NASA CONTRACTOR
REPORT

NASA CR-161293

EXTRATERRESTRIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS, Volume III: Executive Summary

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September 1979

Final Report

(NASA-CR-161293-Vol-3) EXTRATERRESTRIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS. VOLUME 3: EXECUTIVE SUMMARY Final Report (Massachusetts Inst. of Tech.) 51 p HC A04/MF A01 CSCL 22A G3/12
N79-33229
Unclas
35956

Prepared for

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1. INTRODUCTION

One of the promising options for the manufacture of large space systems is the use of lunar materials for construction, probably in situ, of the required structure and as many of the operating components as can be made from the available materials.

The present study considers the design of the manufacturing facility required for such a scenario. The study was initiated in February of 1978 and terminated on August 31, 1979. Work was performed by the Space Systems Laboratory of the Department of Aeronautics and Astronautics, M.I.T.. The NASA Marshall Space Flight Center Contracting Officers Representative was Georg F. von Tiesenhausen. The MIT Principal Investigator was Professor R. H. Miller, and the Study Manager was David B. S. Smith. Table 1.1 lists the MIT study participants.

The final study objectives, arrived at after discussions with MSFC and taking into account the findings of complementary studies, are listed in Table 1.2.

TABLE 1.1: STUDY PARTICIPANTS

Participating Faculty	
Rene H. Miller	Principal Investigator
James W. Mar	
Leon Trilling	
John F. Elliott	
P. Guenther Werner	
Research Staff	
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Eric D. Thiel	

TABLE 1.2: UPDATED STUDY OBJECTIVES

1)	Define space program scenarios for production of large space structures (including SPS's) from lunar materials, and define in detail the large space structure components to be produced.
2)	Define the SMF refining, alloying, and other processes required to convert the refined lunar material inputs into feedstock for the required manufacturing processes.
3)	Define the SMF manufacturing, assembly, and other processes required to convert the feedstock into components of large space structures.
4)	Define types and quantities of Earth materials needed in the production of the large space structure components.
5)	Develop conceptual layouts of all major SMF equipment and facilities.
6)	Design a "reference SMF", including definition of the SMF operations, equipment, and facilities required to implement the processes in (2) and (3) above, including support equipment, storage facilities, personnel requirements, and habitation facilities.
7)	Present a preliminary cost analysis and assessment which includes development, acquisition of all SMF elements, initial and operating cost, maintenance and logistics cost, cost of terrestrial materials, and transportation cost for each major element. Define uncertainties and sensitivities for each element.
8)	Present all study numerical results in tabulated and graphical form that will permit obtaining values for any intermediate parameters other than those used in the study.

In order to place this study in context, the following comparative summary may be helpful.

1.1: THE SPACE MANUFACTURING FACILITY CONCEPT

Figure 1.1 presents the major elements in an earth-based large space structure construction scenario. Components of large space structures, after manufacture on Earth, are launched to an Earth Orbit Terminal. There they are repackaged (possibly including subassembly of large space structure components) and ferried to the Geosynchronous Orbit Complex for final assembly and checkout. Studies have shown that the major costs of such a scenario is the transportation from the ground to low-earth orbit (LEO) of 1) the structure components and 2) the fuel required for the transfer of those components to geosynchronous orbit (GSO).

An alternative scenario, aimed at reducing these costs, is presented in Fig. 1.2 (adapted from Fig. 1 of the SOW). In this system, most of the materials required for the large space structures would be mined and beneficiated on the Moon, at a Lunar Resource Complex. These lunar materials would then be launched into space to a cargo Transition Point, repackaged, and ferried to a Space Manufacturing Facility. This SMF would process, manufacture, and assemble the lunar materials into components of large space structures. These components would then be shipped to the Geosynchronous Orbit Complex and assembled (together with some terrestrial components) into the de-

GB - Ground Base
EOT - Earth Orbit Terminal
GSOC- Geosynchronous Orbit Terminal

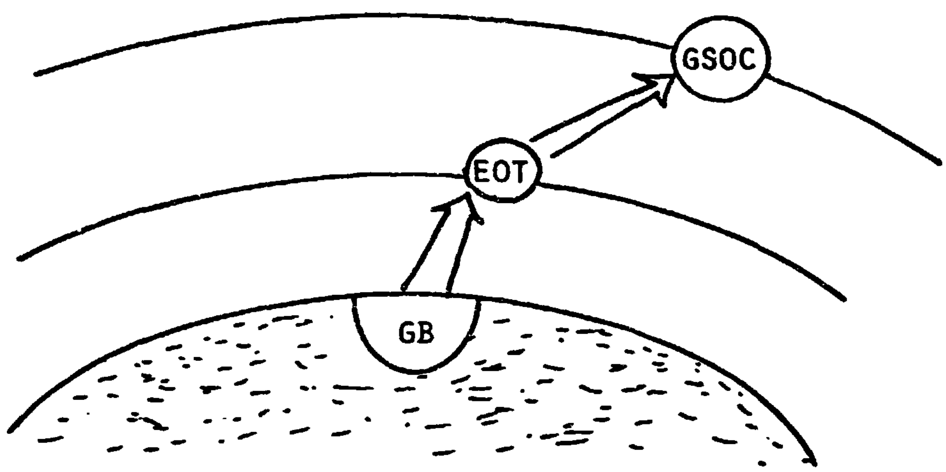


FIGURE 1.1: MAJOR ELEMENTS OF EARTH-BASED CONSTRUCTION SCENARIO

sired large space structures.

The potential advantage of this scenario over its earth-based counterpart is that the bulk of the material required comes from the Moon. This material therefore has a far smaller gravitational field to overcome than material launched from Earth: the energy required for lunar escape at the lunar surface is 4.5% of the energy requirement for earth escape at the Earth's surface. In addition, the lack of lunar atmosphere makes possible the use of catapults (such as the electromagnetic mass-driver) to launch payloads without use of propellant.

The lunar surf e material can also be refined to yield propellants for rockets. These propellants can fuel launch systems from the lunar surface (an alternative to catapults),

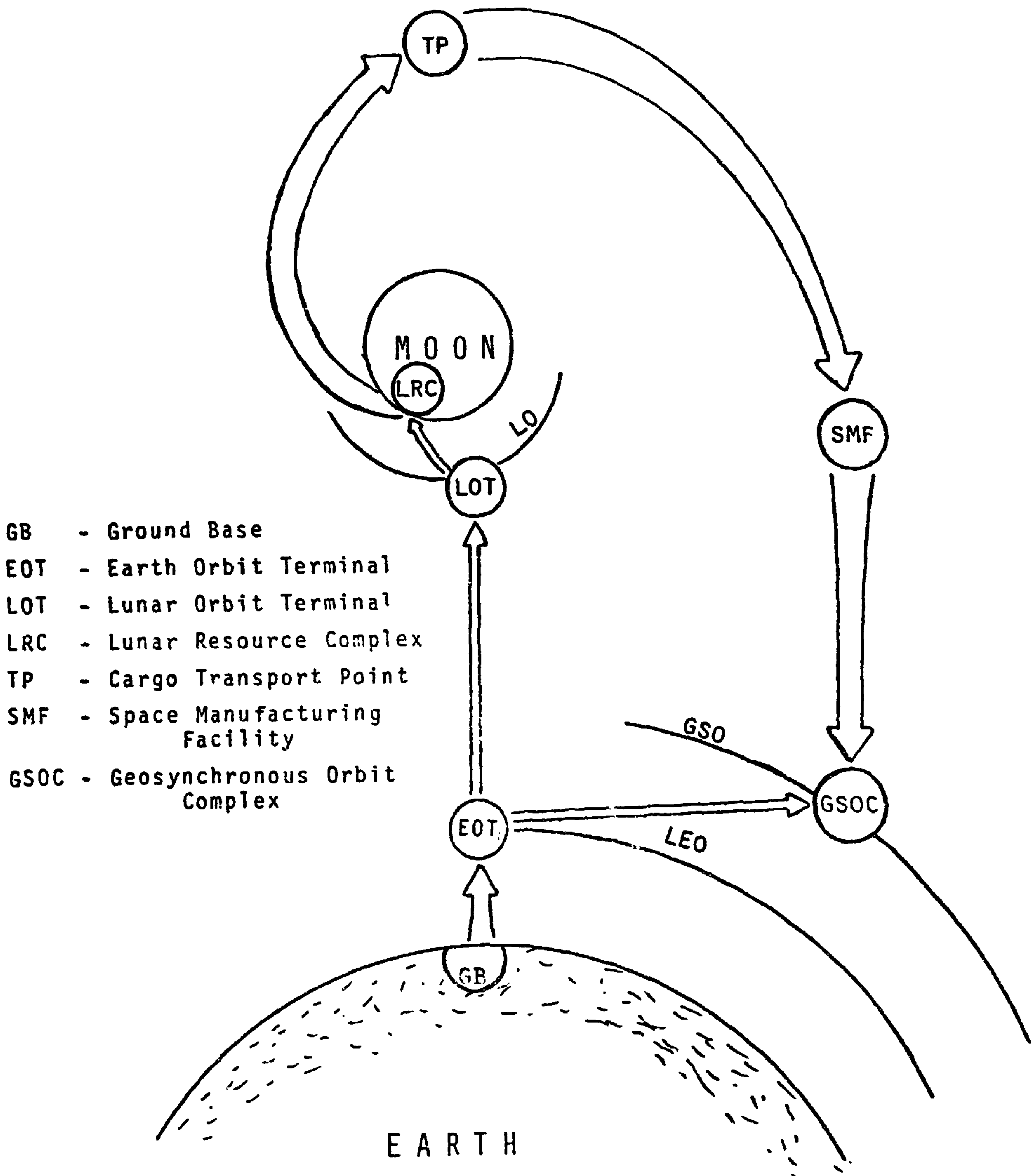


FIGURE 1.2: MAJOR ELEMENTS OF LUNAR MATERIAL SCENARIO

and orbital transfer vehicles between various points in the system, including the transportation legs between LEO and lunar orbit (LO) and between LEO and GSO. This use of lunar-derived fuel can therefore reduce transportation costs even for the required terrestrial inputs.

However, the lunar-material scenario requires a number of facilities (e.g. lunar base, cargo transition point, SMF) and devices (e.g. lunar landers, TP-SMF interorbital transports) not needed by the earth-based construction scenario. Also, personnel must travel farther from Earth in the lunar material system, adding to their transportation costs. These financial advantages and disadvantages must be traded off to determine the most cost-effective approach to large-scale space industrialization; hence this study, which investigates one of the key cost elements in the lunar-material scenario: the Space Manufacturing Facility.

Figure 1.3 presents a more specific schematic of the SMF concept, showing major inputs and outputs (these are treated in detail in Volume I of the main report). As described earlier, the bulk of the input raw materials comes from the Moon; other raw materials come from Earth. The required personnel and logistics supplies travel between Earth and the SMF.

The most likely source of power for the SMF is solar energy; a less likely alternative is nuclear energy. Thus the cost of energy for the SMF operations resembles the cost pattern for SPS's: a large initial outlay for the solar array,

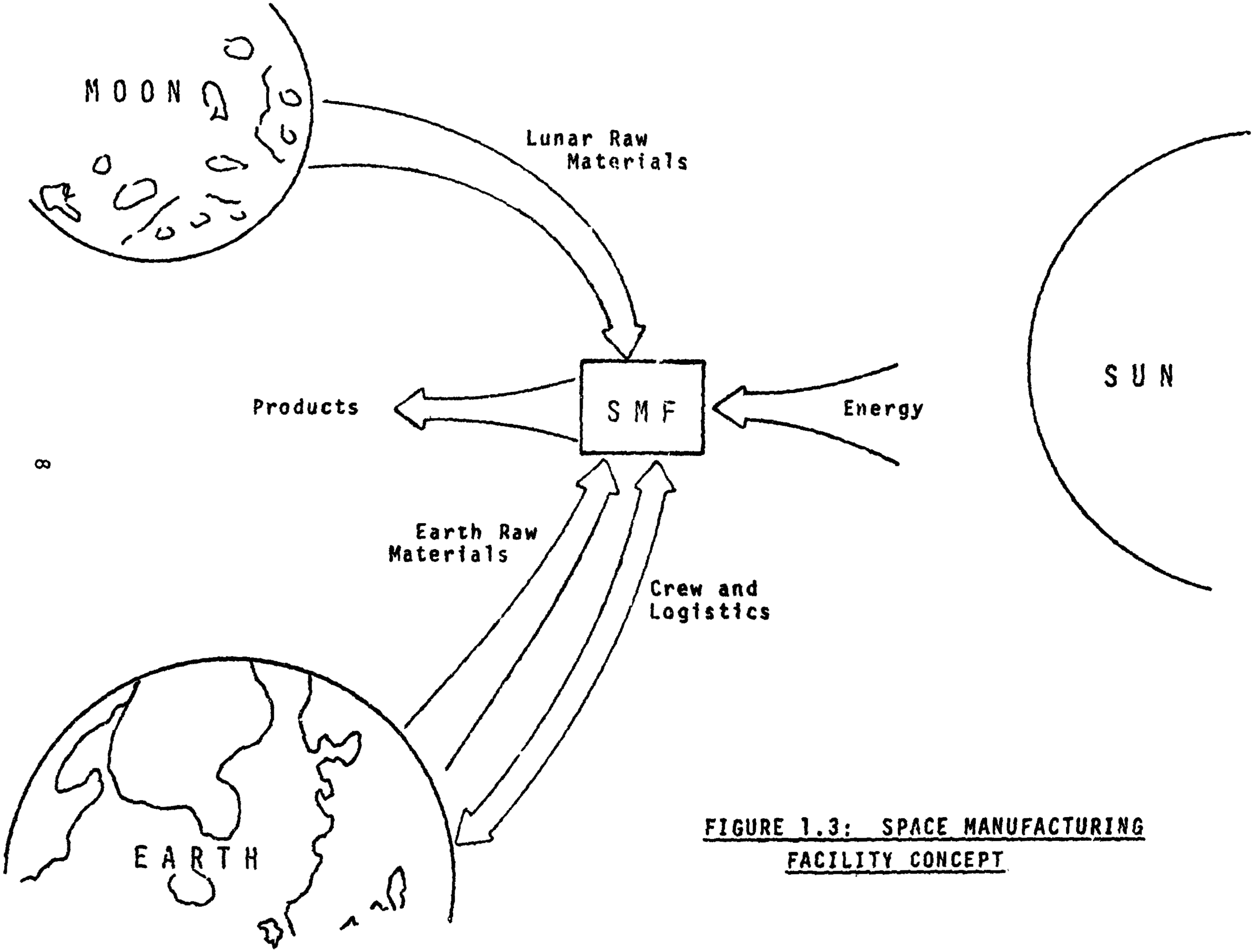


FIGURE 1.3: SPACE MANUFACTURING FACILITY CONCEPT

followed by a very low operating cost (due to the absence of need for fuel and the low maintenance requirement). Th[illegible] for long operating times, the cost of energy in SMF operations can be substantially lower than the cost of energy in earth manufacture; this is another potential cost reduction in the lunar material scenario over the earth-based construction scenario.

The location of the SMF was unspecified in the SOW, and remained open during the contract. A number of locations are possible (e.g. lunar orbit, the Lagrange points, resonant earth-moon orbits, GSO), but the determination of the optimum location depends on tradeoffs involving transportation systems, personnel stay time, and availability of materials and energy, which are beyond the scope of this contract. In any case, location had little effect on the design of the SMF production equipment; the areas affected are pointed out and discussed throughout the report.

2. SMF INPUTS AND OUTPUTS

The major assumptions on which this study is based are listed in Table 2.1.

The types and quantities of materials in the SMF outputs are listed in Table 2.2.

The inputs to the SMF are listed in Table 2.3.

TABLE 2.1: GENERAL ASSUMPTIONS

SMF Products:

- SMF output includes SPS components.
- SPS's produced are the JSC-Boeing baseline design, modified to use lunar materials.
- Beyond the lunar-material substitutions, there are no major redesigns of the SPS.

SMF Lunar Inputs:

- Possible inputs are silicon, silica, aluminum, iron, calcium, magnesium, titanium, oxygen, and slag.
- Inputs arrive at the SMF in refined condition.
- Inputs arrive at the SMF in specialized shapes, e.g. rods.

Technology Level in SMF Design: the year 1990.

TABLE 2.2 TYPES AND QUANTITIES OF MATERIALS IN SMF OUTPUTS

(for 1 10-GW SPS withou growth margin)

Lunar Inputs	Masses (in tons)
Al (total mass, 3.8×10^4)	
In solar cell arrays	1.3×10^3
In structural member ribbon	2.3×10^4
In klystron assemblies	1.0×10^4
In waveguides	1.0×10^2
In busbar strips	2.8×10^3
In DC-DC converters	3.0×10^2
In electrical wires and cables	3.8×10^2
In DC-DC converter radiators	5.6×10^2
In end joints	8
In joint clusters	8
SiO_2	
In solar cells	3.0×10^4
Si (total mass, 1.3×10^4)	
In solar ce arrays	1.3×10^4
In structural member ribbon	92
In DC-DC converters	1.0×10^2
In end joints	negligible
In joint clusters	negligible

(continued)

TABLE 2.2 Continued

Lunar Inputs	Masses (in tons)
Natural Lunar Glass	
In waveguides	1.1×10^4
Fe (total mass, 1.6×10^3)	
In klystron assemblies	7.3×10^2
In DC-DC converters	8.5×10^2
S-Glass (total mass, 1.4×10^3)	
In klystron assemblies	9.0×10^2
In DC-DC converters	1.9×10^2
In electrical wires and cables	2.9×10^2
Mg (total mass, 1.6×10^2)	
In structural member ribbon	1.6×10^2
In end joints	negligible
In joint clusters	negligible
Earth Inputs	
Klystron Parts	
In klystron assemblies	3.2×10^3
DC-DC Converter Parts	
In DC-DC converters	6.3×10^2
Kapton Tape	
In solar cell arrays	3.9×10^2
Foaming Agents	
In waveguides	1.5×10^2
Dopants	
In solar cell arrays	negligible
Total Mass	1.0×10^5 Tons

TABLE 2.3 TYPES AND QUANTITIES OF MATERIAL INPUTS FOR THE REFERENCE SMF

(for 1 10-GW SPS without growth margin)

Lunar Inputs	Masses (in tons)
Al (total mass, 4.4×10^4)	
In solar cell arrays	3.1×10^3 (58% waste)
In structural member ribbon	2.5×10^4 (10% waste)
In klystron assemblies	1.1×10^4 (10% waste)
In waveguides	1.7×10^2 (39% waste)
In busbar strips	3.1×10^3 (10% waste)
In DC-DC Converters	3.3×10^2 (10% waste)
In electrical wires and cables	4.2×10^2 (10% waste)
In DC-DC converter radiators	6.2×10^2 (10% waste)
In end joints	9 (10% waste)
In joint clusters	9 (10% waste)
SiO_2	
In solar cells	5.0×10^4 (40% waste)
Si (total mass, 2.7×10^4)	
In solar cell arrays	2.7×10^4 (52% waste)
In structural member ribbon	1.0×10^2 (10% waste)
In DC-DC converters	1.1×10^2 (10% waste)
In end joints	negligible
In joint clusters	negligible
Natural Lunar Glass	
In waveguides	1.8×10^4 (37% waste)
Fe (total mass, 1.7×10^3)	
In klystron assemblies	8.0×10^2 (10% waste)
In DC-DC converters	9.4×10^2 (10% waste)
S-Glass (total mass, 1.5×10^3)	
In klystron assemblies	9.9×10^2 (10% waste)
In DC-DC converters	2.1×10^2 (10% waste)
In electrical wires and cables	3.2×10^2 (10% waste)
Mg (total mass, 1.8×10^2)	
In structural member ribbon	1.8×10^2 (10% waste)
In end joints	negligible
In joint clusters	negligible

(continued)

TABLE 2.3 Continued

Earth Inputs	Masses (in tons)
Klystron Parts	
In klystron assemblies	3.5×10^3 (10% waste)
DC-DC Converter Parts	
In DC-DC converters	7.0×10^2 (10% waste)
Kapton Tape	
In solar cell arrays	4.2×10^2 (10% waste)
Foaming Agents	
In waveguides	2.4×10^2 (37% waste)
Dopants	
In solar cell arrays	negligible
Total Mass	1.5×10^5 Tons

3. DESIGN OF THE SMF

The complete SMF concept developed in this study included some sixty subsystems, each of which had many components. For the purposes of this summary, and for illustrative purposes, only two of the subsystems will be discussed. These are the direct vaporization process and the alloying furnace.

The overall layout of the SMF is shown in Fig.3.1. It consists of five principal sections. The input/output station receives the raw materials from the Moon, and the raw materials, logistics support, and personnel from Earth. It also dispatches the finished products to their destinations. The production work is done in a set of factories which will be discussed in more detail later. A habitation section houses the onsite personnel, and a powerplant feeds electrical power to all sections of the SMF. The production control section manages the operations of the entire facility; this section is a general function rather than a seperate facility.

In order to provide a basis for the design and costing of a Space Manufacturing Facility, it was decided to use the manufacture of solar power satellites as a case example. The so-called 'reference SMF' is therefore designed and sized to produce one 10-GW solar power satellite (SPS) per year. The SPS design used was the NASA Johnson Space Center/ Boeing Aerospace baseline design with lunar-material substitutions for the Earth material components wherever possible. The

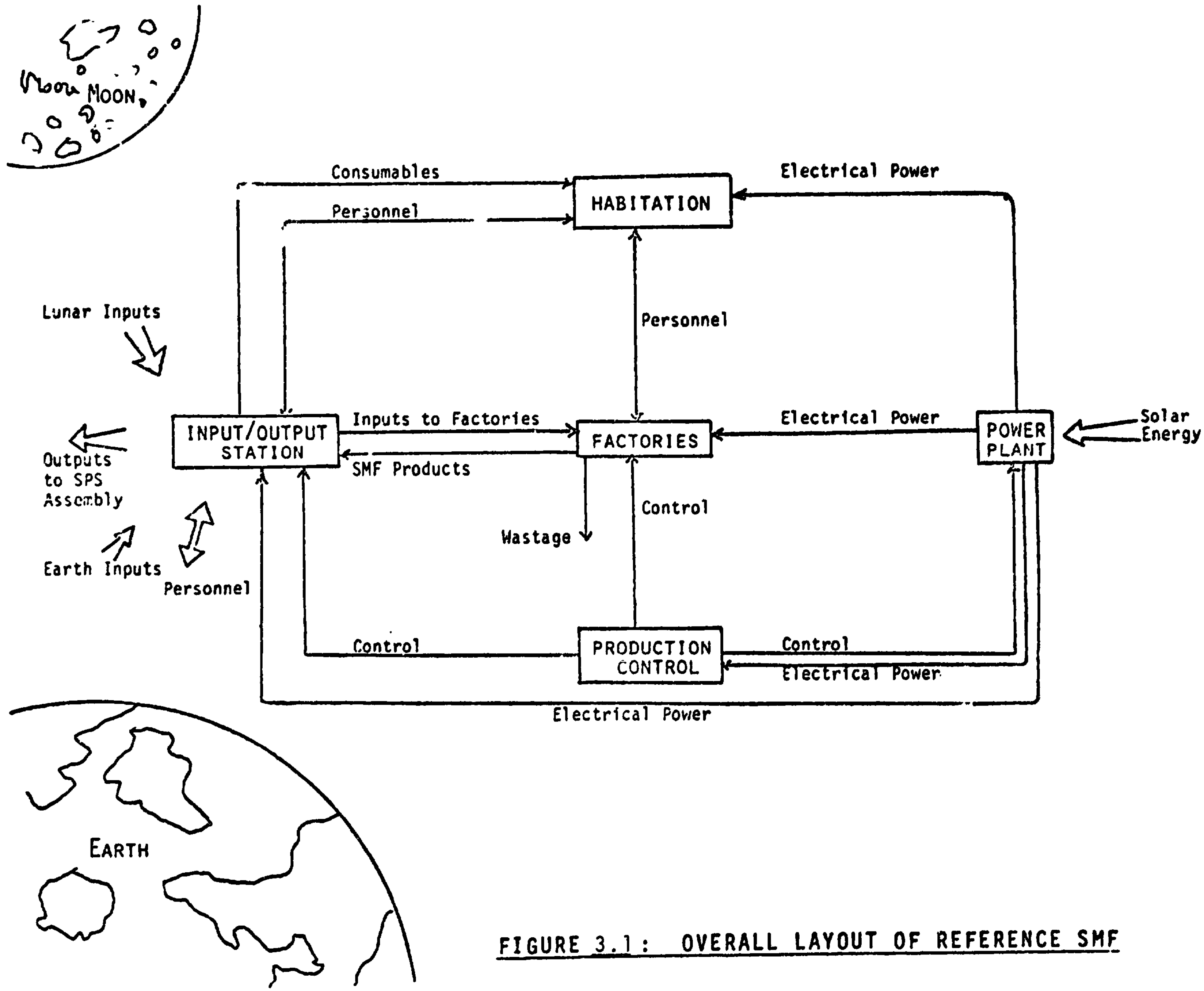


FIGURE 3.1: OVERALL LAYOUT OF REFERENCE SMF

output of the reference SMF is therefore roughly 100,000 tons per year, of which 4400 tons are materials and components brought from Earth. An additional 3400 tons of earth components are added to the SPS during assembly. Thus the lunar-material percentage of the completed SPS is roughly 90%.

The output products of the SMF of Table 2.2 are summarized in Table 3.1 Although the SMF products in the list are components of solar power satellites, many could be components of other structures as well. For example, solar cells, structural members, end joints, joint clusters, radiators, and electrical wires and cables could be used in a wide variety of satellites. Other products (i.e., DC-DC converters, klystron assemblies) are representative of some of the sophisticated components which might be used in space equipment. Therefore the reference SMF, though keyed to the production of the SPS, is a useful example of space manufacturing facilities in general.

TABLE 3.1: SMF OUTPUTS

Solar Cells
Structural Members
Klystron Assemblies
Waveguides
Busbar Strips
DC-DC Converters
DC-DC Converter Radiators
Electrical Wires and Cables
End Joints
Joint Clusters

Table 3.2 lists the SMF input materials. From the Moon come aluminum, iron, silicon, and magnesium in metallurgical grade-purity, optical quality silica glass, fiber-quality S-glass, natural lunar glass, and propellant-grade oxygen. From the Earth come klystron, and DC-DC converter components which are too difficult to manufacture in space, kapton and dopants for the solar cells, and glass foaming agents (e.g., sulfates, carbon, water) which are unavailable on the Moon.

TABLE 3.2: SMF INPUTS

FROM THE MOON	FROM THE EARTH
Aluminum	Klystron Parts
Iron	DC-DC Converter Parts
Silicon	Kapton Tape
Silica	Dopants
S-glass	Glass Foaming Agents
Natural Lunar Glass	
Magnesium	
Oxygen	

A rough sketch of the reference SMF is shown in Fig. 3.2. The physical layout of the factories is planar, i.e., the thickness of the equipment (into the paper in the figure) is on the order of 10-20 meters. At the right is the solar array, which is perpendicular to the plane of the factories, and which shields the SMF from direct sunlight.

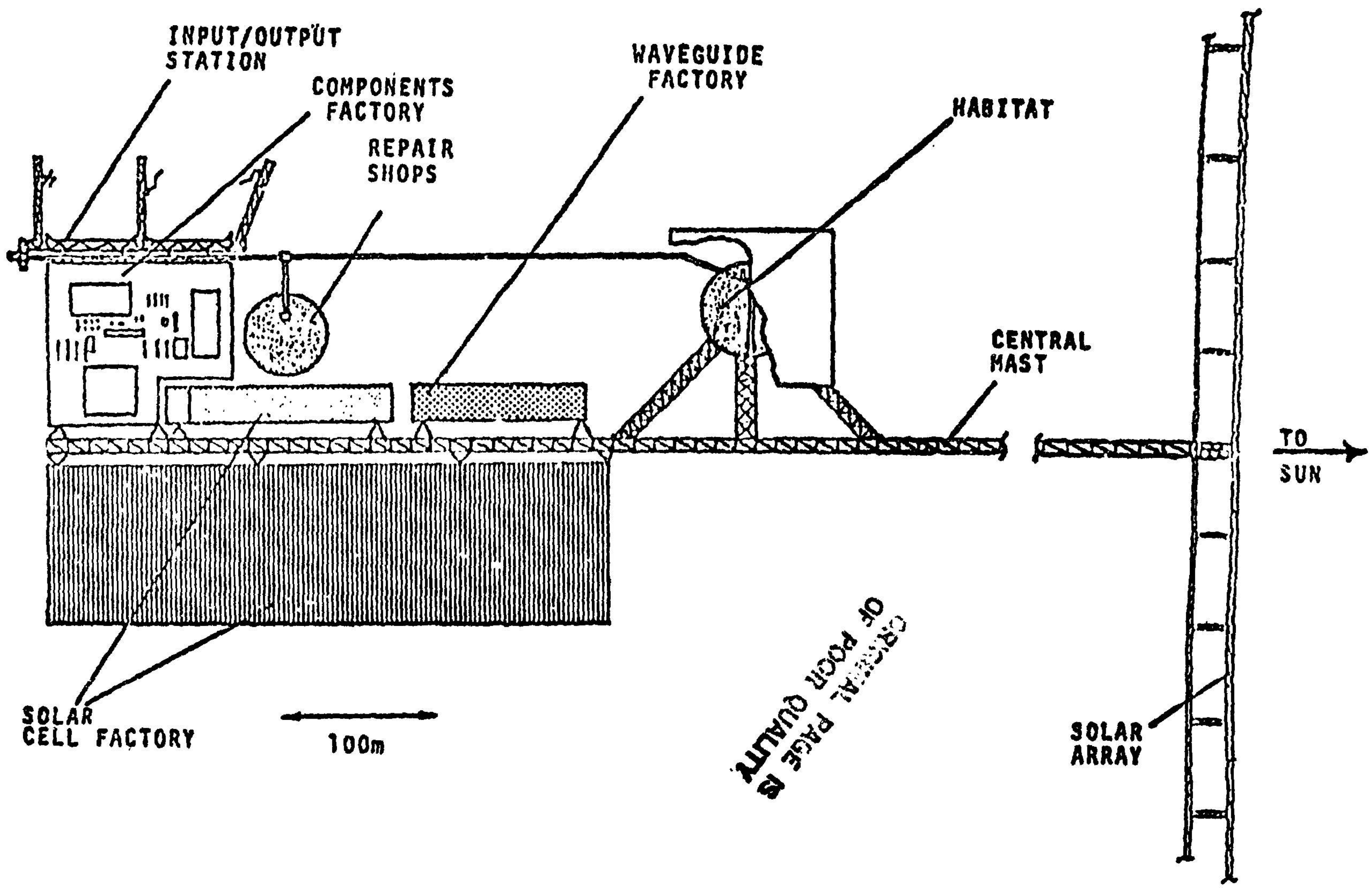


FIGURE 3.2 : "TOP" VIEW OF REFERENCE SMF

From the solar array extends a central trusswork mast. The habitation section and the factories are attached to this central mast via flexible joints; damping systems in the joints prevent the spread of vibrations, particularly into the solar-cell factory. The solar cell factory appears large because the chosen production sequence uses deposition processes, which require large areas. The individual production lines in the solar cell factory run from bottom to top in the figure.

The habitat is a cylindrical cluster of Shuttle external tanks, shown partially hidden by one of its two radiators. (Radiators for the factories are omitted for clarity.) The habitat is radiation-shielded with lunar materials. The input/output station is sized to hold cargo containers carrying four months of SMF inputs and outputs, and personnel modules for crew-rotation.

The 'factories' box in Fig. 3.1 is expanded into a layout of major operations in Fig. 3.3. The reference SMF can be conceptually separated into three major factories: the solar cell factory, the waveguide factory, and the remaining operations grouped into the 'components' factory. This separation is possible because each factory has its own set of material inputs and process equipment, different from those of the other factories (e.g., the materials and equipment used in solar cell production are unlikely candidates for the production of other SMF outputs). Within the components factory, however, materials and equipment are shared between a variety of products, to minimize equipment requirements.

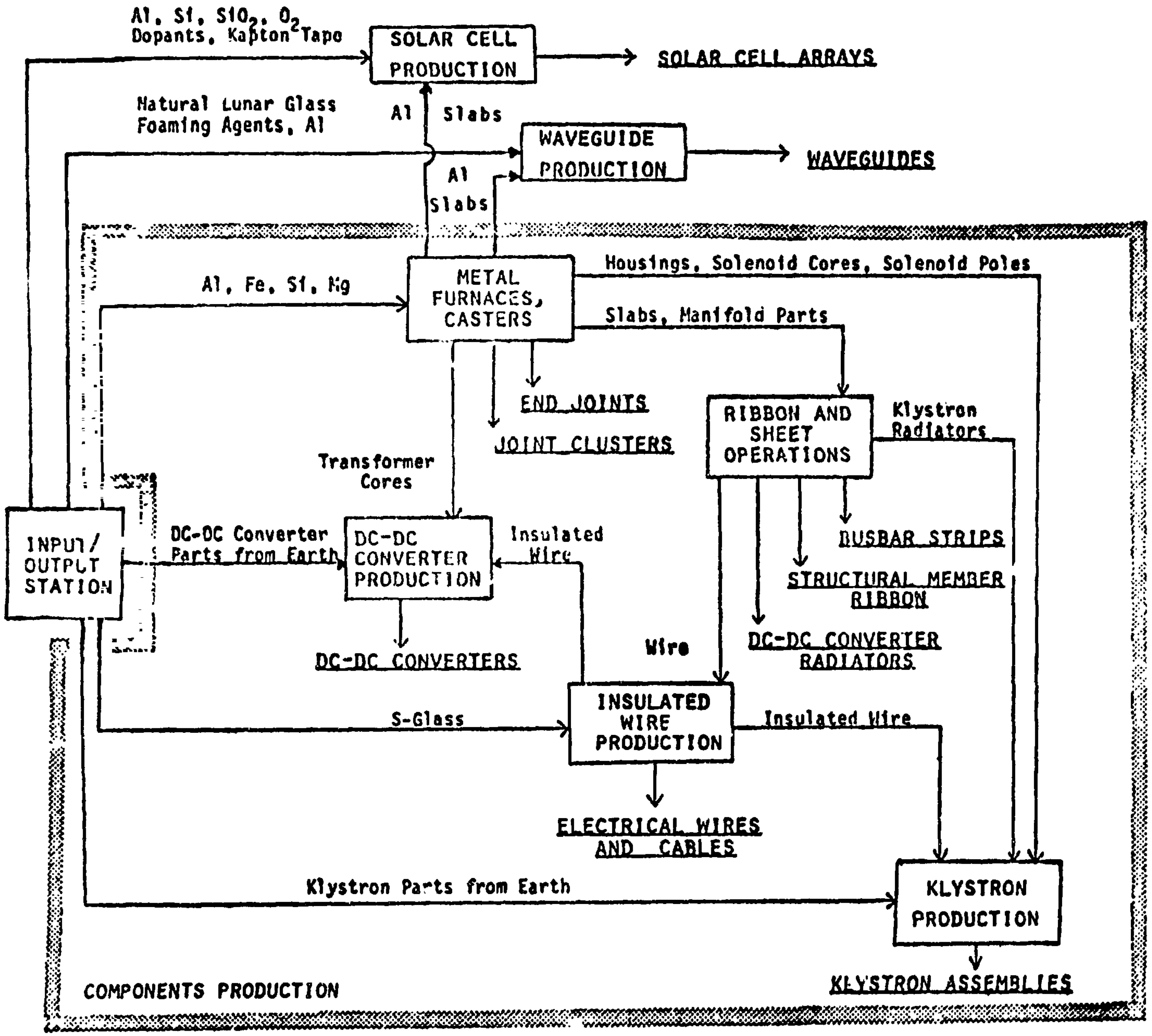


FIGURE 3.3 : MAJOR OPERATIONS LAYOUT OF REFERENCE SMF

As an example of the procedure used for preliminary design of SMF equipment, the 'solar cell production' box in Fig. 3.3 was first separated into the basic processes listed in Table 3.3. Each of these basic processes was then studied to identify candidate processes potentially suitable for the SMF. For example, candidate processes for the production of silicon wafer are listed in Table 3.4, with advantages and disadvantages. Processes range from the traditional Czochralski ingot growth to the highly experimental direct vaporization.

The production of solar cells at a rate roughly two to three orders of magnitude higher than current earth production is the largest technical challenge in the design of the space manufacturing facility. The candidate processes for solar cell manufacture were therefore studied in depth, with particular emphasis on development of processes which would take advantage of environmental factors peculiar to space. For the production of silicon wafer,

TABLE 3.3: BASIC PROCESSES IN SILICON SOLAR CELL PRODUCTION

Purification of metallurgical grade silicon to semiconductor grade silicon
Production of doped silicon wafer
Application of electrical contacts
Production of substrate and optical cover
Cell interconnection and array buildup

the candidate chosen for the reference SMF was direct vaporization (DV),

TABLE 3.4: SILICON WAFER PRODUCTION
ALTERNATIVE PROCESSES

Crystal Growth Processes	Advantages	Disadvantages
Floating Substrate		o Requires gravity or equivalent o Not likely to yield sufficient cell efficiency
Ceramic Plate Dipping		o Requires gravity or equivalent o Not likely to yield sufficient cell efficiency
Czochralski Ingot Growth	o High quality crystal o Established technology	o Requires gravity or equivalent o High waste of material o Requires many sawing machines
Dendritic Web	o Low waste of material o High quality crystal	o Requires gravity or equivalent
Zone Refining and Cutting	o High quality crystal o Existing Tech nology	o High wastage of material o Slow process / many machines
Edge-defined Film-fed Growth	o Existing Technology o Low waste of material o High quality crystal	o Many machines required o Needs pressurized containers
Chemical Vapor Deposition and Recrystallization	o Compatible with some refining processes o Low material waste o May allow deposition of wafer directly onto cell substrate and rear contact	o Requires Earth inputs o Requires pressure vessels and recirculation equipment o Requires additional processes to achieve sufficient crystal quality

(continued)

TABLE 3.4 Continued

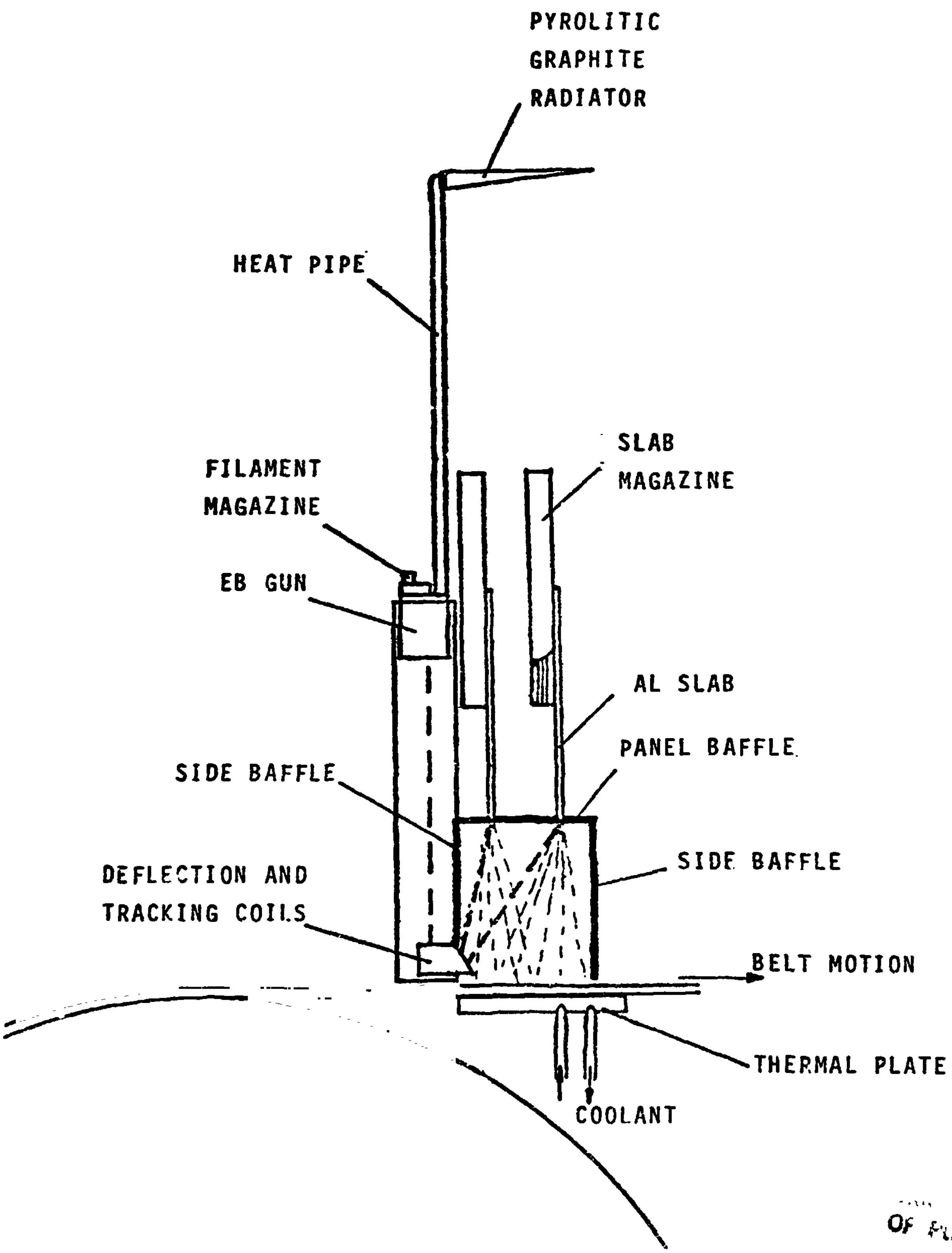
Crystal Growth Processes	Advantages	Disadvantages
*Direct Vaporization and Recrystallization	o Conceptually simple o Does not require pressure vessels o Wafer can be directly deposited onto cell substrate and rear contact o Well adapted to space environment	o Little solid data available o Some waste of material o Requires many material sources o Requires additional processes to achieve sufficient crystal quality
Doping Processes		
Diffusion	o Established technology	o Usually requires liquid application o Difficult to control dopants
*Ion Implantation	o Existing technology o Easily automated on a large scale o Good control over dopants	o Induces defects in crystal structure o Requires closed current loop
Co-deposition	o Can reduce time and complexity of solar cell production	o May not be compatible with all silicon wafer production processes o Only applicable to p-dopant in several wafer production processes

*Chosen for reference SMF

because of its high level of adaptation to the space environment: its principal requirements are vacuum and energy, both cheaply available at the SMF. It should be noted that those same requirements tend to make DV unattractive for large-scale use on Earth; space offers a design environment which is not only physically but economically different from Earth's.

Because the DV process is highly experimental and the results in many cases proprietary, an experimental program was conducted using existing vacuum and EB gun facilities at MIT to determine the factors controlling the quality of vapor deposition of silicon as a function of the controlling parameters, such as substrate temperature and rate. The results, discussed in the body of the report, were encouraging.

After the selection of reference SMF processes came the preliminary design of production equipment. Following the example, Fig. 3.4 shows a DV device to deposit solar-cell rear contacts (DV was selected for several solar-cell production steps). The device consists of a moving belt upon which the material is deposited, a slab which serves as a material source, an electron beam gun to vaporize material from the slab, and a set of baffles to contain the vaporized material to prevent contamination of neighboring equipment. The use of deflection coils and the geometry of the device are intended to maximize the impact angle of the electron beam (to avoid electron sprayoff); to keep the slab within a half-meter of the belt (at the operating pressure of 10^{-6} Torr, this is roughly the mean free path of the vaporized atoms); and to allow access to the equipment from above (for maintenance, repair, and material input).



OF POOR QUALITY

FIGURE 3.4 : DV OF A' RE' ' . SIDE VIEW

The design procedure outlined above led to a complete solar cell production system, shown in Fig. 3.5. A series of deposition sections builds up the solar cell material in layers onto a set of moving belts. The cell material is then cut into individual cells, which are interconnected and built into panels and arrays. The arrays are then packaged and shipped to the SPS assembly site. Figure 3.6 is a side view schematic of the solar cell production sequence, identifying production steps. The dimensions are tentative, since deposition rates are at present uncertain.

As another example of the design procedure, the 'metals furnaces, casters' box in Fig. 3.3 was expanded into a detailed layout, shown in Fig. 3.7. A set of iron and aluminum melting furnaces feed a series of casting devices to produce metal slabs and other components. The aluminum melting furnace, shown in Fig. 3.8 is another example of a space-specific design. It is a magnetic induction furnace, consisting of a refractory container surrounded by induction coils. The coils are used to heat the aluminum (ohmic heating by induced eddy currents), to contain the melt (by magnetic force from left to right in the figure), and to stir in the alloying elements (by inducing rotation in the spherical alloying chamber). The material is fed in as rods, though other shapes are possible. The furnace does not require a pressurized enclosure. Although induction furnaces are used on Earth, this design includes considerable reductions in equipment mass, because it is sized for dynamic loads (mostly handling during maintenance and repair) rather than the large static weight loads in one-g, and because it uses the available vacuum to avoid contamination of the melt.

The individual equipment designs were then tabulated on specifications sheets, as shown in Fig. 3.9, each sheet describes one 'machine'. There are roughly 60 'machines' in the reference SMF, most with 4 or 5 components.

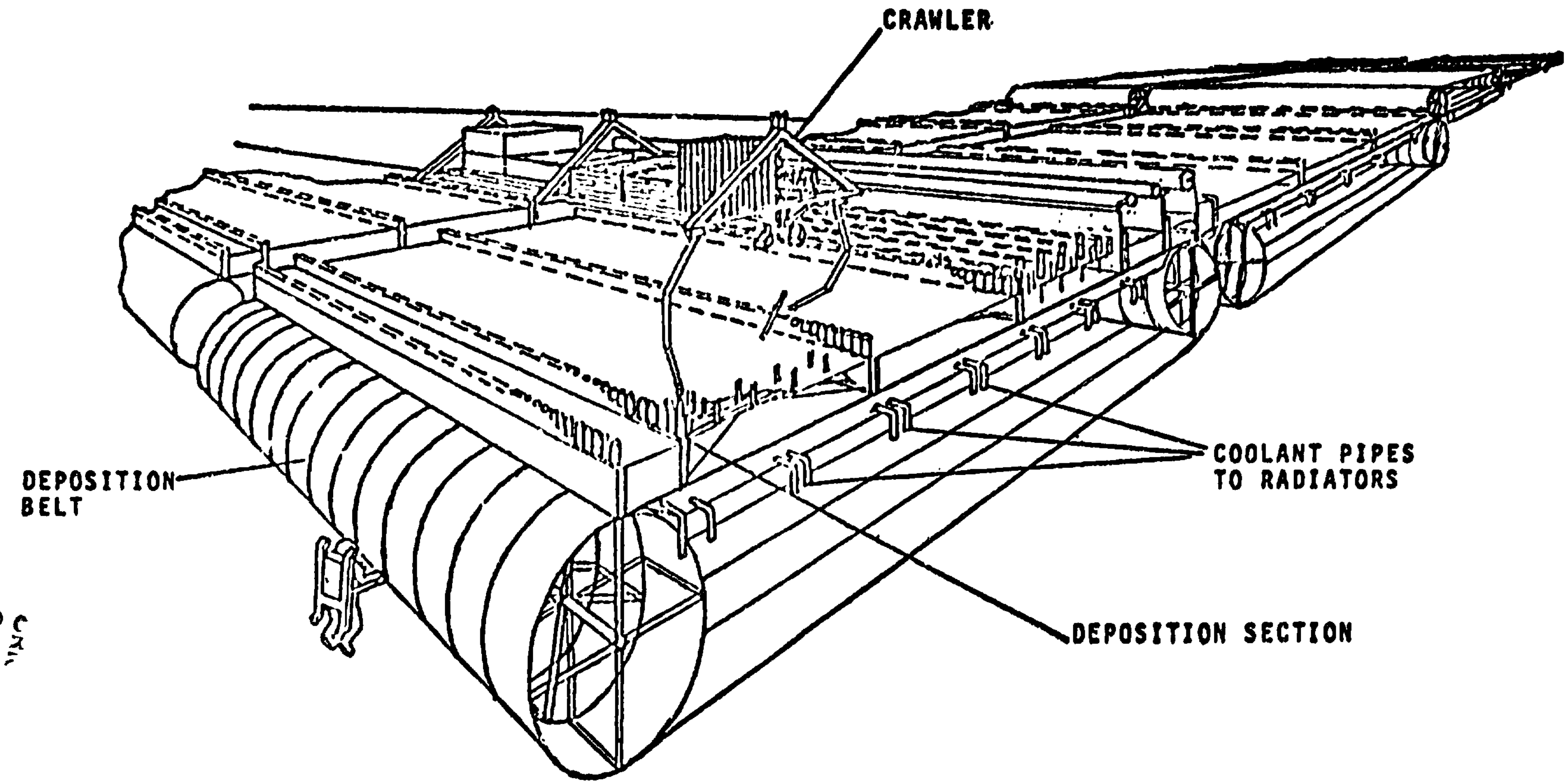


FIGURE 3.5 : SOLAR CELL DEPOSITION AND ASSEMBLY: PERSPECTIVE VIEW

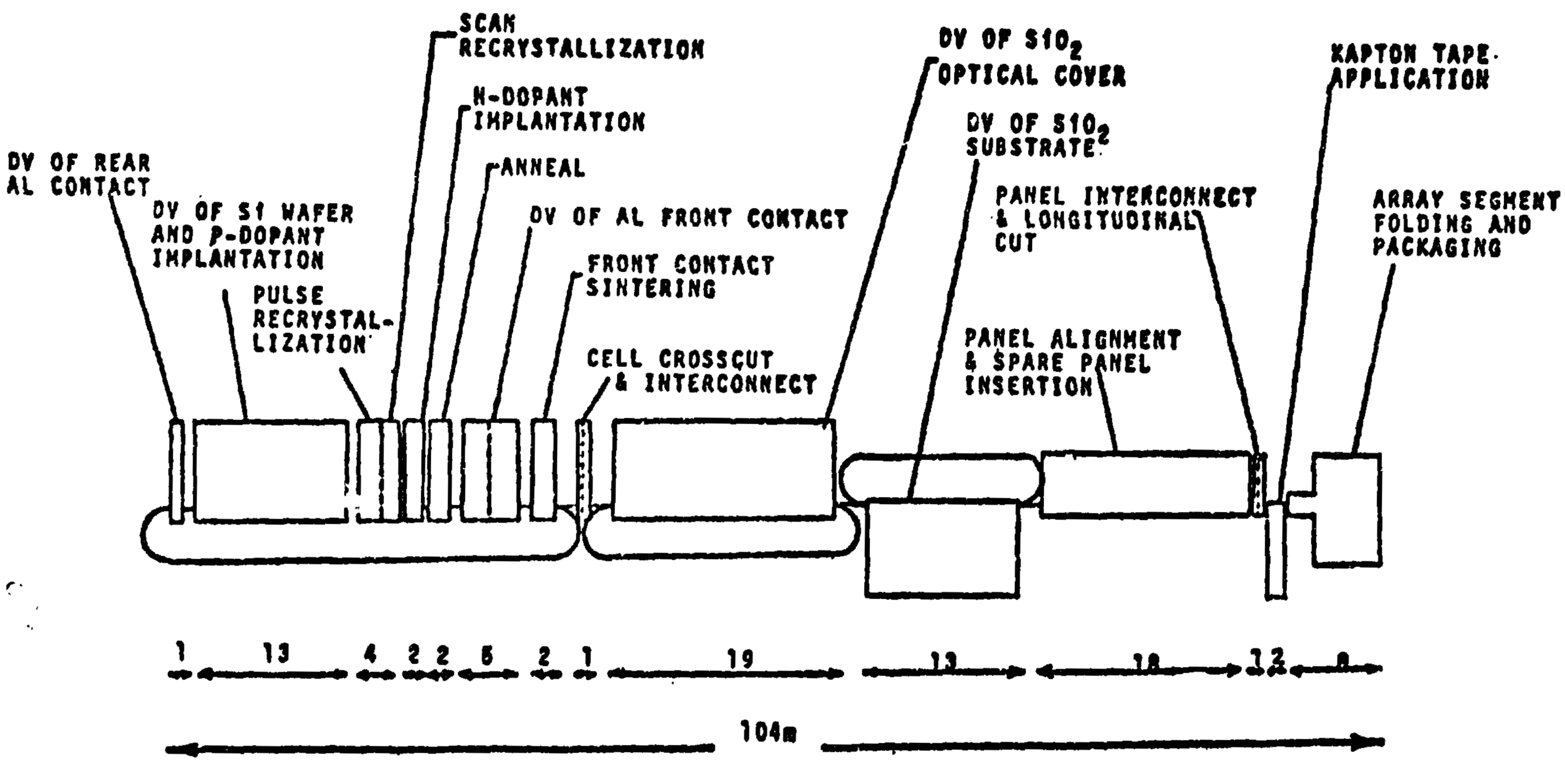


FIGURE 3.6: SOLAR CELL DEPOSITION AND ASSEMBLY: SIDE VIEW SHEMATIC

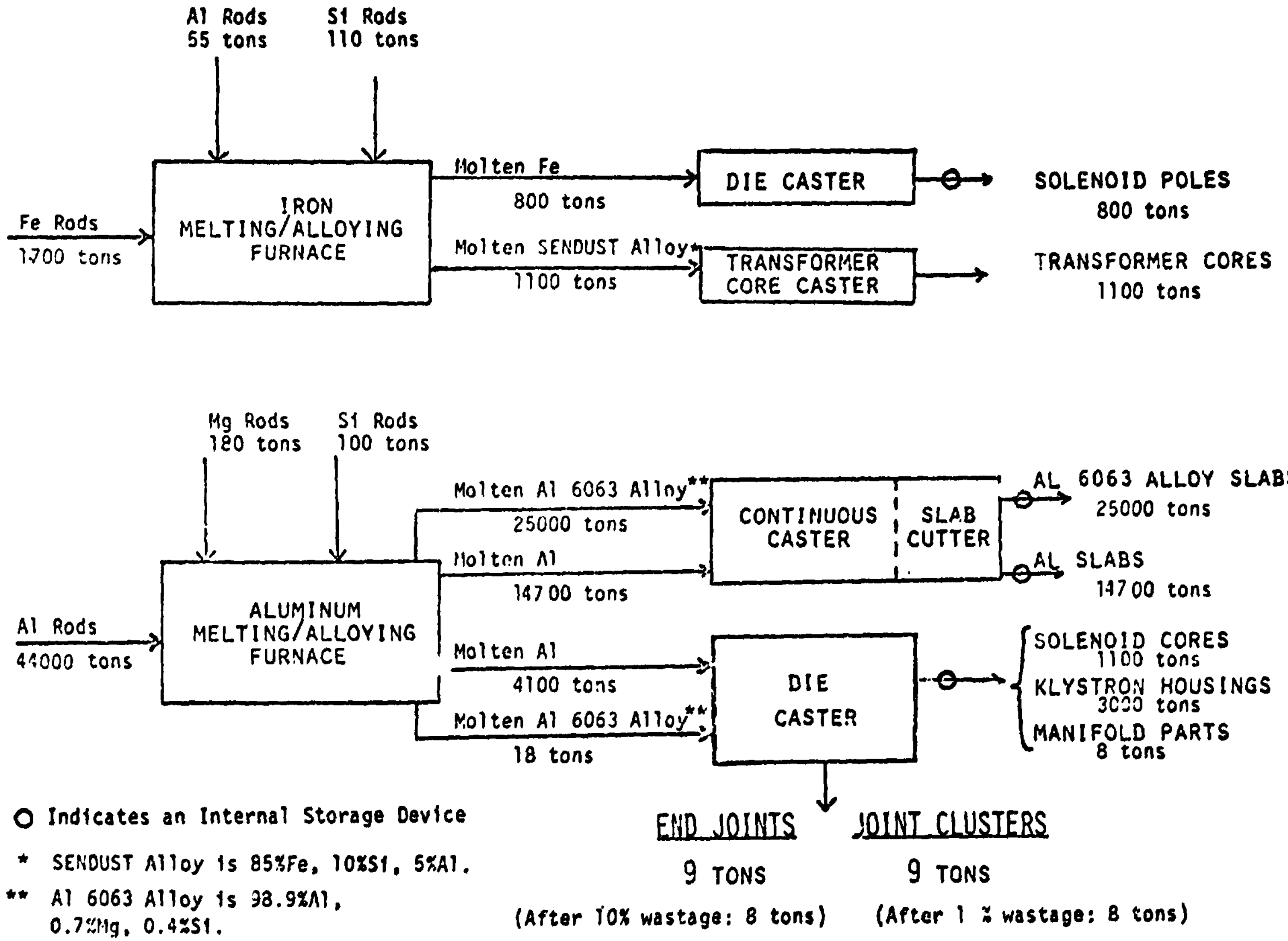


FIGURE 3.7: METAL FURNACES AND CASTERS: DETAILED LAYOUT

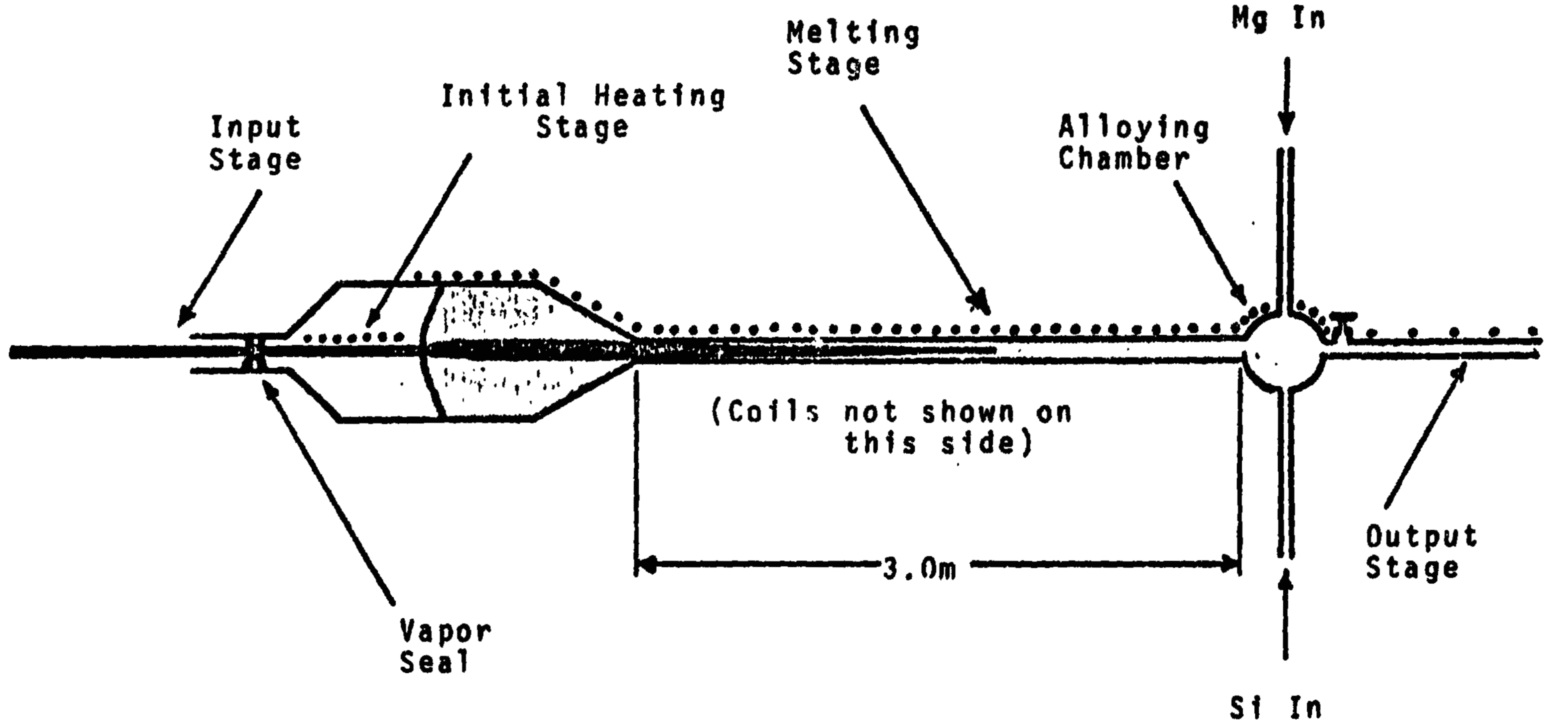


FIGURE 3.8 : ALUMINUM ALLOYING FURNACE

FIGURE 3.9: SPECIFICATION SHEET

Machine Name: Aluminum Alloying Furnace

Function of Machine: To produce either molten Al or Al alloy

Mass of Machine: 1215 kg

Physical Dimensions: 4.8 m length; .7 m maximum diameter

Throughput/Machine (tons/year): 1.4×10^4

Power Requirements (KW/machine): 1160

Number of Machines: 3

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Casing	1	150	0
Coils	1	60	1150
Radiator & Pipes	1	1000	10
Controller	1	5	.1

4. THE COST OF THE SPACE MANUFACTURING FACILITY

Costing sheets (see Fig. 4.1) were then developed from the specification sheets. The procurement costs, duty cycles, repair labor, and replacement parts requirements were defined through literature search and consultations with experts in industry and academia. Research and development costs were estimated according to a high, medium, or low technology rating on the components as shown in Table 4.1 (in dollars per kg)

TABLE 4.1: COSTING BASELINE

	R & D	Procurement
Low	500	50
Medium	5000	500
High	20000	2000
Ultra-high	100000	10000

The data from the costing sheets adds up to some 3000 numbers impacting overall SMF cost. This data was input to a line item costing computer program which calculated nonrecurring and recurring costs of the SMF, including computations of personnel totals, logistics, power, and consumables requirements, mass totals, transportation requirements, and their associated costs.

With the results from the baseline, it is interesting to do a variation of parameters analysis to find solution sensitivity. Figure 4.2 shows the effect of normalized failure rate on the crew size of the SMF. The normalized failure or duty cycle for each machine or process is printed out in the program output given in the Appendix to the main report. For example, the base

NAME OF MACHINE ALUMINUM ALLOYING FURNACE

OPERATORS/MACHINE 0 (PEOPLE)
NUMBER OF MACHINES 3

DURING NORMAL OPERATION:
EARTH INPUTS 0 (KG/HR)
EARTH INPUT COSTS 0 ($/KG)

COMPONENT	NUMBER/MACHINE	MASS (KG)	POWER (KW)	PROCUREMENT COST (K$)	DUTY CYCLE (%)	REPAIR LABOR (CREW HRS/REPAIR HR)	REPLACEMENT PARTS (KG/YEAR)	TECHNOLOGY LEVEL	R&D COSTS (K$)
Casing	1	150	0	300	95	2	150	H	300
Coils	1	60	1150	30	95	1	0	M	30
Radiator & Piping	1	1000	10	500	99	1	10	M	500
Controller	1	5	.1	10	99	1	0	H	10

FIGURE 4.1: SMF COSTING SHEET

case duty cycle for the solar cell factory is 96.2%. The abcissa of this graph is the log of the failure rate, normalized to the baseline component failure rates. Therefore, -1.0 represents a system in which individual components are ten times less likely to fail, whereas 1.0 is a system with components ten times more likely to malfunction. It can be seen that crew size increases rapidly with increasing failure rates. The difference in the two curves ("human" vs. "automated" repair) refers to a tradeoff between repair options 2 and 4 in the solar cell factory; that is, whether the parts replaced by the crawler are repaired by people or automated repair machinery. All on-site work in the solar cell factory is still performed remotely; all repair in the components factory is done manually in either case. The results shown here indicate that it is better to automate the repair shop, although the difference in crew requirements is not large.

Figure 4.3 shows the same variation in component duty cycles, this time plotted against nonrecurring and recurring costs. One assumption used in the program implementation can be clearly seen in this figure: that there is an interrelationship between equipment reliability and initial (R&D and procurement) cost. A scarcity of data exists which is applicable to this problem; and in the final analysis, a log-linear relationship between duty cycle and R&D and procurement costs was assumed. Thus, for the baseline case of high technology, R&D cost was $20,000/kg, and procurement cost was $2,000/kg. If the component duty cycle varied from 99% to 99.9% (10 times less likely to fail), the initial costs also varied by a factor of 10, to $200,000/kg and $20,000/kg, respectively. Similarly, a variation in the

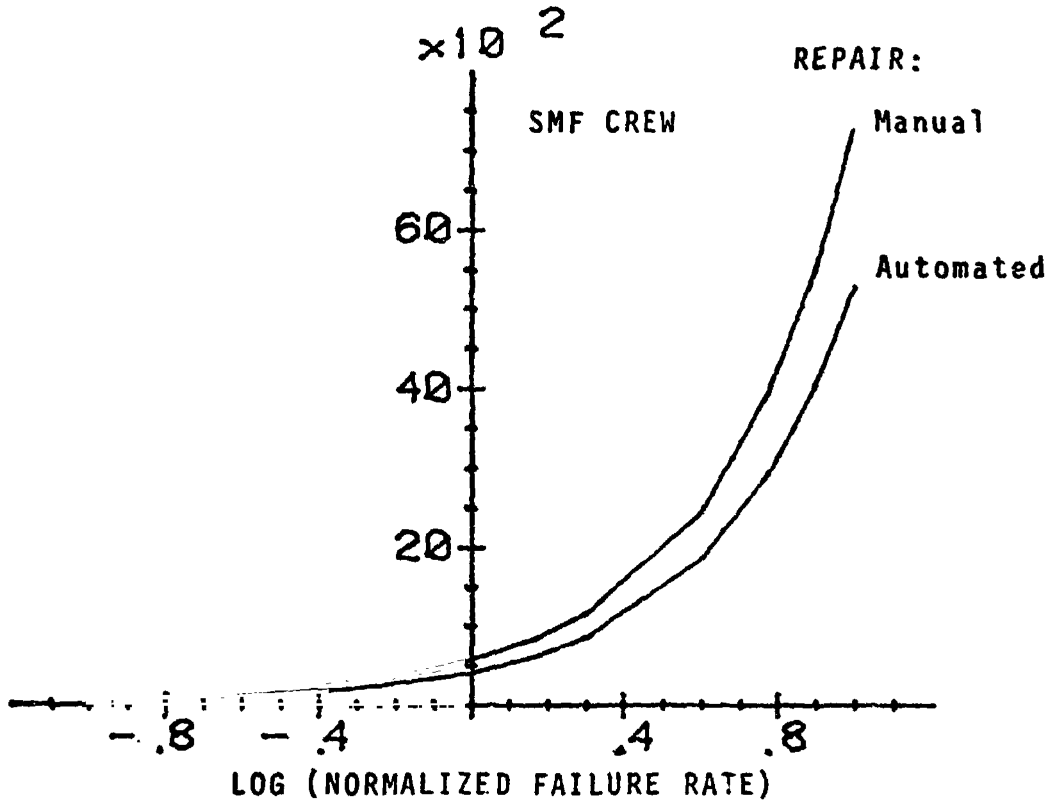


FIGURE 4.2

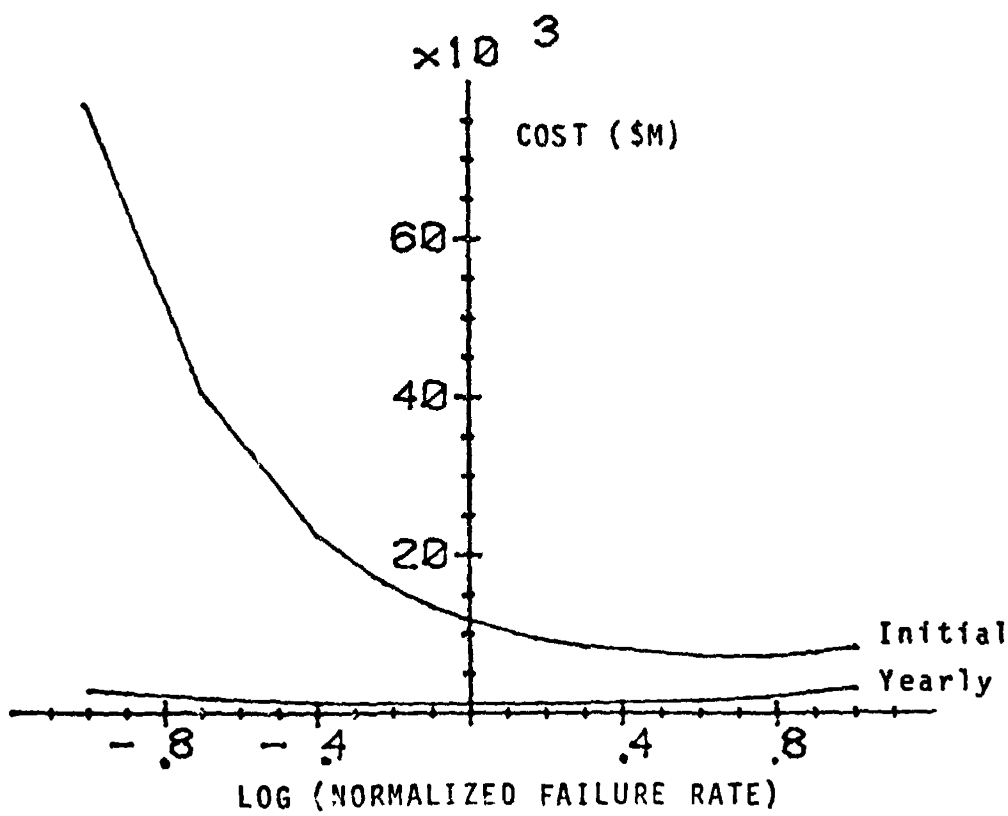


FIGURE 4.3

baseline duty cycle down to 90% reduced costs to \$2000/kg and \$200/kg. The effect of a sizable change in the duty cycle was therefore equivalent to increasing or decreasing the estimated technology level of the component. The effects of this assumption are evidenced in the curves in Fig. 4.3.

Figure 4.4 expands the scale of the ordinate, for a better view of the trends of nonrecurring costs. At lower failure rates, the equipment has higher initial costs. However, as the failure rate increases, the nonrecurring cost per machine decreases, but the number of machines must increase to keep production levels constant with the now increased down time. Therefore, an optimum failure rate exists: at approximately four times the baseline component failure rate, the tradeoff between initial cost per machine and number of machines results in a minimum nonrecurring cost of about \$7.2 billion, compared to a baseline nonrecurring cost of \$11.6 billion.

Similarly, Fig. 4.5 shows the relationship between reliability and number of machines for the recurring costs. Increasing failures creates increasing repair costs. Decreasing failures should decrease repair costs, but all machines have a non-zero minimum maintenance requirement, and as the procurement cost increases, so does the cost of spare parts. A mininum recurring cost coincidentally occurs at a failure rate about that of the baseline assumptions of reliability.

Although several man-years (and CPU-days) of effort could be spent in further variation of parameters studies, two basic conclusions come out of this costing analysis. The first is that the total SMF system costs, derived from the best estimates of machine characteristics as presented in the

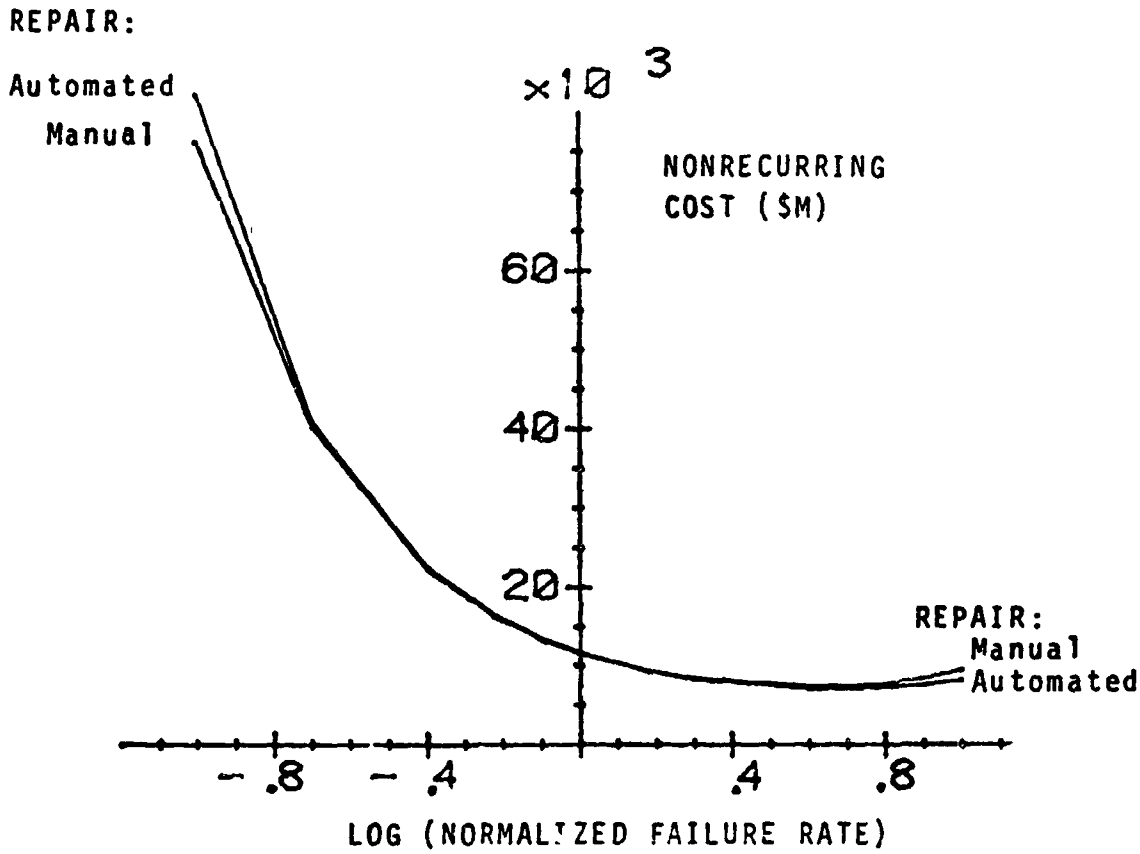


FIGURE 4.4

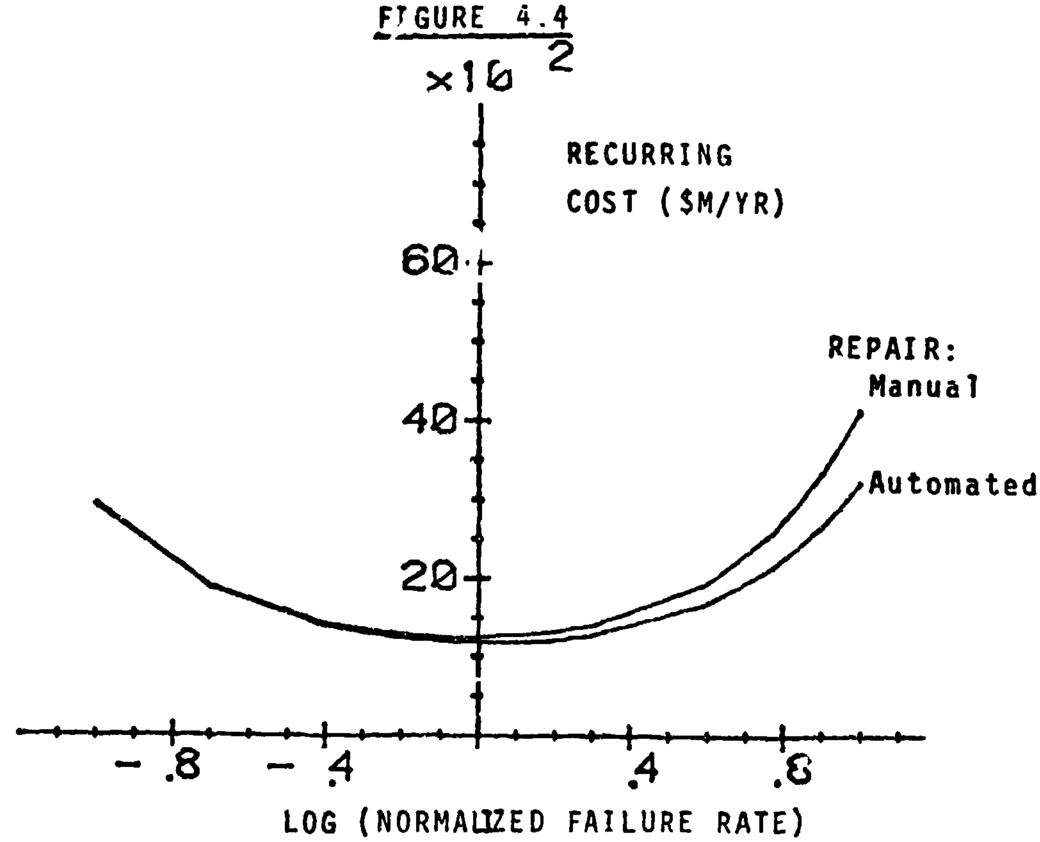


FIGURE 4.5

baseline SMF design, are $11.6 billion for nonrecurring, and $1.2 billion per year for recurring costs. These costs are competitive with ground-base production of the same product, one solar power satellite per year. The second is that, based on an assumed relation between nonrecurring parts costs and reliability, optimum failure rates exist which result in minimum nonrecurring and recurring costs. However, these minima generally do not occur at the same failure rate. A further tradeoff study between initial and yearly costs is necessary.

The life cycle costs for the SMF producing one SPS per year for twenty years at a discount rate of 10% follows direcly from Fig. 4.2 and is shown in Fig. 4.6. Again, it must be emphasized that these are SMF incurred costs and do not include either the lunar base or terrestrial facilities such as the rectenna and distribution systems, as well as operating costs for these facilities.

Finally, it must be emphasized that cost estimates of future, and speculative, space systems must inevitably be based on a high degree of uncertainty. In this section the study group has attempted to demonstrate the effects of varying one of the parameters which has the greatest degree of uncertainty: failure rate of equipment and hence machine duty cycle. It is of course possible to conduct similar parameter variation analyses with other of the many sensitive parameters of the system, such as transportation costs, productivity of labor in space, and the many factors discussed in Chapter 12 and 13 of the main report; however the above example is sufficiently illustrative of the sensitivity of costs to the assumptions used in this analysis.

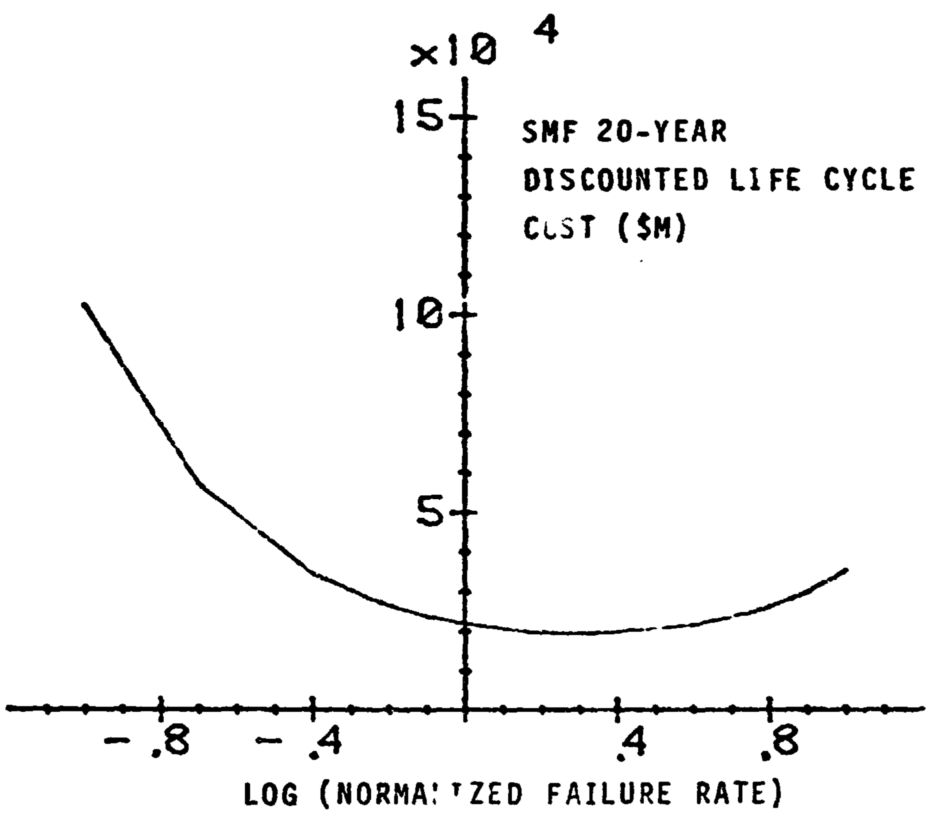

x10 4
15
10
5
SMF 20-YEAR
DISCOUNTED LIFE CYCLE
COST ($M)
-.8
-.4
.4
.8
LOG (NORMALIZED FAILURE RATE)

FIGURE 4.6

Another area of uncertainty involves the cost of developing the specialized equipment for the SMF. This cost is covered partly by the R&D costing baseline of Table 4.1 and partly by an additional process development and systems integration cost assigned to each of the sixty processes which make up the SMF. These costs were assigned even to a well established process on the assumption that space rating would add new operational constraints requiring further development. The cost for each process is listed in the Appendix and varies from $\$10 \times 10^6$ to $\$100 \times 10^6$ depending on complexity and maturity of the process. The lower amount was applied to well developed systems, the upper limit to new and novel space oriented concepts.

As mentioned previously the costs presented here are based on extensive discussions with organizations well acquainted with the terrestrial application of most of the processes used. However, in the final analysis, translation of this collective experience to an operating system in space is a highly subjective process. Different experiences and different view points will result in different estimates as to the baseline costs. It is hoped that the degree of detail used in defining the SMF and its many subsystems as well as the flexibility built in to the costing algorithms will allow readers to arrive at their own conclusions as to the system cost.

The costs presented here should be considered as first estimates only, based on the best available information and on as detailed a component breakdown as time permitted. As such they indicate that the proposed concept is an attractive choice for the manufacture of SPS, and probably other space hardware, worthy of further investigation.

5. Technology Evolution and Systems Tradeoffs

5.1 Technology Evolution Program

The development steps required to establish the technology for this SMF have been summarized from the discussions of Chapter 12 of Volume II as follows:

1. R&D: METALS FURNACES AND CASTERS

Conceptual studies of furnace options

Refractory material tests

Metal solidification experiments

Continuous caster design

Die caster and large-piece caster design

Prototype furnaces

Prototype casters

Space prototypes of furnaces and casters

Prototype slab cutter

2. R&D: RIBBON AND SMF OPERATIONS

Prototype rolling mill

Prototype electron beam cutters

Prototype electron beam welders

Prototype ribbon slicer

Development of striated heat pipes and heat pipe fluids

Prototype striator

Prototype form roller

Design of sheet layout and klystron radiator assembly station

Prototype of sheet layout and klystron radiator assembly station

Design of DC-DC converter radiator assembly device

Prototype DC-DC converter radiator assembly device

Integration of ribbon and sheet operations ground prototypes

Space prototypes of rolling mill, ribbon slicer, and striator

Space prototypes of integrated sheet and ribbon devices

3. R&D: INSULATED WIRE PRODUCTION

Design of glass fiber producer

Space experiment of fiber production

Prototype glass fiber producer

Prototype insulation winder

4. R&D: DC-DC CONVERTER PRODUCTION

Prototype [illegible]l drill

Prototype [illegible] winder

Definition and [illegible]st of assembly tasks

5. R&D: KLYSTRON PRODUCTION

Design of klystron and klystron assembly production sequence

Prototype klystron assembly production equipment

Space prototypes of klystron assembly production equipment

6. R&D: SOLAR CELL PRODUCTION

Continuous review of developments in solar cell production techniques

Conceptual studies of solar cell production systems

Conceptual study and space experiments on zone refining

Prototype zone refiner

Space prototype zone refiner

Conceptual study and space experiments on direct vaporization

Prototype direct vaporization devices

Prototype ion implantation devices

Conceptual studies and experiments on recrystallization

Space experiments on recrystallization

Prototype recrystallization devices

Space experiments on ion implantation damage anneal

Prototype ion implantation damage annealer

Prototype of direct vaporizer with mask and mask clean-up device

Space experiment of front contact sintering

Prototype of front contact sintering device

Integrated space prototypes of solar cell deposition

Conceptual study and experiments on laser cutting of solar cells

Prototype solar cell cross cutter and longitudinal cutter

Prototype direct vaporizer for interconnects

Prototype solar cell interconnection device

Conceptual studies of optical cover and substrate production options

Prototype panel alignment and insertion device

Prototype kapton tape applicator

Prototype array segment packager

Integration of cell interconnection and panel/array buildup prototypes

Integrated space prototypes of cell interconnection and panel/array buildup devices

Space prototype of complete solar cell production strip

7. R&D: WAVEGUIDE PRODUCTION

Conceptual studies and development of foamed glass for waveguides

Design of space powder mixer

Space prototype of powder mixer

Space experiments on glass foaming

Design of glass foaming facility

Prototype glass foaming facility

Prototype foamed glass sawcutters

Experiments on foamed glass smoothing

Prototype foamed glass smoother

Prototype waveguide Al direct vaporizer

Prototype laser cutters for foamed glass

Design of waveguide assembler and waveguide packages

Prototype waveguide assembler and waveguide packager

Integration of waveguide production prototypes

Space prototype of waveguide production system

8. R&D: SUPPORT EQUIPMENT

Design and ground tests of input/output station

Design and ground tests of internal transport and storage devices

Design and ground tests of crawlers

Design and ground tests of power plant components

Design and ground tests of production control systems

Design and ground tests of habitation components

Design and ground tests of station-keeping and attitude control equipment

Design and ground tests of SMF structure components

Design and ground tests of repair shop components

Design and ground tests of free-flying teleoperators

Integrated space prototypes of habitation, input/output station, and repair shops

Integrated space prototypes of internal transport and storage devices, crawlers, station-keeping and attitude control equipment and structure

Space prototype of free-flying hybrid teleoperator

5.2 System Tradeoffs

The SMF design which has evolved from this study is a reference design and only the obvious tradeoffs have been considered in its evolution. Final optimization of an SMF would require much deeper analysis of the various alternate candidate systems than was possible within the time and cost constraints of this study. The required tradeoffs are discussed in Chapter 13 of Volume II, and may be listed as follows:

1. Optimization of product for use of lunar materials
2. Effect of SPS mass increase
3. Tradeoffs in lunar refining
4. Transportation from the moon
5. SMF production control tradeoffs
6. Waste reprocessing at the SMF
7. SMF buildup sequence
8. Location of facilities

6. CONCLUSIONS AND RECOMMENDATIONS

6.1: CONCLUSIONS

1. The space manufacturing facility is technically feasible, in that a facility can be built which can turn lunar materials into the required outputs. Such a facility can be operated in space on a continuous basis.

2. The production operations of the SMF appear versatile, in that the facility can produce a wide variety of products, from structural members to solar cells to klystron assemblies. The study group concludes that a wide range of satellite components can be manufactured in space, without extensive modifications to the reference SMF.

3. The SMF concept is also flexible, meaning that space manufacutring facilities can be designed for a wide range of production rates. For example, a small solar-cell production operation can be set up by using a small number of production strips. Most of the reference SMF can be scaled up or down, and operated over a range of regimes. Thus commitment to the use of an SMF does not entail commitment to a large output rate; small SMF's are possible.

4. The reference SMF also appears productive, in that it produces a yearly output with roughly ten times the mass of the production equipment. It should be noted that roughly 45% of that output is solar cells, which currently have a far lower (output rate)/(production equipment mass) ratio.

5. The space environment can improve industrial operations, provided that the SMF processes are chosen and designed to take advantage of the characteristics of space, specifically the readily available vacuum and energy, and the low-stress environment of zero-g. The SMF environment, both physically and economically, is different than Earth's and in many cases beneficial.

6. Evaluation of the lunar-material option requires more in-depth systems studies, trading off the various scenario parameters (e.g. characteristics of lunar base, transportation systems, SMF, assembly station, and output SPS).

7. Technology demonstration programs are needed to verify suggested processes. In-space prototypes need not be large, but can benefit from a permanent orbital platform.

8. Based on 1 SPS/year the SMF will require non-recurring costs of $11.6 billion including R & D, procurement, transportation and power supply. Annual recurring costs of $1.2 billion will be required and an operating crew of 440.

6.2: RECOMMENDATIONS

1. Conduct systems tradeoffs outlined in Ch.13 of Vol.II leading to an optimized space manufacturing scenario using lunar materials.

2. Design a smaller, near-term, technology demonstration space manufacturing facility using terrestrial material inputs, possibly located in LEO, including appropriate elements of the technology evaluation program outlined in Chapter 12 of Vol. II.

3. Examine the possibilities of using space specific processes to manufacture products competitively for terrestrial consumption. Several such candidate processes have been identified by this study.