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NONTERRESTRIAL MATERIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS

By Georg F. von Tiesenhausen
Advanced Systems Office

November 1978

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
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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<td>21</td>
</tr>
<tr>
<td>10.</td>
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TECHNICAL MEMORANDUM 78207

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 scenario 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. The Primary Product. 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

<table>
<thead>
<tr>
<th>Construction Materials (Earth Resources)</th>
<th>Satellite Power System (Baseline January 25, 1978)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (tons)</td>
</tr>
<tr>
<td>Glass (Fused Silica)</td>
<td>36 097</td>
</tr>
<tr>
<td>Silicon Solar Cells</td>
<td>14 775</td>
</tr>
<tr>
<td>Graphite Composite</td>
<td>12 533</td>
</tr>
<tr>
<td>Copper</td>
<td>10 774</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>7 747</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6 324</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1 132</td>
</tr>
<tr>
<td>Mercury</td>
<td>266</td>
</tr>
<tr>
<td>Silver</td>
<td>28</td>
</tr>
<tr>
<td>Various</td>
<td>7 874</td>
</tr>
<tr>
<td><strong>Total (per satellite)</strong></td>
<td><strong>97 550</strong></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Elements</th>
<th>Mare</th>
<th>Highlands</th>
<th>Basin Ejecta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identified as</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>39.7-42.3</td>
<td>44.6</td>
<td>42.2-43.8</td>
</tr>
<tr>
<td>Silicon</td>
<td>18.6-21.6</td>
<td>21.0</td>
<td>21.1-22.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5.5-8.2</td>
<td>12.2-14.4</td>
<td>9.2-10.9</td>
</tr>
<tr>
<td>Iron</td>
<td>12.0-15.4</td>
<td>4.0-5.7</td>
<td>6.7-10.4</td>
</tr>
<tr>
<td>Calcium</td>
<td>7.0-8.7</td>
<td>10.1-11.3</td>
<td>6.3-9.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>5.0-6.8</td>
<td>3.5-5.6</td>
<td>5.7-6.3</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.3-5.7</td>
<td>0.3</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.2-0.4</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.2-0.4</td>
<td>0.3-0.4</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.06-0.22</td>
<td>0.07-0.09</td>
<td>0.13-0.46</td>
</tr>
</tbody>
</table>

3. Material Requirements and Availability. Obviously, our goal is the maximum utilization of lunar material 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (ton)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>31,649</td>
<td>32.2</td>
</tr>
<tr>
<td>Natural Glass</td>
<td>20,093</td>
<td>20.4</td>
</tr>
<tr>
<td>Oxygen</td>
<td>19,223</td>
<td>19.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>11,925</td>
<td>12.1</td>
</tr>
<tr>
<td>Iron</td>
<td>5,300</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Total Lunar Material</strong></td>
<td>88,190</td>
<td>89.6</td>
</tr>
<tr>
<td>Metals</td>
<td>2,316</td>
<td>2.4</td>
</tr>
<tr>
<td>Graphite</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>composite</td>
<td>7,874</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Total Earth Material</strong></td>
<td>10,190</td>
<td>10.4</td>
</tr>
<tr>
<td><strong>Total SPS Mass (ton)</strong></td>
<td>98,380</td>
<td>100.0</td>
</tr>
</tbody>
</table>

4. **A Space Industrial Model.** 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

<table>
<thead>
<tr>
<th>Part Manufacture</th>
<th>Component Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foamed Glass</td>
<td>Klystron</td>
</tr>
<tr>
<td>Struts</td>
<td>dc-dc Conv</td>
</tr>
<tr>
<td>Waveguides</td>
<td>Struts</td>
</tr>
<tr>
<td>Solar Cells</td>
<td>Radiators</td>
</tr>
<tr>
<td>Si Cells</td>
<td>Heat Pipes</td>
</tr>
<tr>
<td>Cover Glass</td>
<td>Solar Cells</td>
</tr>
<tr>
<td>Al Contacts</td>
<td></td>
</tr>
<tr>
<td>Machining</td>
<td></td>
</tr>
<tr>
<td>Klystron Parts</td>
<td></td>
</tr>
<tr>
<td>Tubing</td>
<td></td>
</tr>
<tr>
<td>Heat Pipe</td>
<td></td>
</tr>
<tr>
<td>End Fggs</td>
<td></td>
</tr>
<tr>
<td>Insulate Wire</td>
<td></td>
</tr>
<tr>
<td>Klystron</td>
<td></td>
</tr>
<tr>
<td>dc-dc Conv</td>
<td></td>
</tr>
<tr>
<td>Plating</td>
<td></td>
</tr>
<tr>
<td>Klystron</td>
<td></td>
</tr>
</tbody>
</table>

**Subassembly Fabrication**

<table>
<thead>
<tr>
<th>Photovoltaic Blankets</th>
<th>Array Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide Modules</td>
<td>MPTS Structure</td>
</tr>
<tr>
<td>Power Busses</td>
<td>Klystron Module</td>
</tr>
<tr>
<td>MPTS Rotary Joints</td>
<td>dc-dc Conv Module</td>
</tr>
</tbody>
</table>

**Final Assembly**

10 GW SPS
### 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**

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

![Diagram of magnetic gas removal furnace](image)

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 m³ liquid metal)
Estimated Production Rate: 1200 kg steel/hr (.17 m³ liquid metal)
Estimated Mass of Crucible: 130 kg

Figure 5. Electric melting furnace.
Figure 6. Electric reduction furnace.

Note: Heating coils omitted for clarity.
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 km² 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>
<thead>
<tr>
<th>Stock Products</th>
<th>Equipment Description</th>
<th>Facility Estimate</th>
<th>Production Rate</th>
<th>Mass Robots</th>
<th>Power (kw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Sheet 1 mm x 1 m</td>
<td>Electron Beam Vapor Deposition, (7) 1200 kw Guns and Fixtures</td>
<td>3</td>
<td>8.783</td>
<td>34</td>
<td>1222</td>
</tr>
<tr>
<td>Aluminum Wire 1.13 mm Dia from Sh</td>
<td>Sitting Rolls, EB Welder, (8) Wire Drawing Machines</td>
<td>7</td>
<td>9.603</td>
<td>38</td>
<td>28</td>
</tr>
<tr>
<td>Steel Sheet 0.25 x 7 cm</td>
<td>Electron Beam Vapor Deposition, (6) 1200 kw Guns and Fixtures</td>
<td>12</td>
<td>1.222</td>
<td>12</td>
<td>750</td>
</tr>
<tr>
<td>Steel Sheet 1.02 x 16 cm</td>
<td>Electron Beam Vapor Deposition, (3) 400 kw Guns and Fixtures</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Aluminum Castings 0.8 and 3.54 kg/Part</td>
<td>(1) 50 kw Induction Furnace, (1) Permanent Mold Casting Machine</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Sendcastings 2.18 ton/Part</td>
<td>(1) 600 kw Induction Furnace, Sand Casting Equipment, Fiber Bushings and Collecting Drum, Spool</td>
<td>18</td>
<td>1.4 Part/day</td>
<td>1</td>
<td>20.5 MW</td>
</tr>
</tbody>
</table>

Total Production Rate: 2.51 ton/hr
### TABLE 7. PARTS MANUFACTURING FACILITIES

<table>
<thead>
<tr>
<th>Parts</th>
<th>Production Rate</th>
<th>Equipment Description</th>
<th>Indus Robots</th>
<th>Mass (ton)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum End Ftgts For Struts (Sht)</td>
<td>64.8 kg/hr</td>
<td>Blanking Presses, Roll Formers, EB Welders and Fixtures</td>
<td>2</td>
<td>8</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>184 Parts/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Housings for Klystron (Sht)</td>
<td>51.4 kg/hr</td>
<td>Blanking Presses, Roll Formers, EB Welders and Fixtures</td>
<td>2</td>
<td>28</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>49 Parts/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Klystron Cavity Copper Plate</td>
<td>11.3 kg/hr</td>
<td>Electroplating Tank, Electrolyte, and Handling Fixtures</td>
<td>1</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>25 Parts/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foamed Glass Tubes and Waveguides</td>
<td>4.82 ton/hr</td>
<td>Ball Mills, Conveyors, Kilns, Cutters, Molds, and Tooling</td>
<td>70</td>
<td>845</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>1.78 km/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Deposition on MPTS Waveguides</td>
<td>24 kg/hr</td>
<td>Electron Beam Vapor Deposition (6) 160 kW Guns and Fixtures</td>
<td></td>
<td>5</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>138 m/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Heat Pipes (Sht Material)</td>
<td>3.1 kg/Part</td>
<td>Roll Formers, EB Welders, Press, Tube Benders and Tooling</td>
<td>5</td>
<td>62</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>146 Parts/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass Fiber Insulation on Elect Wire</td>
<td>94.2 kg/hr</td>
<td>Glass Filament Coater, (334) Braiding Machines</td>
<td>15</td>
<td>355</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>12.7 km/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.52 ton/hr</td>
<td></td>
<td>95</td>
<td>1308</td>
<td>3.9 MW</td>
</tr>
<tr>
<td>Component Assembly</td>
<td>Production Rate</td>
<td>Equipment Description</td>
<td>Indust Robots</td>
<td>Mass (ton)</td>
<td>Power (kW)</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------</td>
<td>-----------------------</td>
<td>---------------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>dc–dc Converter</td>
<td>1.4 Assy/Day</td>
<td>Fixture with Storage Bins, Wire Spools, Turntable and Locating Tools</td>
<td>2</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4.45 ton/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klystron Assy</td>
<td>25 Assy/hr</td>
<td>Fixture with Turntable, Wire Winding, EB Welders and Tooling</td>
<td>12</td>
<td>30</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>32 kg/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dc–dc Converter</td>
<td>1.4 Assy/Day</td>
<td>Alum Cutting, Forming Press, Roll Seam Welder and EB Welder</td>
<td>2</td>
<td>72</td>
<td>24</td>
</tr>
<tr>
<td>Radiator Assy</td>
<td>300 m²/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klystron</td>
<td>25 Assy/hr</td>
<td>Alum Cutting, Brazing Furnace, Fixtures and Tooling</td>
<td>8</td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>Radiator Assy</td>
<td>2.6 m²/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural</td>
<td>92 Assy/hr</td>
<td>Furnaces, Swaging Machines, Crimping Machines and Fixtures</td>
<td>6</td>
<td>32</td>
<td>115</td>
</tr>
<tr>
<td>Member Assy</td>
<td>$f = 6.5–144$ m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPTS Waveguide</td>
<td>1.74 Assy/hr</td>
<td>Lasar Welding Equip, Positioning Fixtures</td>
<td>2</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Subarray Assy</td>
<td>114 m²/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>144 Assy/hr</td>
<td></td>
<td>32</td>
<td>185</td>
<td>0.41 MW</td>
</tr>
</tbody>
</table>
Figure 7. Solar cell factory (side view).

is a $350 \times 70 \times 10$ 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

<table>
<thead>
<tr>
<th>Component Assembly</th>
<th>Production Rate</th>
<th>Equipment Description</th>
<th>Induct. Robots</th>
<th>Mass (ton)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Glass Solar Cell Covers and Substrate</td>
<td>2.72 ton/hr</td>
<td>Melting Furnace, Molten Glass Tanks and Refractory Dies, Drawing Machines and Annealing Furnace</td>
<td>15</td>
<td>76</td>
<td>18 170</td>
</tr>
<tr>
<td>75 μm x 1.17 m</td>
<td>1.81 ton/hr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 μm x 1.17 m</td>
<td>181 m/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Deposition on Glass Substrate</td>
<td>87.5 kg/hr</td>
<td>(4) 250 kW EB Vapor Dep Guns Plus Masking and Etching Equip</td>
<td>—</td>
<td>4</td>
<td>1 200</td>
</tr>
<tr>
<td></td>
<td>181 m/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon Refining to PPB Level</td>
<td>2.2 ton/hr</td>
<td>Silane/Silicon Process Plant Reactors, Stills, Pumps, Tanks, etc.</td>
<td>—</td>
<td>5 900</td>
<td>15 360</td>
</tr>
<tr>
<td>Silicon Solar Cells, EFG Process, 50 μm x 7.7 cm</td>
<td>1.86 ton/hr</td>
<td>(4283) Ribbon Growing Machines, 10 Ribbons each at 7.5 cm/min</td>
<td>203</td>
<td>8 736</td>
<td>135 000</td>
</tr>
<tr>
<td></td>
<td>3181 m/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cut Ribbon, Dope Apply Contacts and Anneal</td>
<td>1.86 ton/hr</td>
<td>(83) 550 kW Integrated Ion Beam Implanters, EB Annealing and Contact Coating</td>
<td>166</td>
<td>2 560</td>
<td>46 100</td>
</tr>
<tr>
<td></td>
<td>695 Parts/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Cell Module Assembly 1.29 m²</td>
<td>164 Assy/min</td>
<td>Automated Module Assembly Mach, Electrostatic Bonding Equip</td>
<td>254</td>
<td>4 100</td>
<td>28 170</td>
</tr>
<tr>
<td></td>
<td>254 Parts/Assy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.5 ton/hr</td>
<td></td>
<td>638</td>
<td>21 372</td>
<td>248 MW</td>
</tr>
</tbody>
</table>
TABLE 10. HABITAT SIZING

<table>
<thead>
<tr>
<th></th>
<th>Volume/Person (m³)</th>
<th>Area/Person (m²)</th>
<th>Earth Mass/Person (ton)</th>
<th>ET Mass/Person (ton)</th>
<th>Lunar Mass/Person (ton)</th>
<th>Total Mass/Person (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500-person SMF Habitat with Galactic Radiation Shielding</td>
<td>85.3</td>
<td>28.7</td>
<td>2.94</td>
<td>0.83</td>
<td>57.0</td>
<td>60.77</td>
</tr>
</tbody>
</table>

Note: Does not include power supplies.

SMF HABITAT (1,500 PEOPLE)

- 72 Residential modules
- 12 Core modules
- 2 Hub modules

![Habitat configuration](image)

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.
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.

Figure 9. Socio-economic effects.