite Power System (Baseline January 25, 1978) Mass (tons)	Total (percent)
Glass (Fused Silica)	36 097	37
Silicon Solar Cells	14 775	15
Graphite Composite	12 533	13
Copper	10 774	11
Stainless Steel	7 747	8
Aluminum	6 324	7
Tungsten	1 132	1
Mercury	266	—
Silver	28	—
Various	7 874	8
Total (per satellite)	97 550	100

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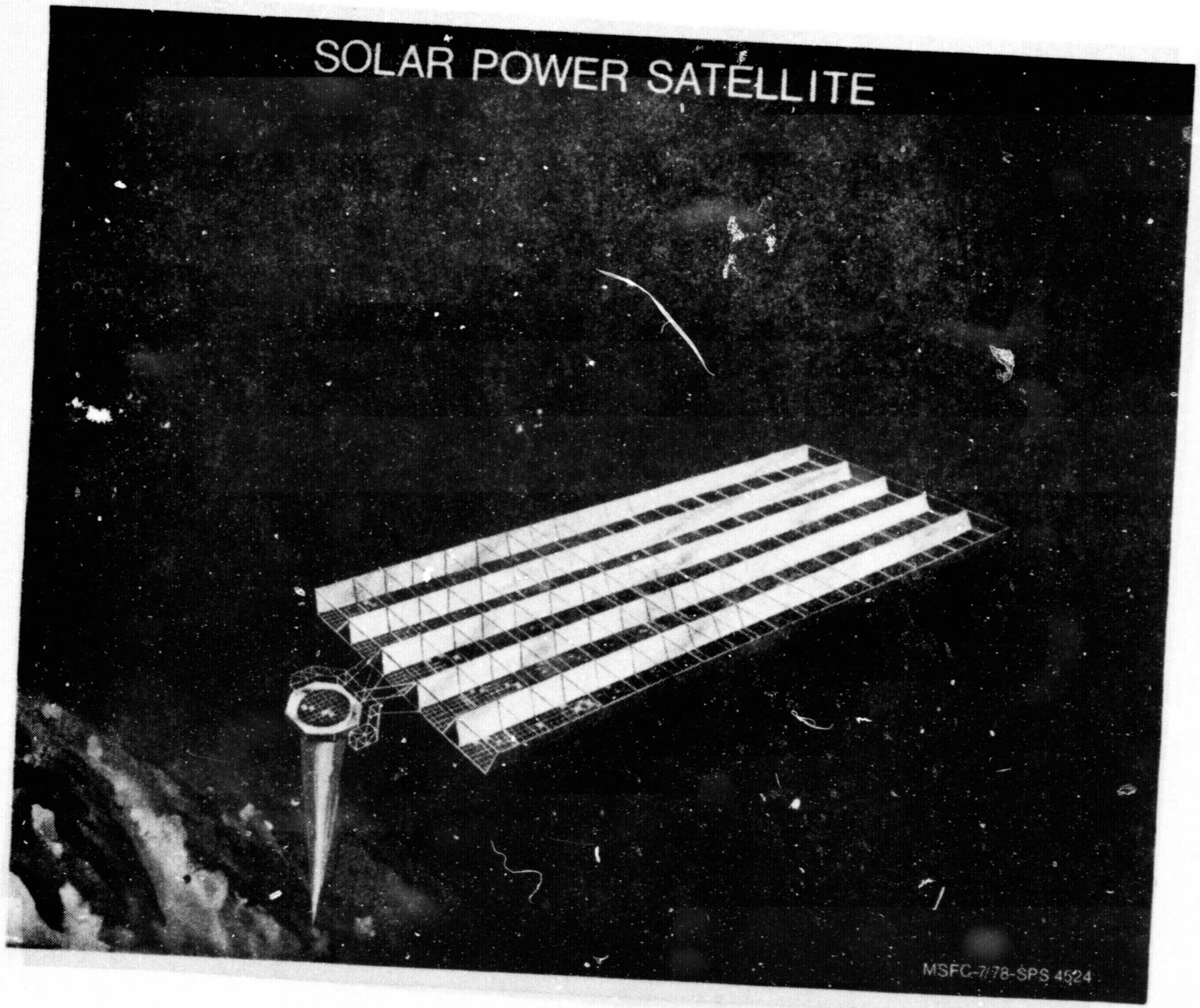


Figure 1. Solar Power Satellite.

2. Lunar Material Abundances. Based on our direct knowledge derived from the Apollo lunar landings between 1969 and 1972, the elements presented in Table 2 are available from lunar material. Noteworthy is the great abundance of oxygen, aluminum, iron and silicon locked, however, in rather complex chemical compounds.

TABLE 2. LUNAR MATERIALS AVAILABLE

	Elements	Percent by Weight		
		Mare	Highlands	Basin Ejecta
Identified as Principal Requirements For Constructing SPS	Oxygen	39.7-42.3	44.6	42.2-43.8
	Silicon	18.6-21.6	21.0	21.1-22.5
	Aluminum	5.5- 8.2	12.2-14.4	9.2-10.9
	Iron	12.6-15.4	4.0- 5.7	6.7-10.4
Other Useful Materials of ≥ 0.1 percent Availability	Calcium	7.0- 8.7	10.1-11.3	6.3- 9.2
	Magnesium	5.0- 6.8	3.5- 5.6	5.7- 6.3
	Titanium	1.3- 5.7	0.3	0.8- 1.0
	Chromium	0.2- 0.4	0.1	0.2
	Sodium	0.2- 0.4	0.3- 0.4	0.3- 0.5
	Manganese	0.2	0.1	0.1
	Potassium	0.06-0.22	0.07-0.09	0.13-0.46
Trace Elements Useful in Processing and Manufacturing	Hydrogen, Carbon, Nitrogen Fluorine, Zirconium, Nickel			100 ppm
	Zinc, Lead, Chlorine Sulfer, Other Volatiles			5 to 100 ppm

3. Material Requirements and Availability. Obviously, our goal is the maximum utilization of lunar materials for SPS construction. Table 3 presents a breakdown of requirements between lunar material and supplementary Earth material.

Table 3 indicates that approximately 90 percent of the material requirements can be satisfied by lunar materials. It is to be noted that graphite has been replaced by foamed silicon glass and copper has been replaced by aluminum.

TABLE 3. LUNAR RESOURCE SPS MATERIAL REQUIREMENTS

		Maximum Lunar Utilization	
		Mass (ton)	Total (%)
Lunar Material Requirements	Silicon	31 649	32.2
	Natural Glass	20 093	20.4
	Oxygen	19 223	19.5
	Aluminum	11 925	12.1
	Iron	5 300	5.4
Total Lunar Material		88 190	89.6
Earth Material Requirements	Metals	2 316	2.4
	Graphite composite	0	0
	Various	7 874	8.0
Total Earth Material		10 190	10.4
Total SPS Mass (ton)		98 380	—
			100.0

4. <u>A Space Industrial Model</u>. To provide a clear insight into the overall picture of space processing and manufacturing from lunar materials, a schematic model of the total scenario is presented in Figure 2.

Mining of lunar materials, preprocessing and shipping into space occurs at the Lunar Resource Complex (LRC). The material is flown to the Space Manufacturing Facility (SMF) where, together with supplementary terrestrial materials, the final processing and manufacturing of SPS components and elements take place.

The finished products are shipped to the final destination in geosynchronous orbit where, together with supplementary terrestrial products, the final assembly occurs.

The following presentation will describe the SMF within this model. Omitted will be the LRC and the assembly operations in geosynchronous orbit as well as the various required transportation systems.

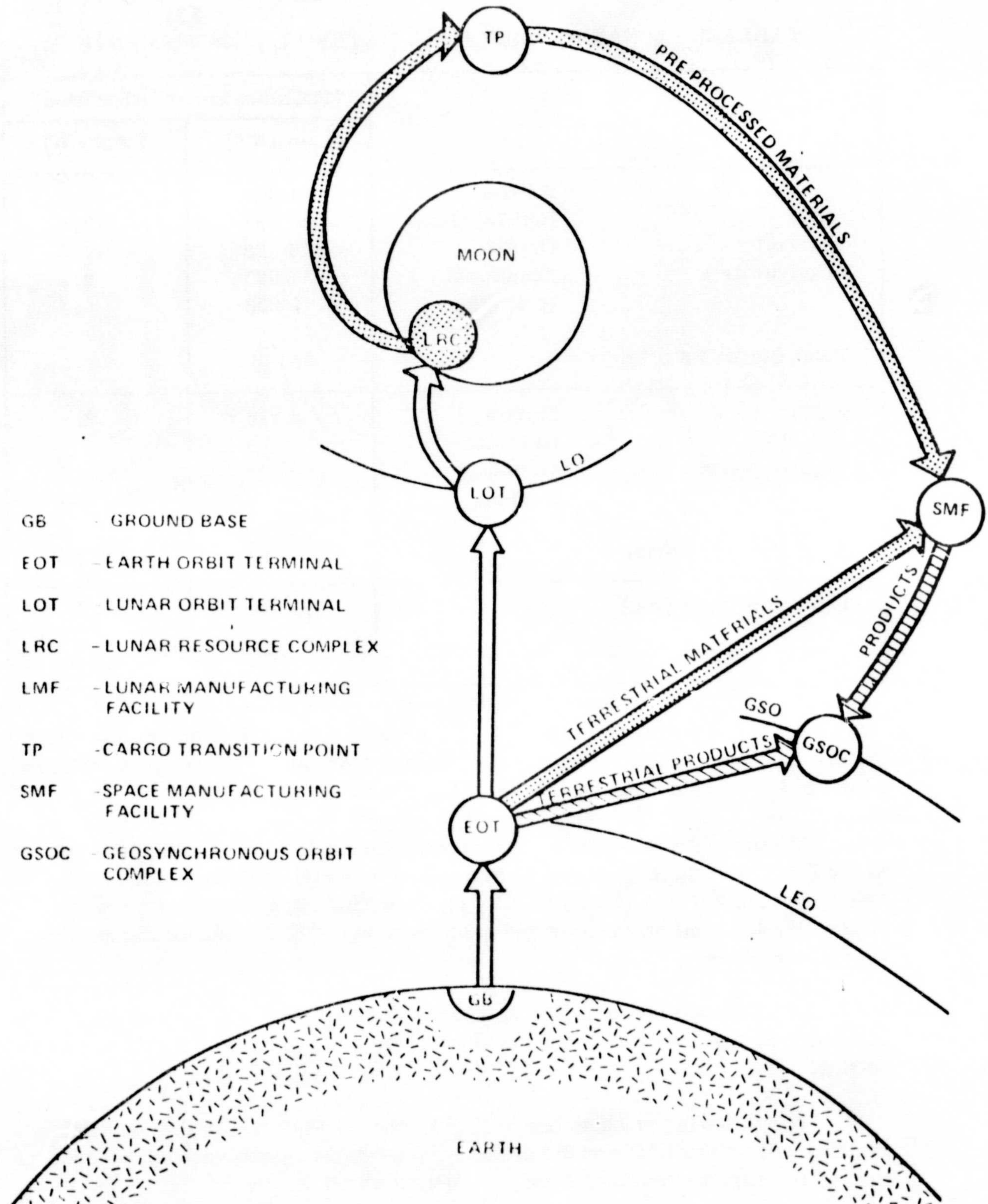


Figure 2. Model of extraterrestrial processing and manufacturing of large space systems.

II. SPACE MANUFACTURING FACILITY (SMF)

An SMF differs from a terrestrial manufacturing facility in that it is subject to the special environment of space: vacuum, weightlessness, direct solar radiation, and an infinite heat sink. Physical and chemical material processes, material handling and transportation, and manufacturing activities must consider this environment to function as required. In many instances the space environment provides a considerable advantage over terrestrial conditions, particularly by the fact of practically unlimited energy availability.

An SMF with an annual output of products of approximately 100 000 metric tons is described here. The assembly of these products will be an SPS which would provide 10 GW of power at a receiving station on Earth.

A. General Processing and Manufacturing Flow

Figure 3 presents the overall concept of the material flow from mine to factory. The lunar highlands is shown with an annual output of over 500 000 metric tons of regolith, iron, aluminum, and silica. The lunar beneficiating and preprocessing of these materials also produce over 86 000 metric tons of liquid oxygen to be used as rocket propellant to transfer the materials to the SMF.

The material inputs to the SMF are then as follows:

17 330 metric tons of aluminum and iron ingots
14 670 metric tons of silicon
20 093 metric tons of glass particles
36 097 metric tons of silica marbles.

The following sections (Table 4) comprise the SMF:

Material Processing and Refining
Stock Manufacture
Parts Manufacture
Component Assembly
Subassembly Fabrication.

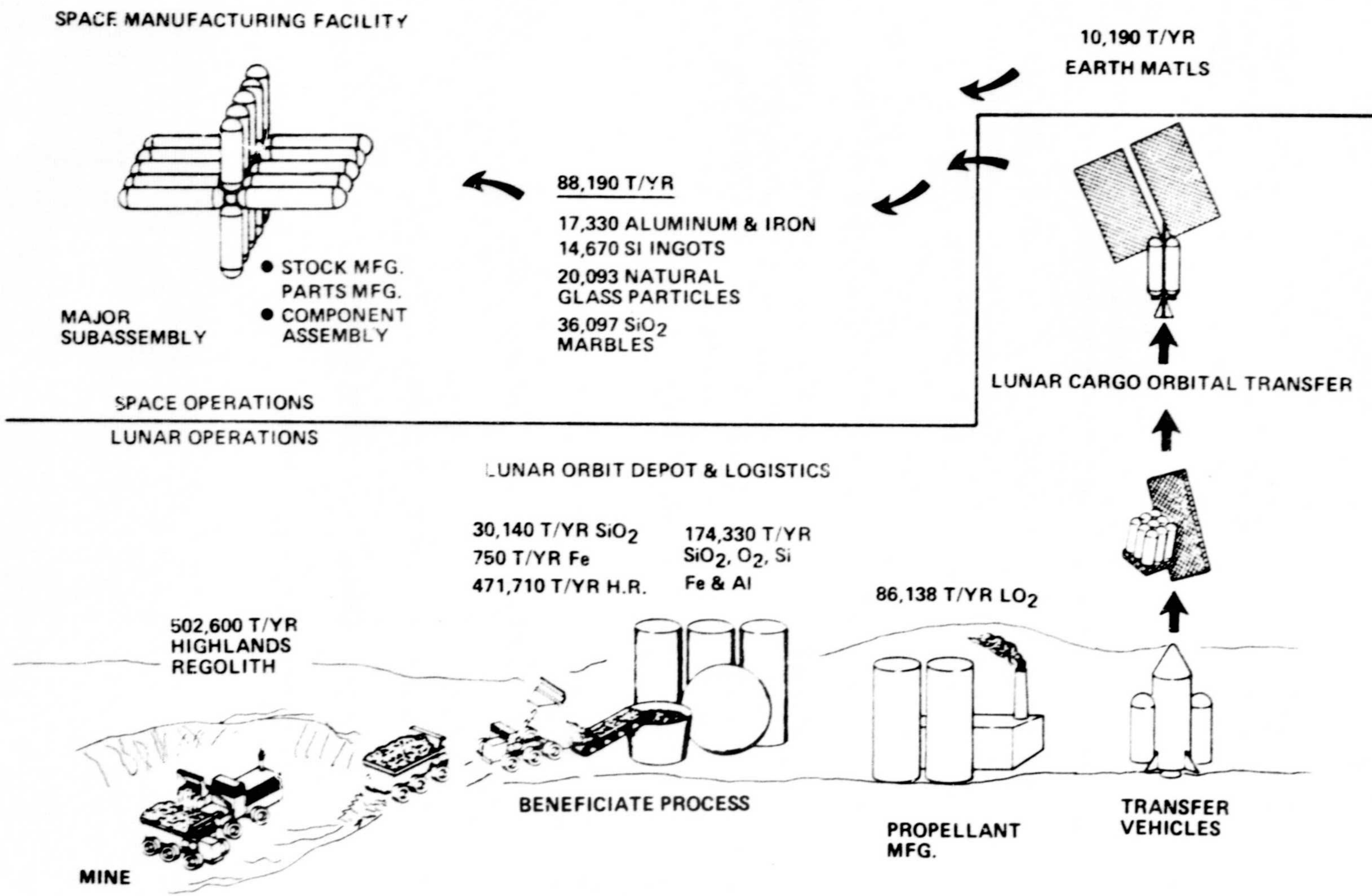
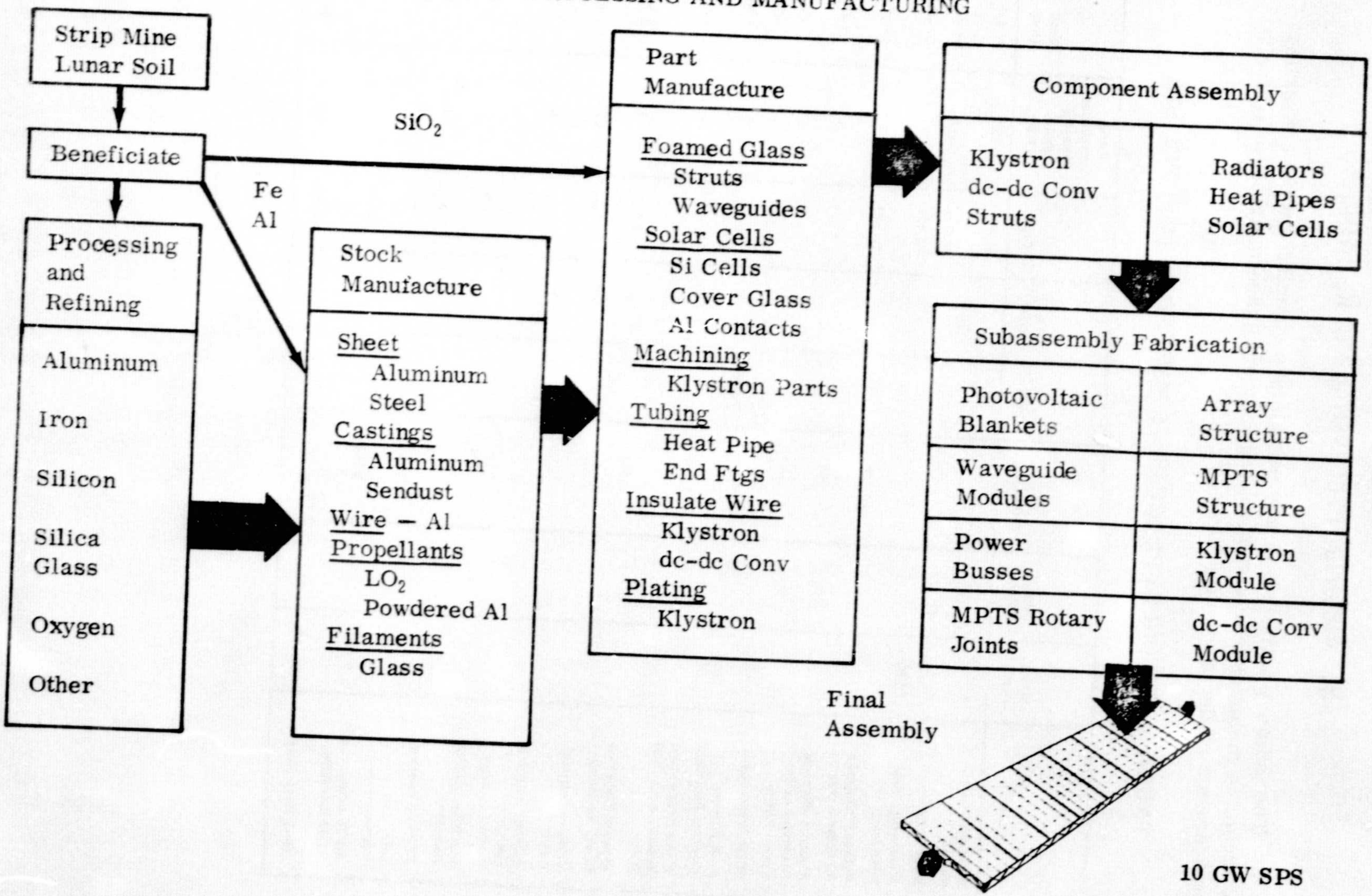


Figure 3. General processing and manufacturing flow.

TABLE 4. PROCESSING AND MANUFACTURING



B. Material Processing and Refining

The primary activities in this section are directed toward converting the incoming material into equivalent commercial grade material to fit the requirements of the products (Table 5).

TABLE 5. LUNAR REPLACEMENT MATERIALS (ton) FOR SPS

Application	Silica Glass	Pure Silicon	Aluminum	Iron	Other	Total	Earth Constituent Material Mass (ton)	Total (ton)
Photovoltaic Cell Covers	21 658					21 658	0	21 658
Solar Cells		14 775				14 775	<<1	14 775
Photovoltaic Cell Substrate	14 439					14 439	0	14 439
Primary Structure for Solar Array			15 830			15 830	0	15 830
Klystron and dc-dc Converter Cells, Power Cables			2 865			2 865	0	2 865
MPTS Waveguides	5 252				(O_2) 5	5 257	0	5 257
Heat Pipe for Klystron Radiators				3 542		3 542	350	3 892
Power Transmission Busses, Array and MPTS			3 535			3 535	0	3 535
Klystron and dc-dc Conv. Radiators			2 749			2 749	0	2 749
Klystron Solenoid Cavity			785			785	90	875
Klystron Solenoid and Transfer for dc-dc Converter				1 758		1 758	0	1 758
Klystron Collector Radiators			779			779	0	779
Klystron Housing			515			515	0	515
Solar Cell Interconnects			697			697	0	697
MPTS Antenna and Other Structure			3 086			3 086	0	3 086
Total Mass (ton)	41 350	14 775	30 840	5 300	5	92 270	440	92 710

An example of a materials refining process is shown in Figure 4, i.e., the removal of gas enclosures from raw ingot material by magnetic forces.

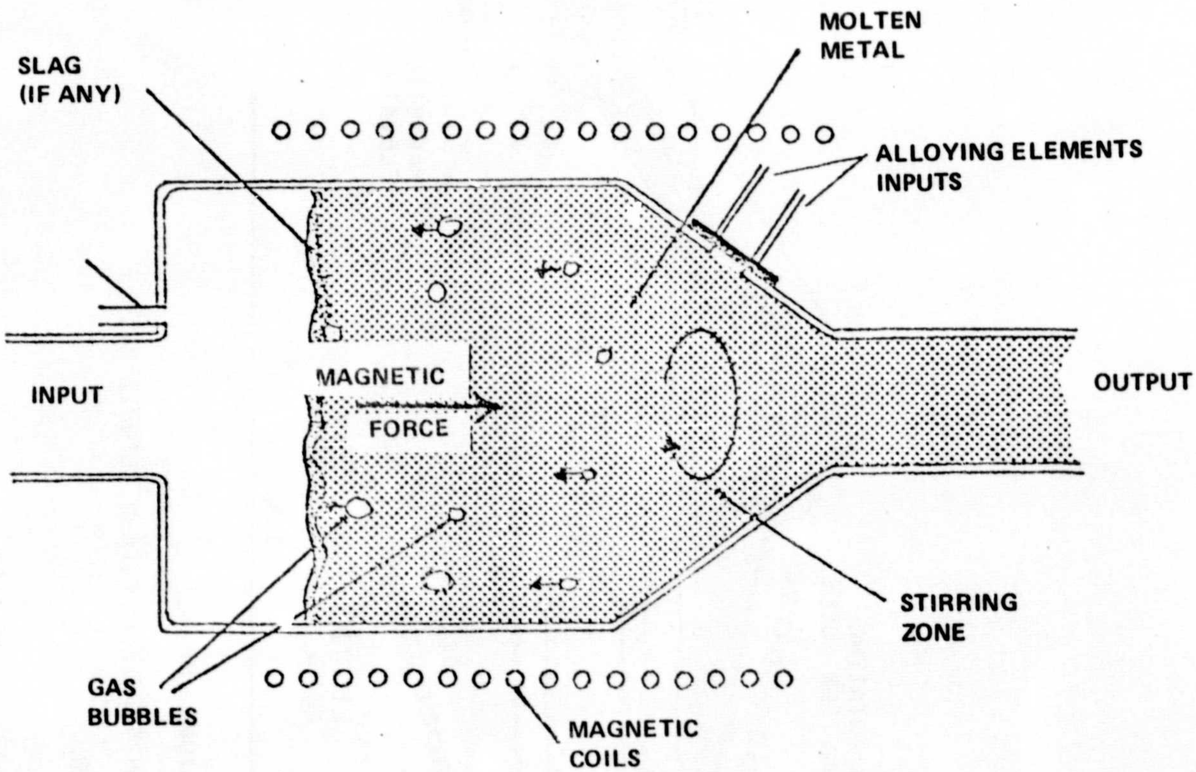
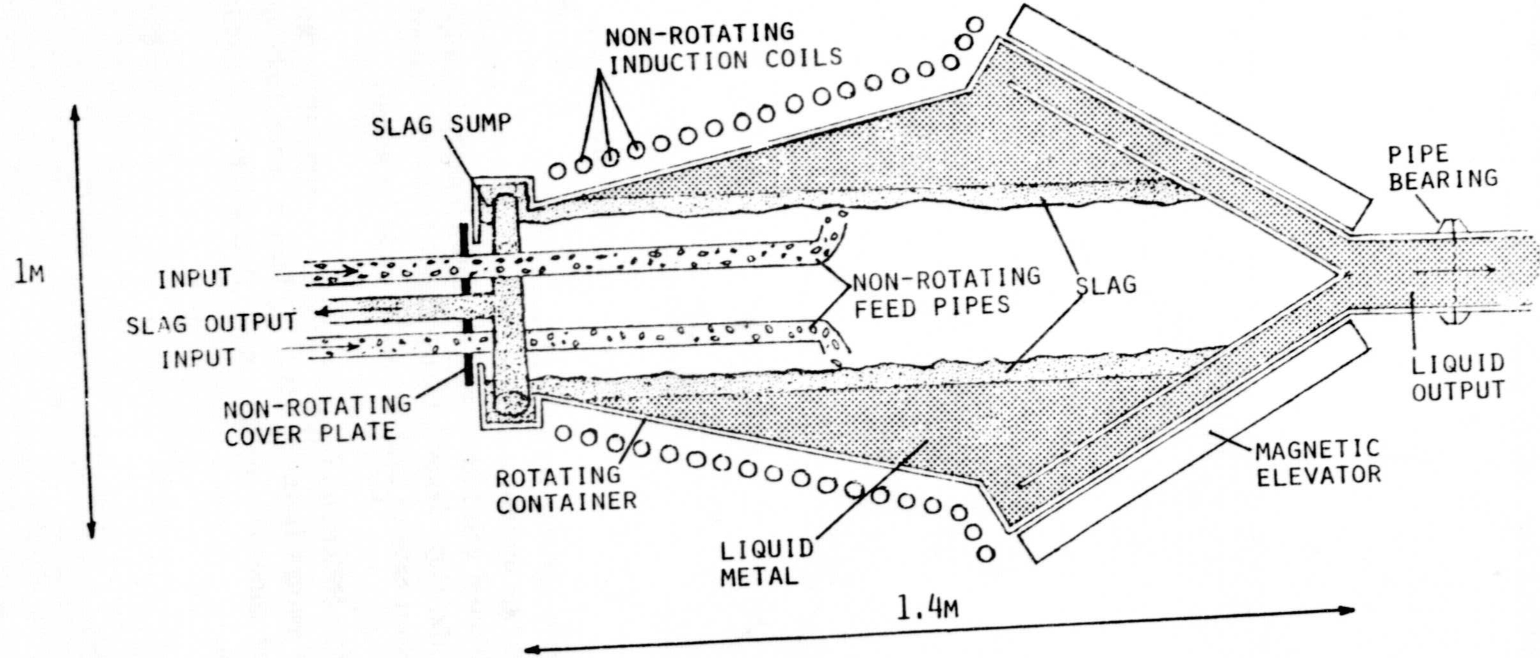


Figure 4. Magnetic gas removal furnace.

An electric melting furnace (Fig. 5) for space processing consists of a rotating container of molten metal inside non-rotating induction coils. The input material is preheated and introduced through nonspinning pipes. Centrifugal force separates the high-density liquid metal from low-density slag. The high potential production rate of this concept should be noted.

An electric reduction furnace (Fig. 6), similar to the melting furnace concept, has two sumps in its rotating container, each lined with an electrode. A passing current generates oxygen gas at the anode while iron ions migrate to the cathode sump.

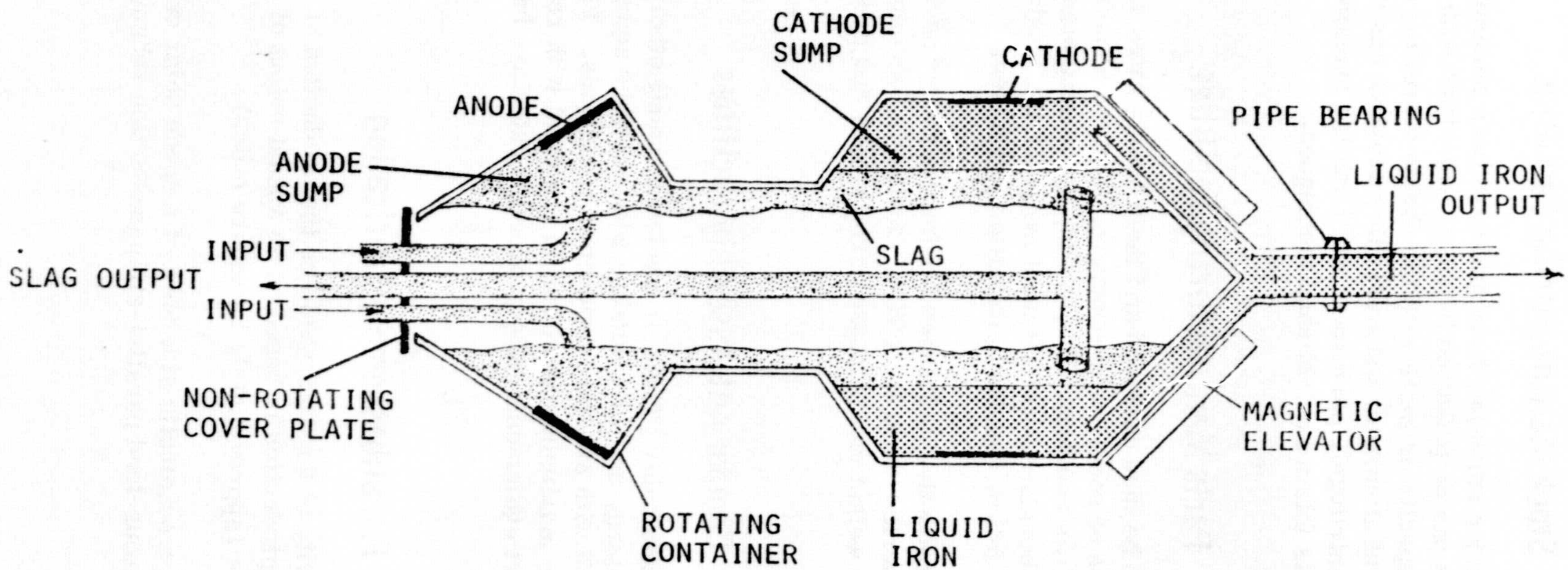


CAPACITY: 2600 KG STEEL (.37 M^3 LIQUID METAL)

ESTIMATED PRODUCTION RATE: 1200 KG STEEL/HR (.17 M^3 LIQUID METAL)

ESTIMATED MASS OF CRUCIBLE: 130 KG

Figure 5. Electric melting furnace.



NOTE: HEATING COILS OMITTED FOR CLARITY.

Figure 6. Electric reduction furnace.

C. Stock Manufacturing Facilities

Table 6 shows major stock products that have been studied. Aluminum coated steel alloy sheets can be produced by vapor deposition with electron beam guns of up to 1200 kW capacity or more with the sheets travelling at least at 3 m/s. The production of aluminum and steel alloy castings can be done by induction melting and centrifugal, permanent mold casting machines. The production of glass filaments follows established techniques.

D. Parts Manufacturing Facilities

Selected parts to be manufactured and their hourly rates are shown in Table 7. The production of sheet metal products, klystron housings, heat pipes, and copper plating involves conventional operations requiring standard facilities and techniques. Also fiberglass braiding machinery for the insulation of electrical conductors would follow standard production processes.

Facilities and production processes for foam glass tubes would be according to Demidovich as carried out in the USSR. Obviously, equipment would be redesigned to minimize weight and increase performance and reliability for space operations.

E. Component Assembly Facilities

The component assembly (Table 8) involves, among others, metal cutting, brazing, welding, crimping, and wire winding with standard equipment redesigned for space operations and with standard production techniques. The facilities will be automated to the maximum extent that is practical with robotized handling, assembly, and transport equipment. The production rates are based on one SPS per year.

F. Subassembly Fabrication

The major activity of the SMF would be the production of solar cell blankets. The rate of production is based on an annual output of approximately 100 km^2 of solar arrays (approximately 20 square miles).

Figure 7 shows a schematic side view of a space solar cell factory operating on the continuous-feed parallel-strip production scheme. The factory

TABLE 6. STOCK MANUFACTURING FACILITIES

Stock Products	Production Rate	Equipment Description	Indust Robots	Facility Estimate Mass (ton)	Facility Estimate Power (kW)
Aluminum Sheet 1 mm × 1 m	1.20 ton/hr 7.08 m/hr	Electron Beam Vapor Deposition, (7) 1200 kW Guns and Fixtures	3	34	8 783
Aluminum Wire 1.13 mm Dia from Sht	0.36 ton/hr 127 km/hr	Sitting Rolls, EB Welder (8) Wire Drawing Machines	2	7	32
Steel Sheet 0.25 × 7 cm	0.54 ton/hr 390 m/hr	Electron Beam Vapor Deposition, (8) 1200 kW Guns and Fixtures	3	38	9 603
Steel Sheet 1.02 × 16 cm	80 kg/hr 7.42 m/hr	Electron Beam Vapor Deposition, (3) 400 kW Guns and Fixtures	2	12	1 222
Aluminum Castings 0.8 and 3.54 kg/Part	108 kg/hr ~1 Part/min	(1) 50 kW Induction Furnace, (1) Permanent Mold Casting Machine	6	28	126
Sendust Castings 2.18 ton/Part	125 kg/hr ~1.4 Part/day	(1) 600 kW Induction Furnace, Sand Casting Equipment	1	50	750
Glass Filaments	94 kg/hr	Induction Furnace, Fiber Bushings and Collecting Drum, Spool	1	4	7
Total	2.51 ton/hr		18	173	20.5 MW

TABLE 7. PARTS MANUFACTURING FACILITIES

Parts	Production Rate	Equipment Description	Indust Robots	Facility Estimate	
				Mass (ton)	Power (kW)
Aluminum End Ftgs For Struts (Sht)	64.8 kg/hr 184 Parts/hr	Blanking Presses, Roll Formers, EB Welders and Fixtures	2	8	37
Aluminum Housings for Klystron (Sht)	51.4 kg/hr 49 Parts/hr	Blanking Presses, Roll Formers, EB Welders and Fixtures	2	28	77
Aluminum Klystron Cavity Copper Plate	11.3 kg/hr 25 Parts/hr	Electroplating Tank, Electrolyte, and Handling Fixtures	1	5	35
Foamed Glass Tubes and Waveguides	4.82 ton/hr 1.78 km/hr	Ball Mills, Conveyors, Kilns, Cutters, Molds, and Tooling	70	845	2020
Aluminum Deposition on MPTS Waveguides	24 kg/hr 138 m/hr	Electron Beam Vapor Deposition (6) 160 kW Guns and Fixtures	—	5	1200
Steel Heat Pipes (Sht Material)	3.1 kg/Part 146 Parts/hr	Roll Formers, EB Welders, Press, Tube Benders and Tooling	5	62	107
Glass Fiber Insulation on Elect Wire	94.2 kg/hr 12.7 km/hr	Glass Filament Coater, (334) Brading Machines	15	355	420
Total	5.52 ton/hr		95	1308	3.9 MW

TABLE 8. COMPONENT ASSEMBLY FACILITIES

Component Assembly	Production Rate	Equipment Description	Indust Robots	Facility Estimate	
				Mass (ton)	Power (kW)
dc-dc Converter	1.4 Assy/Day 4.45 ton/Assy	Fixture with Storage Bins, Wire Spools, Turntable and Locating Tools	2	12	30
Klystron Assy	25 Assy/hr 32 kg/Assy	Fixture with Turntable, Wire Winding, EB Welders and Tooling	12	30	180
dc-dc Converter Radiator Assy	1.4 Assy/Day 360 m^2/Assy	Alum Cutting, Forming Press, Roll Seam Welder and EB Welder	2	72	24
Klystron Radiator Assy	25 Assy/hr 2.6 m^2/Assy	Alum Cutting, Brazing Furnace, Fixtures and Tooling	8	14	30
Structural Member Assy	92 Assy/hr ℓ = 6.5-144 m	Furnaces, Swaging Machines, Crimping Machines and Fixtures	6	32	115
MPTS Waveguide Subarray Assy	1.74 Assy/hr 114 m^2/Assy	Lasar Welding Equip, Positioning Fixtures	2	25	30
Total	144 Assy/hr		32	185	0.41 MW

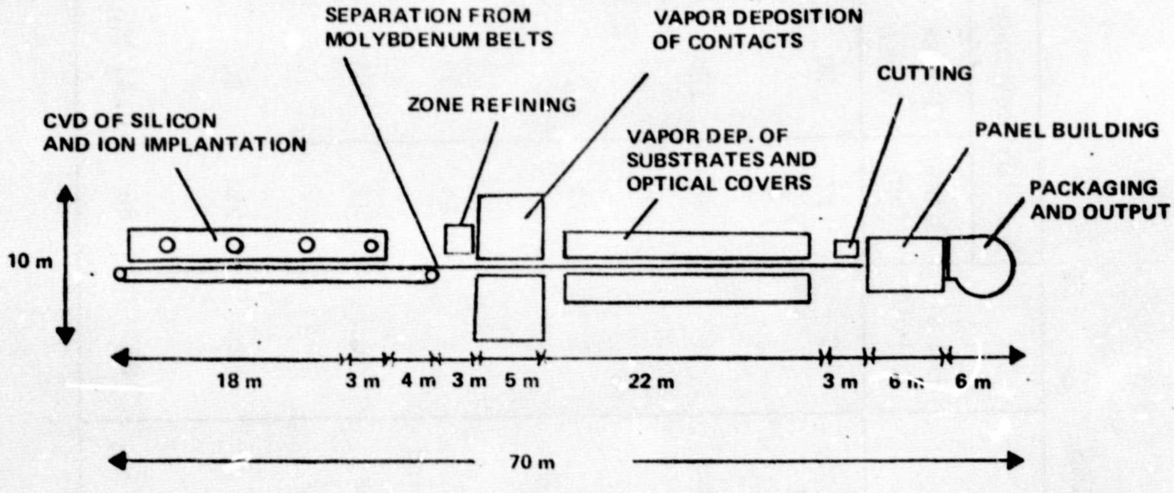


Figure 7. Solar cell factory (side view).

is a 350 × 70 × 10 m planar structure with 2000 continuously moving silicon strips which move side by side in a plane. These strips become the solar cells as they move through the factory.

Major individual assembly activities are shown in Table 9. Again, maximum automation will be a major goal.

G. Manpower Requirements and Habitats

In space industrial operations, particularly of the size discussed in this report, manpower requirements must be optimized and balanced with extensive automation of all processing and manufacturing activities. The number of people required at the space manufacturing facility involves great uncertainties due to lack of detailed task definitions; however, even with advanced automation, supervisory and maintenance personnel will be required. The present estimate is 1500 people to be resident at all times at this facility. The habitat would be a part of the overall manufacturing complex. It would be shielded from galactic radiation by slag material, a by-product of the materials processing operations. Habitat dimensions and a possible configuration that provides one third of Earth gravity are shown in Table 10 and Figure 8. It should be noted that the habitat may make intensive use of discarded Shuttle External Tank (ET) material for structural units.

TABLE 9. SOLAR CELL PANEL FACILITIES

Component Assembly	Production Rate	Equipment Description	Indust Robots	Facility Estimate Mass (ton)	Facility Estimate Power (kW)
Silica Glass Solar Cell Covers and Substrate $75\ \mu m \times 1.17$ m $50\ \mu m \times 1.17$ m	2.72 ton/hr 1.81 ton/hr 181 m/min	Melting Furnace, Molten Glass Tanks and Refractory Dies, Drawing Machines and Annealing Furnace	15	76	18 170
Aluminum Deposition on Glass Substrate	87.5 kg/hr 181 m/min	(4) 250 kW EB Vapor Dep Guns Plus Masking and Etching Equip	—	4	1 200
Silicon Refining to PPB Level	2.2 ton/hr	Silane/Silicon Process Plant Reactors, Stills, Pumps, Tanks, etc.	—	5 900	19 360
Silicon Solar Cells, EFG Process, $50\ \mu m \times 7.7$ cm	1.86 ton/hr 3181 m/min	(4283) Ribbon Growing Machines, 10 Ribbons each at 7.5 cm/min	203	8 736	135 000
Cut Ribbon, Dope Apply Contacts and Anneal	1.86 ton/hr 695 Parts/sec	(83) 550 kW Integrated Ion Beam Implanters, EB Annealing and Contact Coating	166	2 560	46 100
Solar Cell Module Assembly 1.29 m^2	164 Assy/min 254 Parts/Assy	Automated Module Assembly Mach, Electrostatic Bonding Equip	254	4 100	28 170
Total	6.5 ton/hr		638	21 372	248 MW

TABLE 10. HABITAT SIZING

	Volume/ Person (m³)	Area/ Person (m²)	Earth Mass/ Person (ton)	ET Mass/ Person (ton)	Lunar Mass/ Person (ton)	Total Mass/ Person (ton)
1500-person SMF Habitat with Galactic Radiation Shielding	85.3	28.7	2.94	0.83	57.0	60.77

Note: Does not include power supplies.

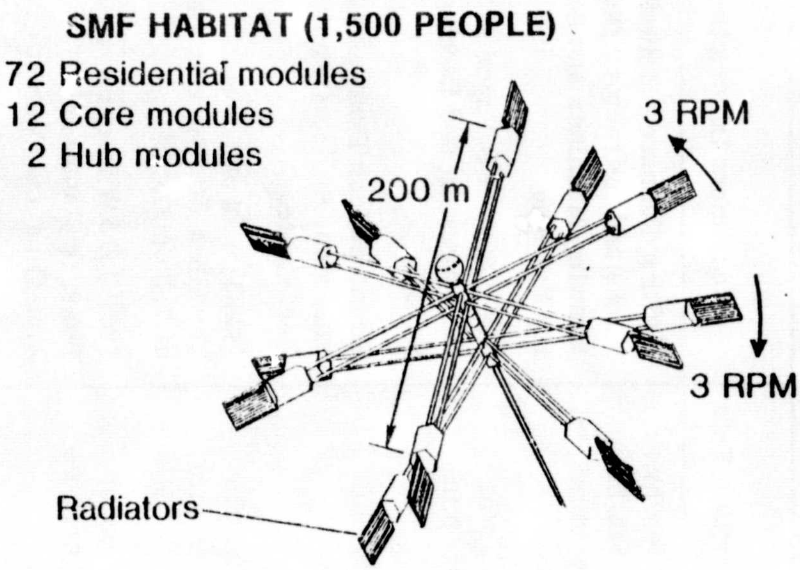


Figure 8. Habitat configuration.

III. SOCIAL AND ECONOMIC CONSEQUENCES OF SPACE INDUSTRIALIZATION

Early space industrialization is a billion dollar/year business now; in 30 years it could grow by 100 times that amount. Based on 2 years of thorough studies [2,3], a rather conservative estimate of the effect of space industrialization on the creation of new jobs (on Earth) and new revenues is shown in Figure 9.

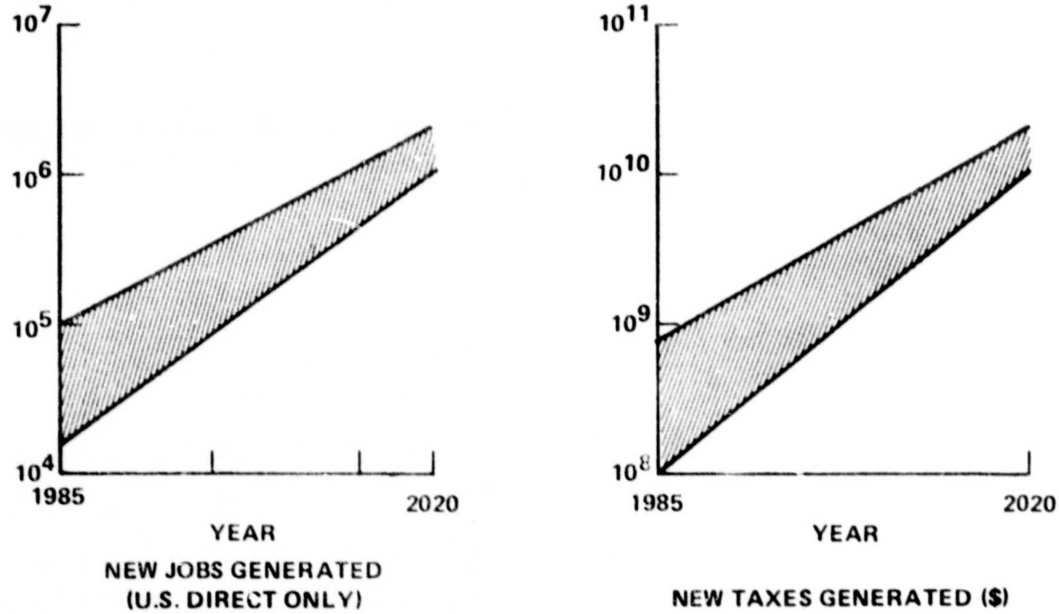


Figure 9. Socio-economic effects.

The true impact on new jobs is some two to four times the numbers shown. The optimum utilization of space material resources and in-space processing and construction of future service, product, and energy systems for terrestrial needs can effectively contribute to the solution of national and global social, economic, and environmental problems. In the words of Krafft Ehricke [3], the technological advances from space industrialization will give us a powerful capacity for the generation of global prosperity rather than managing scarcity.