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EXTRATERRESTRIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS, Volume II

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CHAPTER 7

PRODUCTION EQUIPMENT SPECIFICATIONS

7.1: GENERAL REMARKS

Figures 7.1, 7.2, and 7.3 show the overall layout of the reference SMF. The diagrams serve to illustrate the likely relative positions and dimensions of the different sections of the facility. Figures 7.1 and 7.2 are "top" and "side" views, respectively, of the SMF, drawn to the same scale. These figures illustrate the planar shape of the facility. Figure 7.3 is an "end" view of the facility, drawn to a larger scale to show some of the detail of the components and solar cell manufacturing areas.

Several features are omitted from the figures for clarity. Figures 7.1, 7.2, and 7.3 do not show the thermal waste radiators for the components factory, above and below that factory; the solar cell deposition radiators which collectively cover roughly half of the top and the entire bottom of the solar cell factory; the active radiators for the waveguide factory, above and below that factory; the support structure holding the machinery together within the factories; and the internal transport tracks between all of the SMF sections. Part of one of the two habitat radiators is shown in Fig. 7.1, and the support truss for those radiators is partially seen in Figs. 7.2 and 7.3. When the various radiators for the SMF are included, they cover much of the top and bottom surfaces of the facility. Since most of these radiators are 1-mm thick aluminum sheets, they protect the SMF equipment and personnel from micrometeorites.

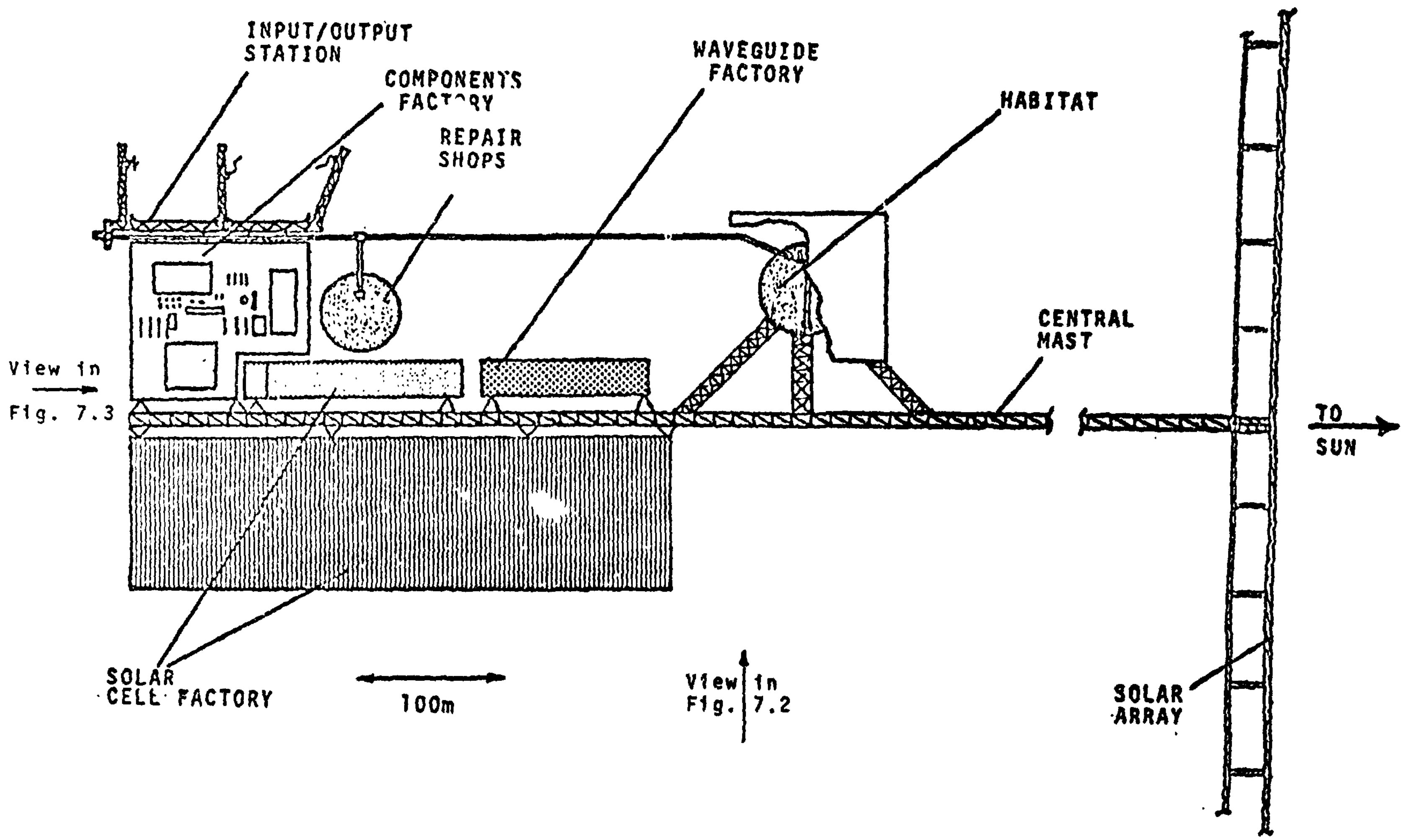


FIGURE 7.1: "TOP" VIEW OF REFERENCE SMF

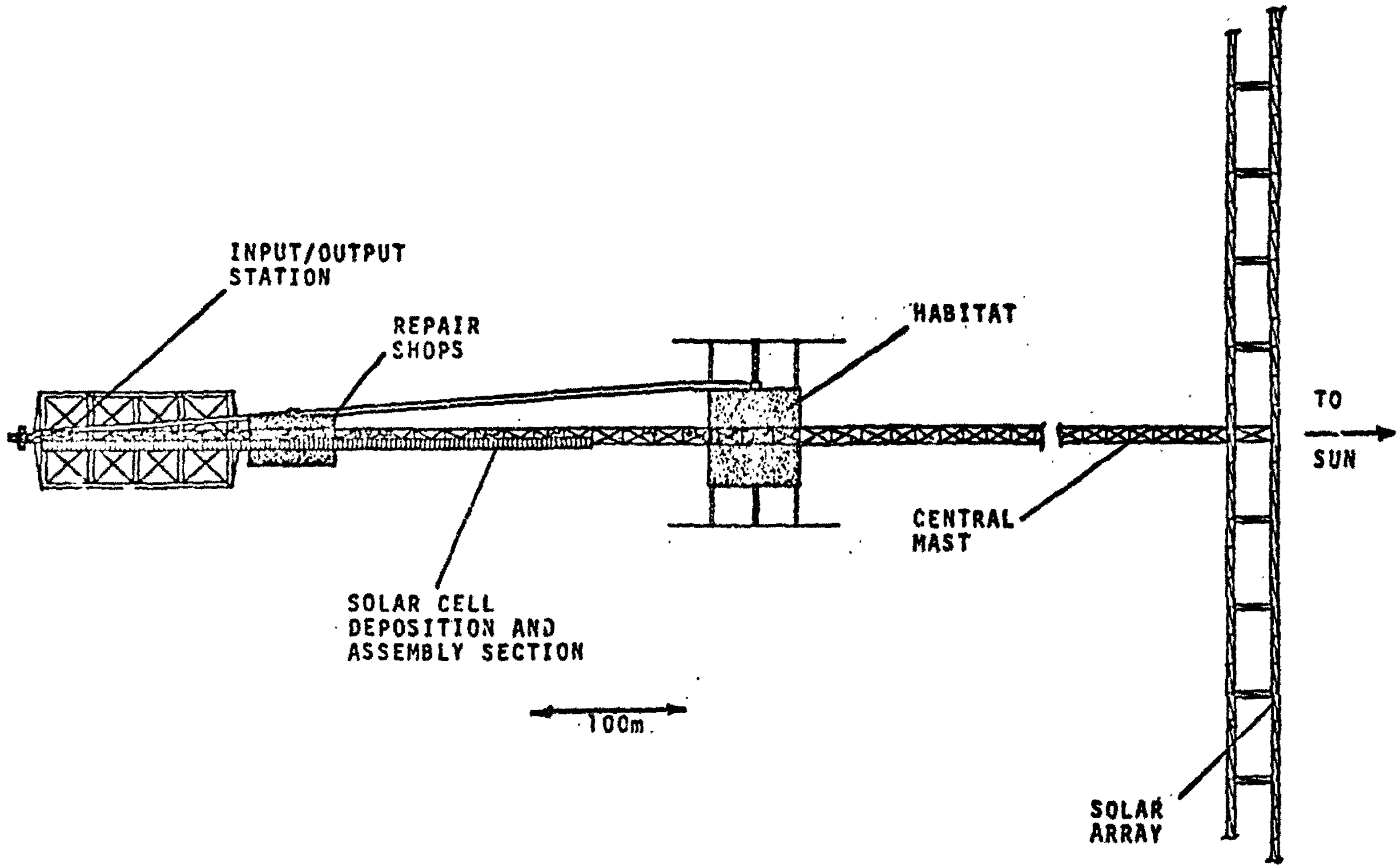


FIGURE 7.2: "SIDE" VIEW OF REFERENCE SMF

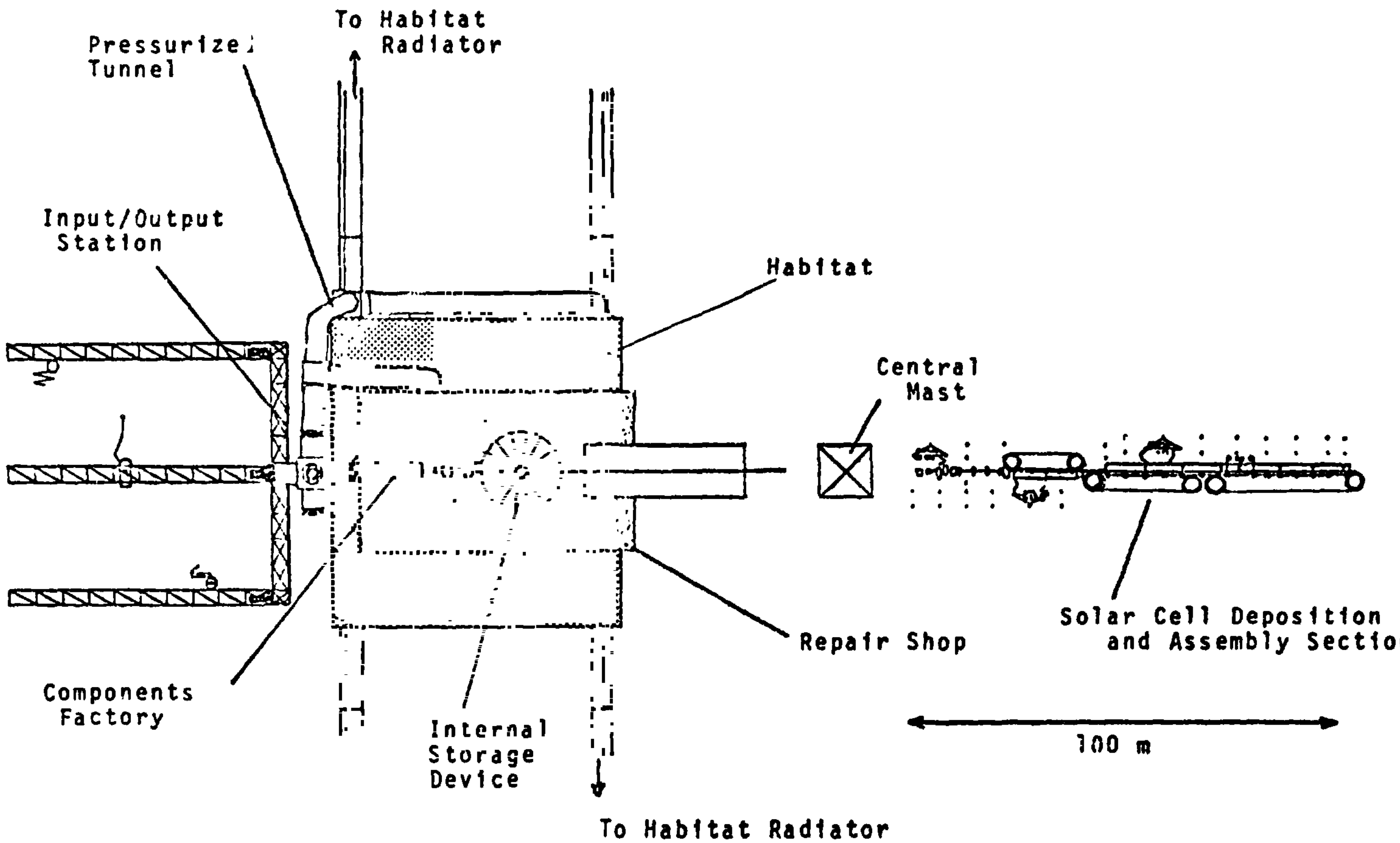


FIGURE 7.3: "END" VIEW OF REFERENCE SMF

The solar array, partially shown in Figs. 7.1 and 7.2, is omitted from Fig. 7.3. This array shades the rest of the facility from direct sunlight, reducing the thermal input to the SMF. The array produces baseload power for the entire SMF. The reference SMF design requires 240 MW for its operation, which, assuming a solar cell efficiency of 12.5%, equates to an array area of 1.4 km^2. The solar cell array is the only section requiring close pointing to the Sun ($\pm$ 1°). The rest of the factory does not require close attitude control, but should stay in the shadow of the solar array to alleviate heat waste problems and thermal deformations.

The array is connected via a flexible joint (including flexible power cables) to a central mast extending down the length of the facility. The mast serves three functions: 1) It acts as a structural mast to which the solar array and other sections of the factory are attached. (The factory sections are attached by joints which use active damping systems to prevent vibrations being transmitted through the facility.) 2) It carries the main busbars and power conditioning equipment for the SMF. 3) It is designed to allow transporters travelling between the solar cell factory and the rest of the facility to pass through it.

The SMF production machinery is conceptually divided into three areas: the components factory (which produces all components other than solar cells and waveguides), the solar cell factory, and the waveguide factory. The components factory produces klystron assemblies, structural member ribbon, busbar strips, DC-DC converters, electrical wire and cables, DC-DC converter radiators, end joints, and joint clusters. This factory is located adjacent to the input/output station (at the left of Fig. 7.1). Details of the factory layout are shown in Fig. 7.4, and the production equipment designs are described in Secs. 7.2 through 7.6 of this chapter. As shown in Fig. 7.3, the layout of this section is essentially planar, except for the wheel-like internal storage devices. Omitted from the views of the components factory are the waste heat radiators located above and below it.

The waveguide factory is shown in Fig. 7.1, adjacent to the zone refining area. The factory is designed to allow the minimum of handling of the thin foamed glass sheets from which the waveguides are formed. The details of the waveguide production processes are discussed in Sec. 7.7.

The single largest section in the reference SMF is the solar cell factory (shown in Figs. 7.1, 7.2, and 7.3, and shown in a larger scal top view in Fig. 7.5). The solar cell factory consists of two major structural units, one containing the zone refining and interconnect deposition sections, and the other the deposition and assembly equipment for the solar cell array production. Each of these structural units is attached to the central mast at several discrete points. The connections are flexible and include active damping systems to keep vibrations from propagating into the solar cell factory, which might damage the fragile solar cells. The connections between the central mast and the sections of the

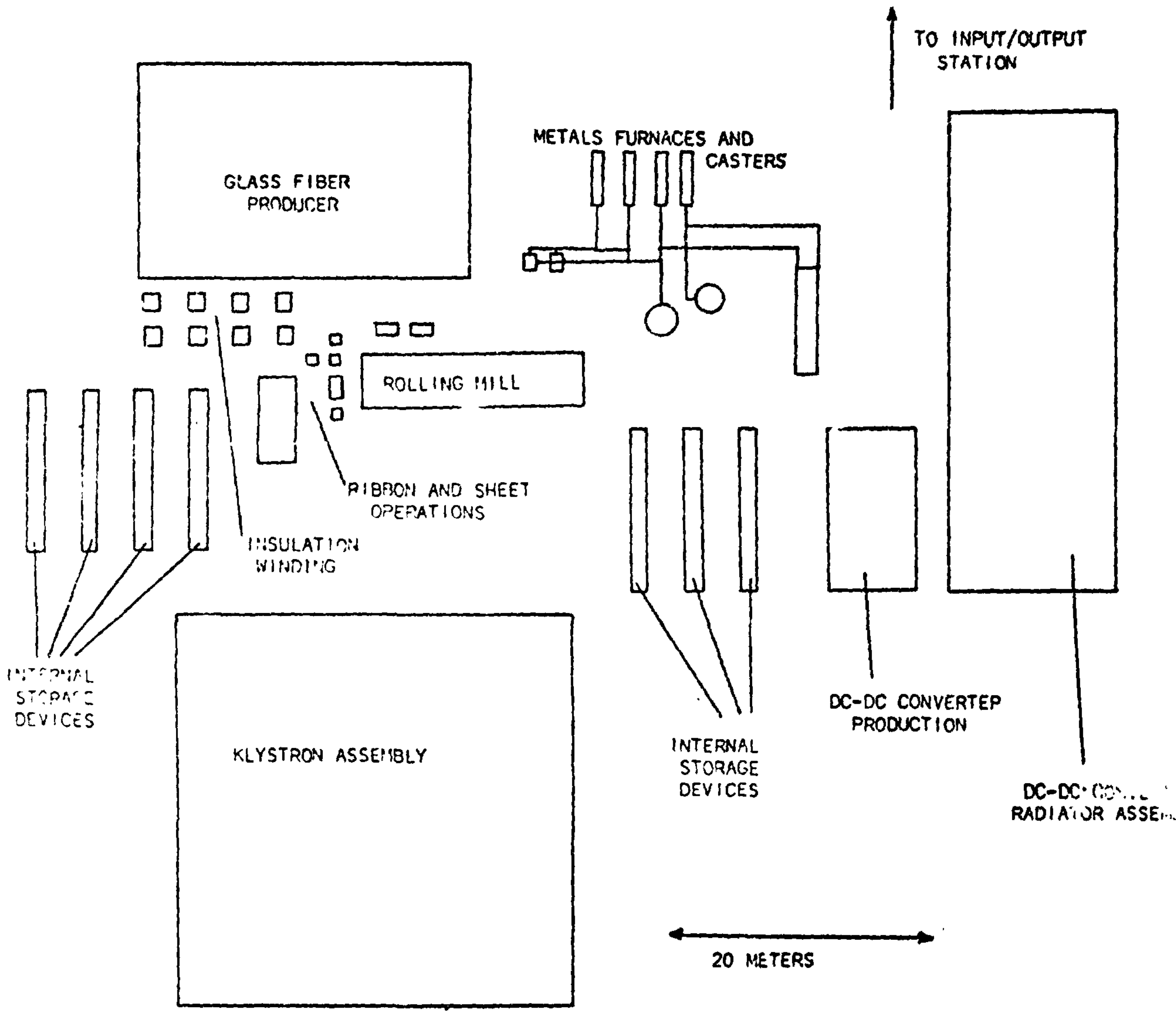


FIGURE 7.4: LAYOUT OF COMPONENTS FACTORY

solar cell factory also carry electrical busbars and internal transport tracks. The transport tracks bring inputs to the factory, move some of the intermediate products within the factory, and remove the output solar cell arrays.

Routine feeding and maintenance of the solar cell deposition and assembly processes is done by 'crawlers' running along tracks above the planar factory. More complex repairs are performed by Free-flying Hibrid Teleoperators (FHT's). The crawler tracks are shown as horizontal lines in Fig. 7.5. The crawlers take inputs from, and load outputs into the SMF's internal transport carts. The production lines for deposition and assembly of the solar cells run perpendicularly to the crawler tracks (and thus perpendicularly to the central mast). No radiators for the solar cell factory are shown, but those for the zone refining and interconnect deposition section are above and below that section; those for the electron beam guns in the deposition sections are above those s[illegible]ns; those for the thermal belts in the deposition sections are below the deposition and assembly section, covering the underside of that section. The solar cell factor[illegible] described in detail in Sec. 7.8.

Also shown in Figs. 7.1, 7.2, and 7.3 are support areas such as the input/output station, habitat, and repair shops. These are described in detail in Chap. 8.

This chapter includes tabulated specifications, physical descriptions, and diagrams of each machine in the reference SMF design. Sections 7.2 through 7.8 discuss equipment,

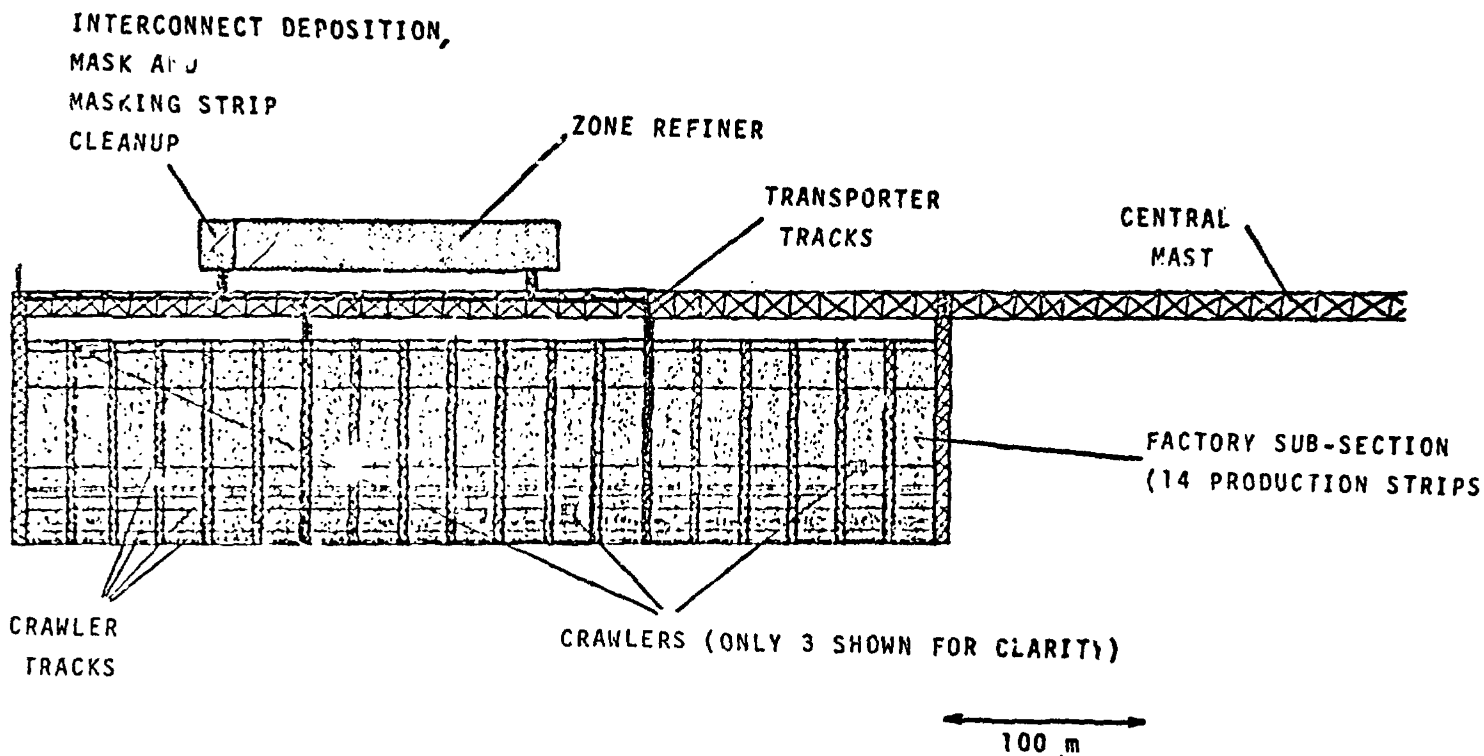


FIGURE 7.5: LAYOUT OF SOLAR CELL FACTORY

grouped by major SMF operations (subsections of components manufacture, waveguide manufacture,solar cell manufacture). Each section begins with a genereal description of the production processes, followed by data on individual machines.

Associated with each machine are: a specification sheet (listing machine mass, physical dimensions, throughtput per machine, power requirements, and the contribution of each component to mass and power requirem^nts), diagram(s), and a written description of the machine's operation.

Terms used in the specification sheet are defined as follows:

Mass of machine -- total mass of one machine.

Throughput per machine -- mass of components produced by each machine per year.

Power requirements -- power required to operate each machine.

Number of machines -- number of this type of machine in the reference SMF.

Number of operators -- number of crew required to operate the machine (during its duty cycle).

Components -- elements which compose the machine.

Number per machine -- number of this type of component per machine.

Mass -- mass of each component.

Power required -- power required for operation of each component.

The written description explains the function of each component, the operation of the machine, and the rationale used in the sizing and costing processes.

7.2: METALS FURNACES AND CASTERS

7.2.1 Overview: Figure 7.6 is a detailed top view of the components factory. The shaded areas highlight the machinery described in this section. Four furnaces -- one producing 6063 aluminum alloy, one producing molten aluminum, one producing SENDUST alloy, and one producing molten iron -- are used. The furnaces are fed with rods imported from the lunar surface, which are heated as they enter. Mixing of the melt is accomplished by electro-magnetic induction. The resultant liquid metals are pumped by electromagnetic pumps along pipelines for further processing.

As shown in the figure, molten iron, molten aluminum, and 6063 aluminum alloy are delivered to die casters. These devices each consist of a central piston chamber which sequentially feeds molten metal through a set of valves to a series of molds. Active cooling systems are used to cool the castings, and the solidified workpieces are ejected from the molds. Parts produced in this manner are solenoid cores, klystron housings, manifold parts, end joints and joint clusters. The SENDUST alloy is fed to a specialized caster which is used to produce the transformer cores for DC-DC converters.

Molten aluminum and 6063 alloy are also fed into a continuous caster, which produces 2 cm thick ribbon that is cut into slabs by a high power electron beam gun. The slabs are dispatched to the ribbon and sheet operations section, described in Sec. 7.3.

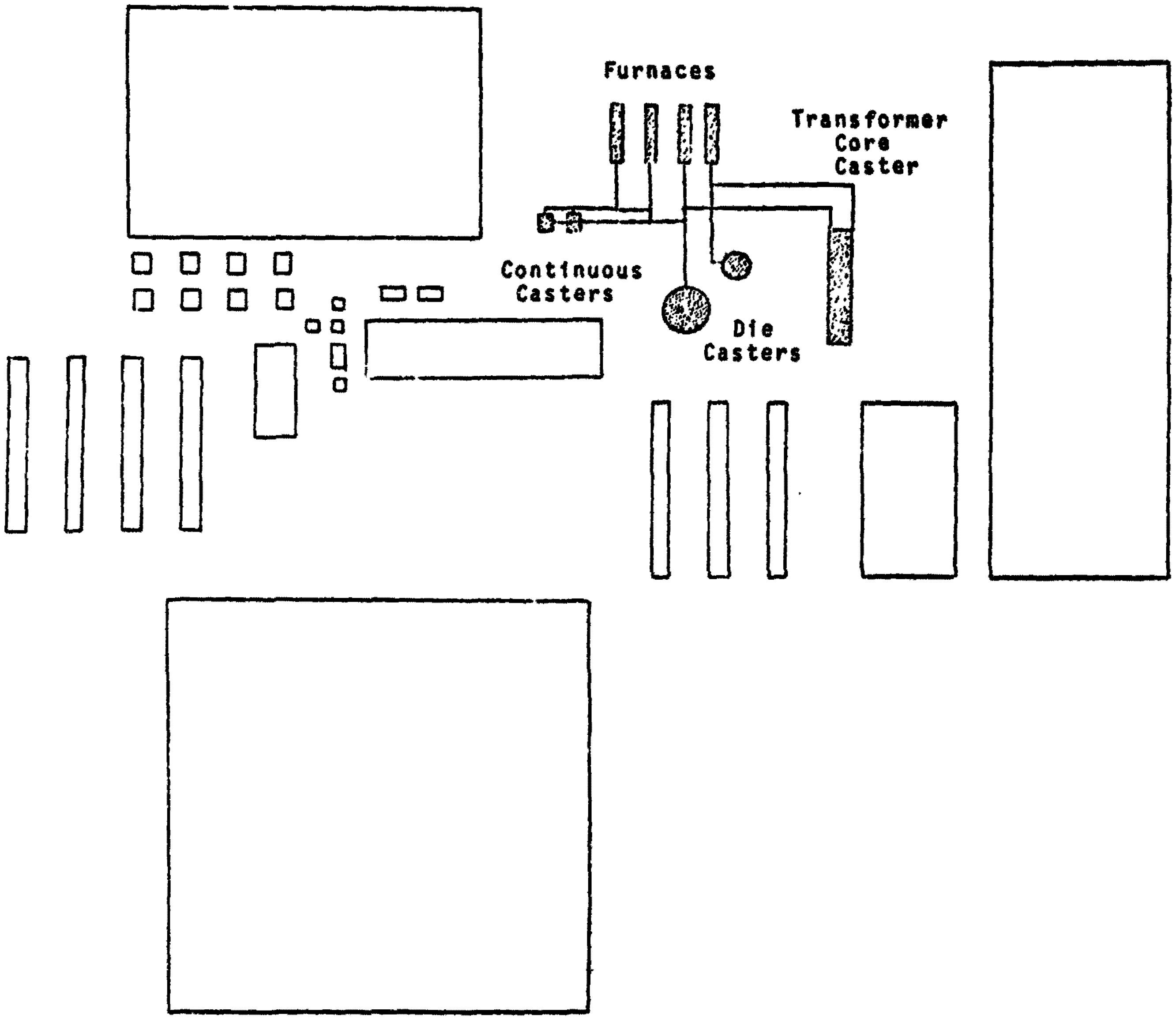


FIGURE 7.6: LAYOUT OF METALS, FURNACES AND CASTERS

7.2.2 Aluminum Alloying Furnace: The aluminum alloying furnace is designed to take in rods of pure aluminum (6.4 cm diameter), melt them, and produce liquid metal at 800°C. Aluminum 6063 alloy may be produced by the addition of 1.7 cm diameter Mg rods and 1.3 cm diameter Si rods.

The furnace body is made of slip-cast, nitride bonded si-silicon carbide, a refractory material resistant to corrosion by liquid metals. The Al, Mg, and Si rods are fed into the furnace through vapor sleeves, and pre-heated with copper induction coils. Induction heating continues as the rods are submerged into the melt. The mean residence time in the alloying chamber for 6063 alloy is 2 minutes. During this time, induction coils act to mix the liquid metal. The maximum production rate for one furnace is .6 kg/sec or 1.9×10^4 tons per year in continuous operation. At capacity, the furnace holds 1250 kg of liquid metal.

The induction coils used to heat and stir the metal in the furnace are 75% efficient; 209 kw must be wasted through an active cooling system. The study group proposes a system which uses liquid sodium to draw heat from the coils and waste it through a radiator. Since the coil resistivity increases with temperature, a tradeoff exists between increased power generation (producing a high temperature) and increased radiator size (allowing radiation at a lower temperature). The radiator is presently designed for an operating temperature of about 300°C.

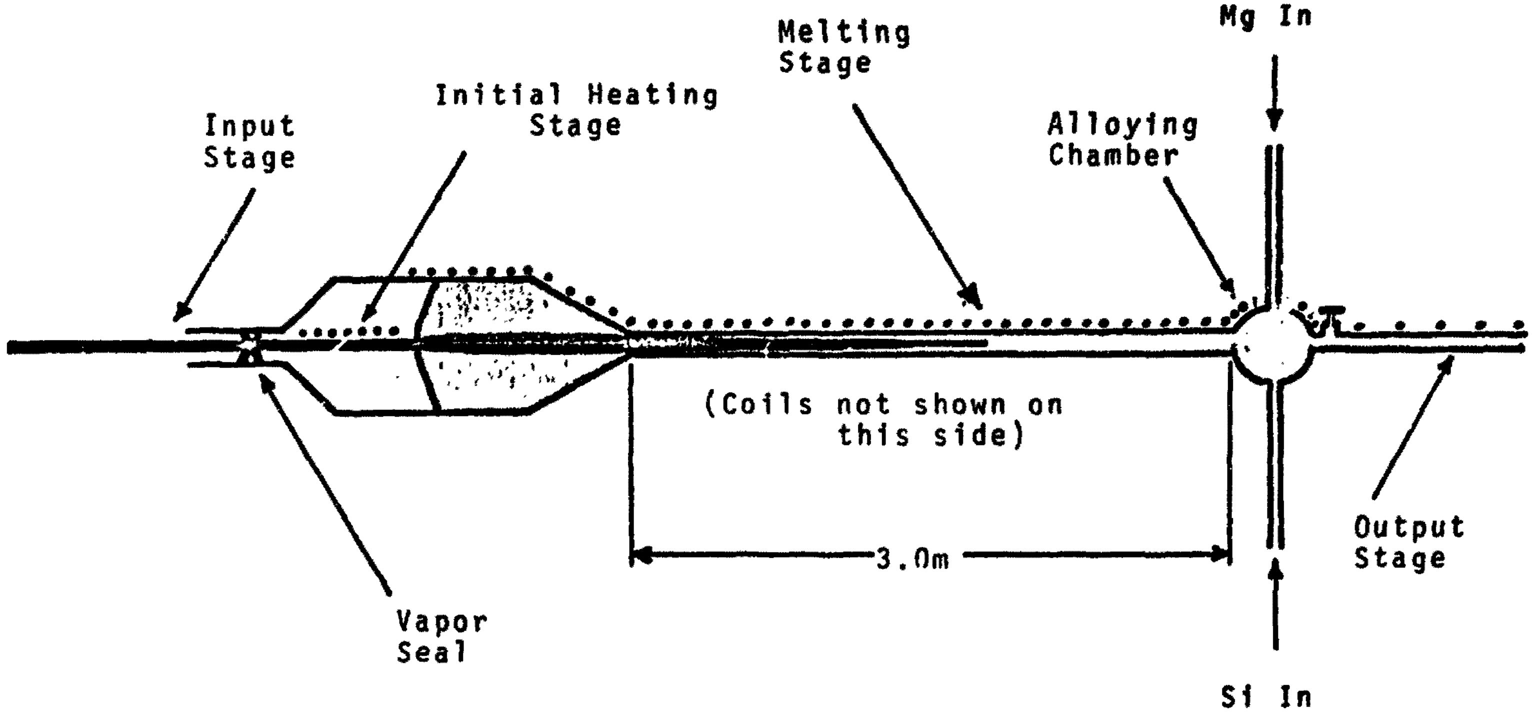


FIGURE 7.7: ALUMINUM ALLOYING FURNACE

Cost estimates for both the aluminum and iron alloying furnaces were developed from consultations with an industrial equipment costing specialist at Kennecott Copper Co. and a member of the research and development division of the Norton Co.

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

7.2.3 Iron Alloying Furnace: The iron alloying furnace is designed to take in rods of pure iron (6.4 cm diameter) and to produce molten iron. With the addition of 2.5 cm diameter aluminum rods and 1.3 cm diameter silicon rods, SENDUST alloy can be produced.

The iron furnace is operated in the same fashion as the aluminum furnace. The body is made of graphite to provide corrosion resistance and the furnace capacity is 3100 kg moving at .56 kg/sec or 1.8 10^4 tons/year. The metal leaves at 1600°C.

SPECIFICATION SHEET

Machine Name: Iron Alloying Furnace

Function of Machine: To produce either molten Fe or SENDUST alloy

Mass of Machine: 1215 kg

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

Throughput/Machine (tons/year): 1.9 x 10^3

Power Requirements (KW/machine): 1160

Number of Machines: 1

Number of Operators: 0

Components:

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

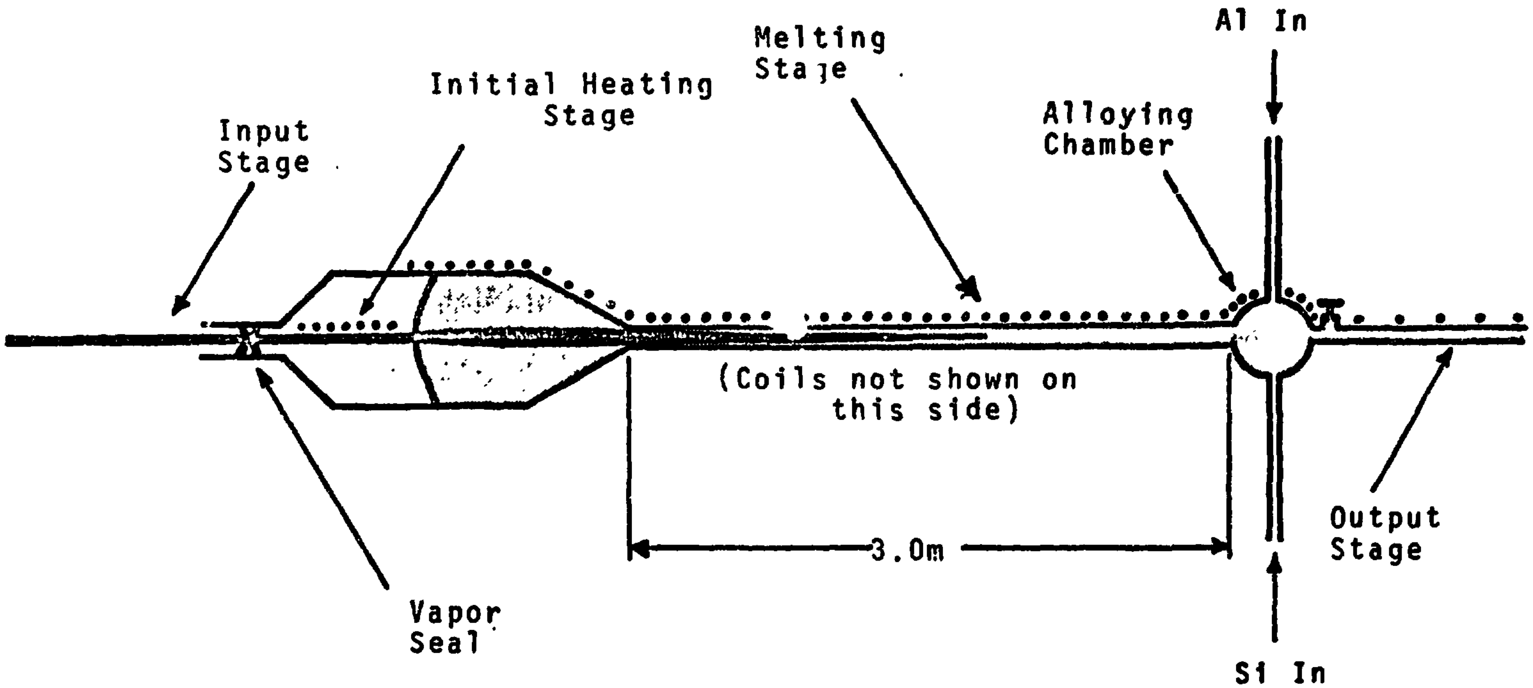


FIGURE 7.8: IRON ALLOYING FURNACE

7.2.4 Liquid Aluminum Pipeline: A liquid aluminum pipeline is needed for the transport of molten Al and Al 6063 within the SMF. The pipe connects the Al furnaces to the metal casters. The pipes were designed for a maximum throughput of .6 kg/sec or 19,000 tons/yr in continuous operation; normal throughput is 10,300 tons/yr.

The pipes are made of silicon carbide in a nitride matrix and are sized to survive handling stresses. Consultations with experts in industry resulted in the selection of a 6 mm pipe wall thickness. Six layers of foil insulation prevent cooling or solidification of the metal. The number of layers of foil was found by using the equation:

$$Q = \varepsilon \sigma T_0^4 \left[\frac{1}{2}(1-r)\right]^n$$

where ε is emissivity, σ is the Stephan-Boltzmann constant, n is the number of foil layers, r is the reflectivity, and Q is the power radiated away through the insulation. Because of the high temperatures involved the first two layers should be titanium and the other four layers should be aluminum.

Electromagnetic pumps (see Fig.7.9) provide the pressure necessary to force liquid metal through the pipe. These work by passing direct current through the liquid metal at right angles to a magnetic field. This produces a force on the fluid. The pumps will have metal contacts (tungsten alloy) extending into the fluid. The pumps may also be designed to provide heat if any cooling does occur. The size of the pump was determined from current industrial pump sizes, and by calculation of the fluid flow rate and pressure needed. Costing for pumps was done by comparison with pumps used by the nuclear power industry. Cost estimates for the pipeline itself were also based on information about currently available materials. R & D for the pipeline should include long term exposure of the materials to vacuum and corrosion resistance testing.

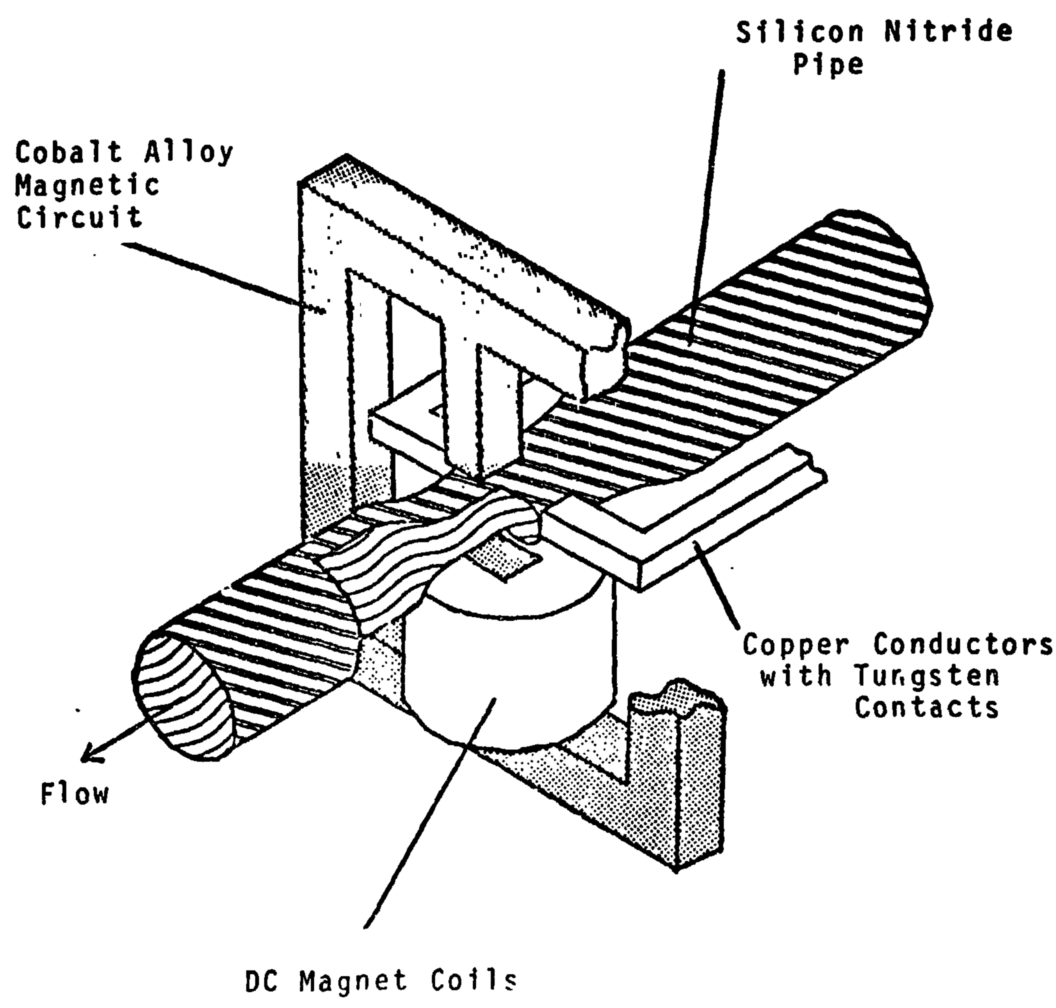


FIGURE 7.9: LIQUID ALUMINUM PIPELINE

SPECIFICATION SHEET

Machine Name: Liquid Aluminum Pipeline

Function of Machine: To transport liquid Al within the SMF

Mass of Machine: 115 kg

Physical Dimensions: 30 m x .2 m; 6 mm wall thickness

Throughput/Machine (tons/year): 1.03×10^4

Power Requirements (KW/machine): .01

Number of Machines: 4

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Pipe Sections	13	3	0
Pipe Joint	11	.5	0
EM Pump	7	10	.01

7.2.5 Liquid Iron Pipeline: The iron pipeline moves liquid iron or SENDUST alloy from the iron furnace to the die caster. The iron pipeline is made of graphite to provide corrosion resistance. Like the aluminum pipeline, the maximum flow rate is .6 kg/sec; however the iron pipeline will only be required to carry 1900 tons/year in mormal operation.

For costing information and other details see Sec. 7.2.4, "Liquid Aluminum Pipeline".

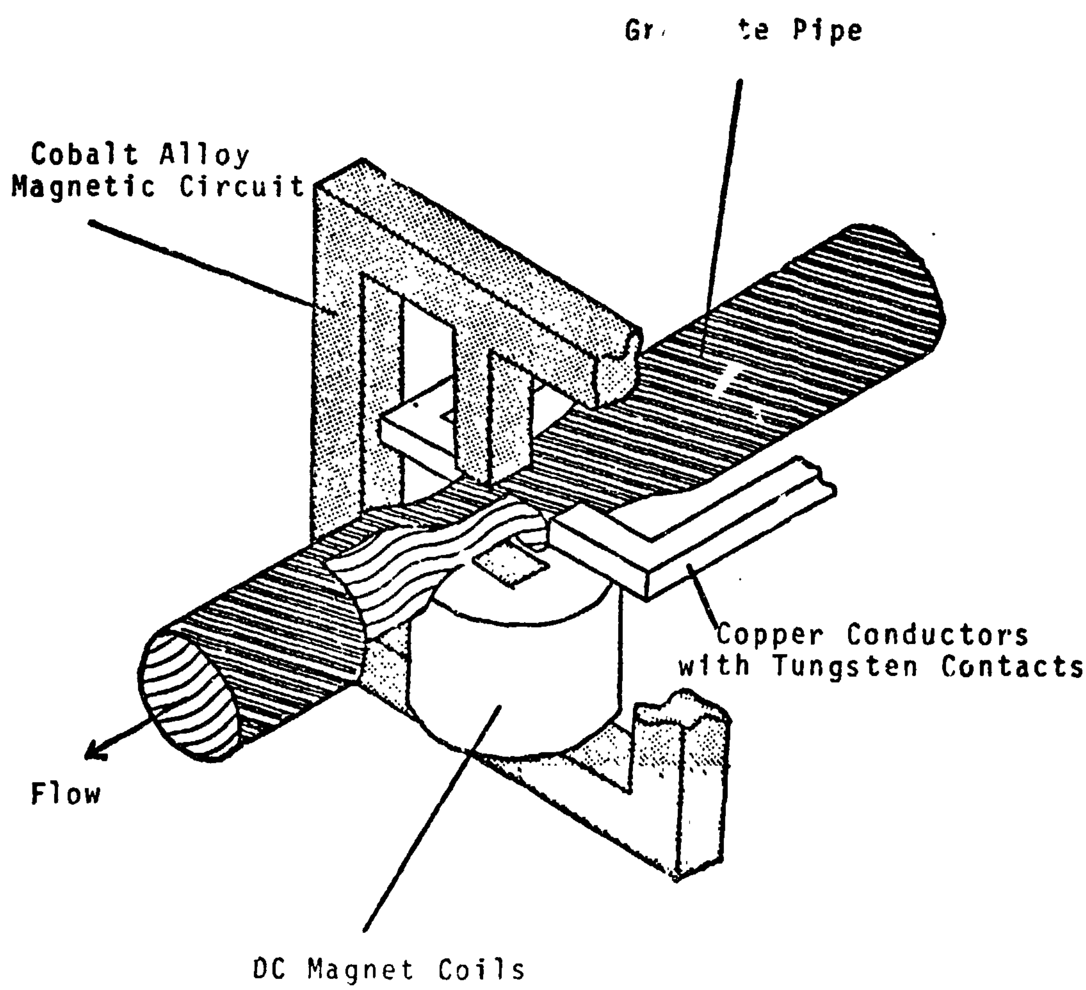


FIGURE 7.10: LIQUID IRON PIPELINE

SPECIFICATION SHEET

Machine Name: Liquid Iron Pipeline

Function of Machine: To transport liquid Fe within the SMF

Mass of Machine: 75 kg

Physical Dimensions: 30 m x .2 m (incl. foil insul.); 2mm wall

Throughput/Machine (tons/year): $1.? \times 10^3$

Power Requirements (KW/machine): 0

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Pipe Segments	5	10	0
Joints	3	1.5	0
EM Pump	2	10	.001

7.2.6 Continuous Caster: The continuous caster is designed to produce aluminum slabs from liquid aluminum. Continuous casting is especially suitable for use in space because it can produce uniform slabs in the absence of troublesome convection currents induced by gravity. The caster consists of a mold and a heat removal systems which circulates a quantity of liquid sodium coolant between the mold and a radiator.

The caster width is sized for structural member ribbon production: each slab has cross-section .70 x .02 meters. After rolling, the width increases to .735 meters, the width required for structural member ribbon. The 2-cm mold thickness is the result of trading off the ease of liquid metal injection and the ease of rolling the resultant slabs. The search for a material that is both highly conductive (for heat removal) and resistant to liquid Al corrosion resulted in the selection of graphite as a mold material.

The cooling system is designed to cool the metal from 800°C at a rate of 1 kg/sec (or 3.2×10^4 tons/year) operating at maximum capacity. Cooling fluid flows in sheets across the upper and lower surfaces of the mold. The temperature of the coolant must be high enough to allow effective heat radiation to space and low enough to prevent the formation of defects in the slabs (which requires a large thermal gradient in the mold). Liquid sodium, used on Earth for cooling at high temperatures, has the advantages of high heat capacity and established pumping and piping technology. Therefore the system is designed to allow sodium to enter the cooling jacket at 200°C and leave at 400°C. At a throughput of 1 kg/sec of metal, liquid sodium must flow at a rate of 2.8 kg/sec, removing 725 kW of power. A radiator of 1 mm thick aluminum with an area of 180 m^2 radiates away heat from the sodium at an effective temperature of 275°C.

Cost estimation for the continuous caster was aided by consultation with experts on sodium cooling systems presently used in nuclear reactors. Such systems, the study group was told, have virtually a 100% duty cycle.

SPECIFICATION SHEET

Machine Name: Continuous Caster

Function of Machine: To produce slabs of Al or Al 6063 alloy

Mass of Machine: 890 kg

Physical Dimensions: .8 m length; .7 m width; ~.1 m thickness

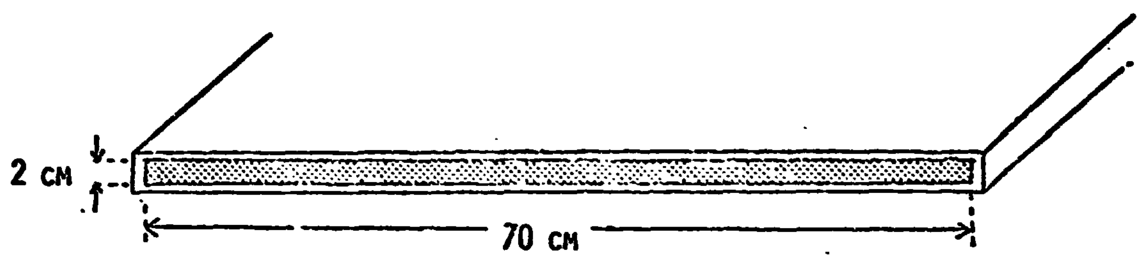
Throughput/Machine (tons/year): 3.65×10^4

Power Requirements (KW/machine): 20

Number of Machines: 2

Number of Operators: 0

Components:	Number/ Machine	Mass (Kg)	Power Required (KW)
Mold	1	100	0
Fluid Coolant	1	100	0
Piping System	1	150	0
Pump	4	10	20
Radiator	1	500	0



Mold Cross-Section

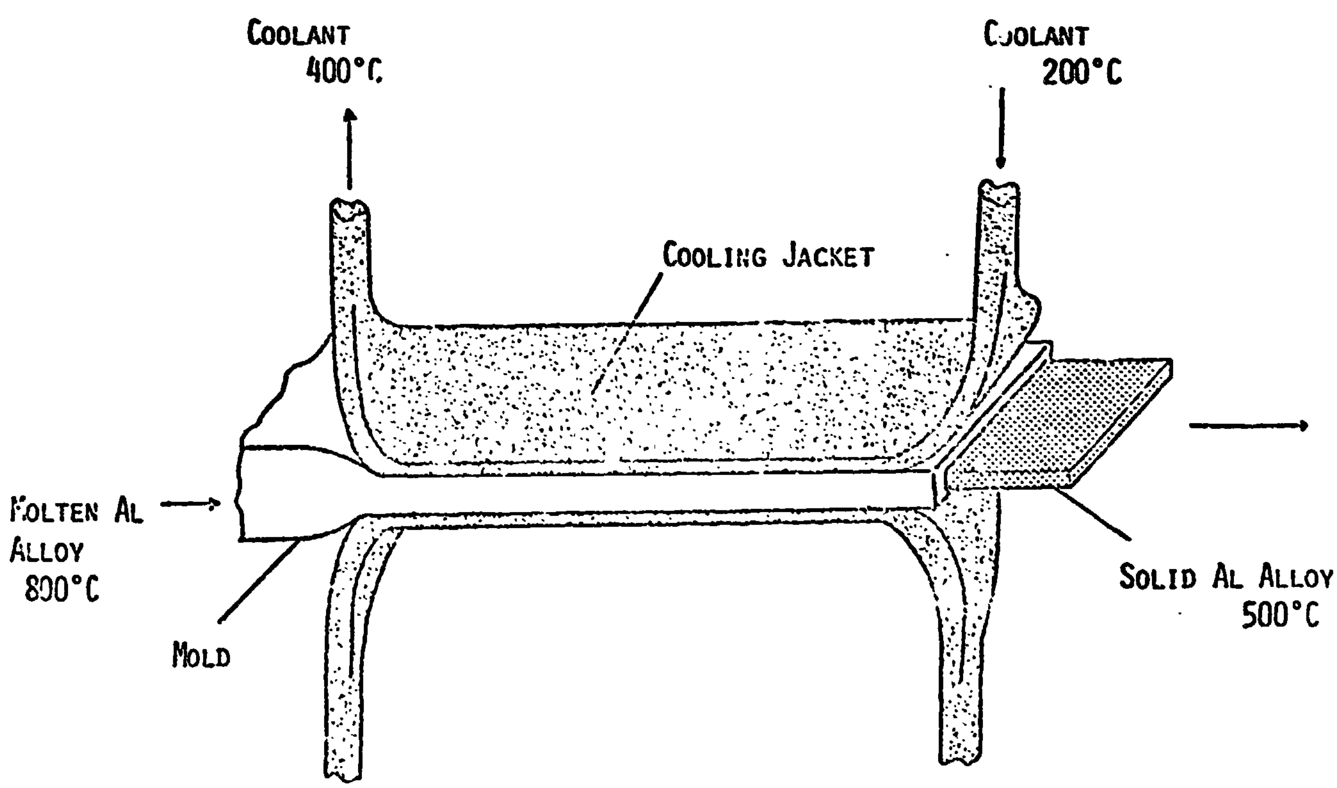


FIGURE 7.11: CONTINUOUS CASTER

7.2.7 Aluminum Slab Cutter: Aluminum emerging from the continuous caster is cut into slabs with cross-sections .70 m x .02 m, and lengths varying according to the needs o later production processes. The cut is made by a heavy duty electron beam gun as shown in Fig. 7.12. The device operates at a power level of 128 kg to cut the 2 cm thick cast aluminum at a rate of 4.2 cm/sec. This assumes typical efficiencies of 50% in the gun and 50% in the sublimation of the metal.

In an electron beam gun, a tungsten filament is heated to incandenscence, causing electrons to boil off. The electrons are formed into a beam and accelerated by a potential of several hundred thousand volts through a cylindrical anode. The electrons are focused by an electromagnetic lens to a 0.1 - 1 mm spot on the slab where they release their kinetic energy, vaporizing the material in the cutting area. Deflection coils provide some lateral movement of the focal point, but the gun also moves along a track inclined at 50 to the direction of motion of the slab, therby making a perpendicular cut across the slab.

Vacuum is the best condition for EB cutting operations, since the electron beam is dispersed by collisions with any gas molecules. Vacuum requirements are the main reason why lasers are more commonly used for beam cutting on earth: electron beam guns, however, are more energy-efficient and penetrate deeper.

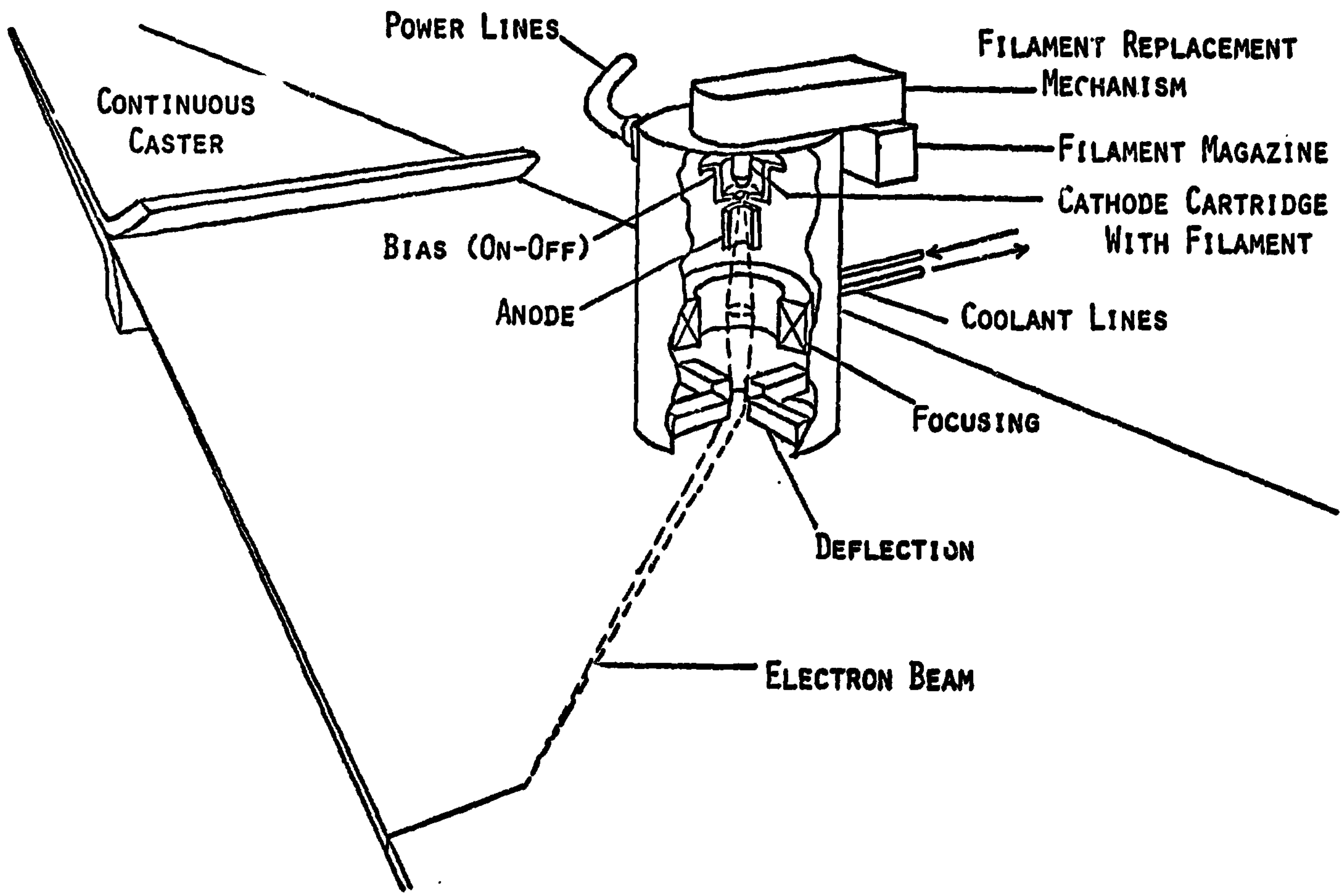


FIGURE 7.12: ALUMINUM SLAB CUTTER

The only consumable item in an EB gun is the tungsten filament which must be replaced every 8 hours (in a cutting gun) because of contaminating vapor from the bombarded material. A refill magazine of 20 filaments and a spare cathode is mounted directly on the gun and automatically replaces a filament when one goes out.

Electron beam guns require a closed current loop to return the electrons to the cathode. Therefore, they can only be used on conductive materials, or the quick build-up of negative charge at the impact point will repel the electron beam, and the build-up of positive charge in the cathode will eliminate the potential difference accelerating the electrons. In slab cutting, electrons are returned to the gun via a metal brush sweeping across the slab surface next to the cutting zone.

Above 10KW power input, an EB gun probably cannot be effectively cooled by a passive radiator. An active cooling system employing liquid sodium is therefore used. Assuming a difference of 100°K between the input and output temperatures, .5 kg/sec of liquid sodium must circulate through the gun.

Accelerating voltage, focusing current, beam current, lateral sweep speed, and gun-to-slab distance are all control parameters of a gun. By increasing the accelerating voltage or focusing current, the size of the focused spot can be decreased, causing deeper penetration. Increasing the beam current or decreasing the sweep speed will also increase DV penetration. The distance between the slab and gun will also affect the intensity of the focused spot since the greater the traveling distance, the higher the space-charge repulsion effect, which 'spreads out' the electron in the beam. Reference 7.1 discusses numerical control of an EB gun.

SPECIFICATION SHEET

Machine Name: Aluminum Slab Cutter

Function of Machine: To cut Al slabs (outputs of continuous caster)

Mass of Machine: 96 kg

Physical Dimensions: 2 m x 1.5 m x 2 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 130

Number of Machines: 2

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	1	50	128
Gun Tracking	1	25	1
Active Cooling System	1	21	1

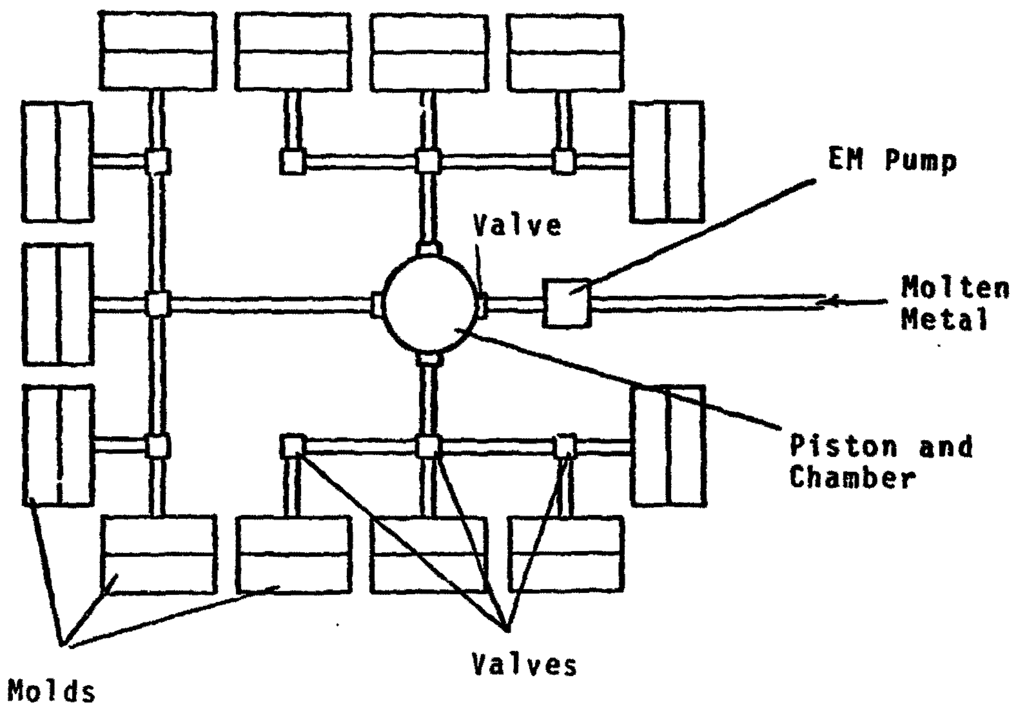
7.2.8 Al and Fe Die Casters: Casting on Earth is accomplished by ladling liquid metal into a sleeve, then driving it into a metal mold with a piston at high pressure (1.5×10^8 N/m^2).

To adapt this process for use in space, a valve is placed near the entrance to the sleeve (see Fig. 7.13). In order to cast many pieces efficiently, the study group has designed a system in which several molds can be fed by one piston and one liquid metal pipeline. The charging of the molds is controlled by valves at one end of the piston sleeve. An active cooling system circulates fluid around each mold. Once the casting in a mold has solidified, the mold is opened, allowing the casting to be removed to a storage frame. Castings produced by the die caster include: solenoid poles, solenoid cores, klystron housings, manifold parts, end joints and joint clusters.

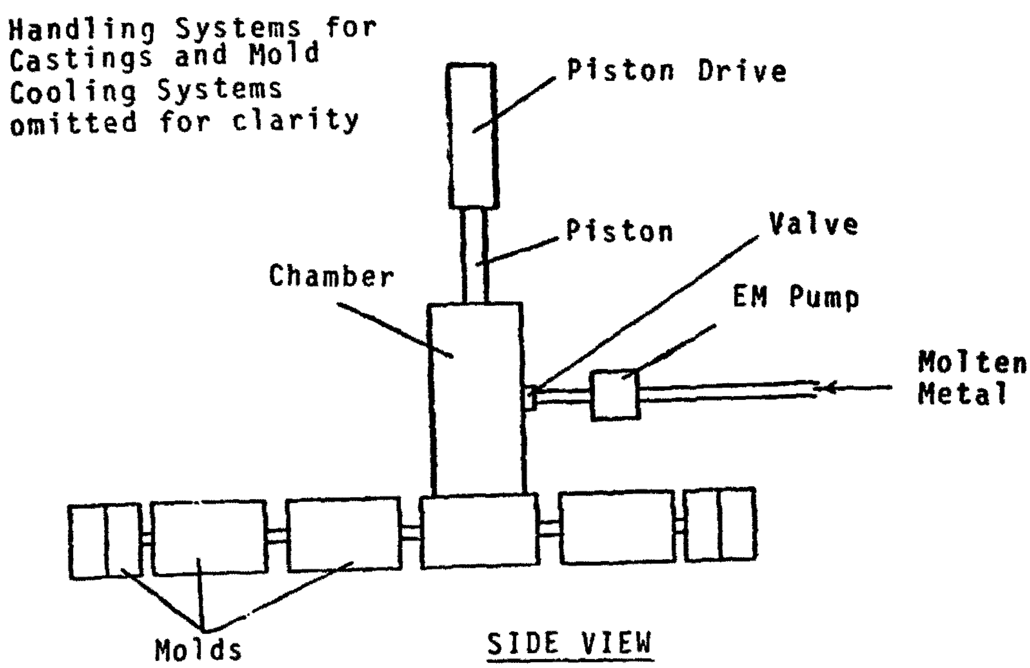
Cost estimates for the die caster were based on the assumption that an earth-based die caster could be reduced in mass by at least 50% when redesigned for space use.

Two such die casters are used in the reference SMF; one for the production of aluminum and aluminum alloy components, the other for the casting of iron pole pieces for klystrons.

The aluminum die caster produces manifold parts, klystron housings, solenoid cores, end joints, and joint clusters. Of the 19 molds, 5 are devoted to the production of alloy end joints and joint clusters, which require approximately 70 hours of production time per year (assuming one molding every two



TOP VIEW



SIDE VIEW

FIGURE 7.13: DIE CASTER

minutes). The remaining 14 molds are used in the manufacture of aluminum products.

The iron die caster is used to produce the soft iron solenoid pole pieces required for klystron production (448,000 per year). One mold is used in the production process.

SPECIFICATION SHEET

Machine Name: Al Die Caster

Function of Machine: To cast parts from liquid Al and Al alloy.

Mass of Machine: 35,500 kg

Physical Dimensions: 6 m x 6 m x 4 m

Throughput/Machine (tons/year): 4.1×10^3

Power Requirements (KW/machine): 290

Number of Machines: 1

Number of Operators: .25

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
Piston and Chamber	1	15000	75
Molds	19	1000	5
Active Cooling System	1	1000	50
Radiator	1	500	0

SPECIFICATION SHEET

Machine Name: Fe Die Caster

Function of Machine: To cast parts from liquid Fe

Mass of Machine: 3150 kg

Physical Dimensions: 4 m x 3 m x 4 m

Throughput/Machine (tons/year): 800

Power Requirements (KW/machine): 23

Number of Machines: 1

Number of Operators: .25

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Piston and Chamber	1	2000	10
Molds	1	1000	5
Active Cooling System	1	100	8
Radiator	1	50	0

7.2.9 Transformer Core Caster: Because the transformer cores are much larger than the other die cast parts, a separate facility has been designed for their production. This facility will be operated in the same fashion as the die caster.

The mold must measure 1 x 2 x 3 meters. After cooling, an operator removes the casting from the mold and delivers it to a storage area.

Mass estimates for this device are based on a scaling up of the die caster (see Sec. 7.2.8).

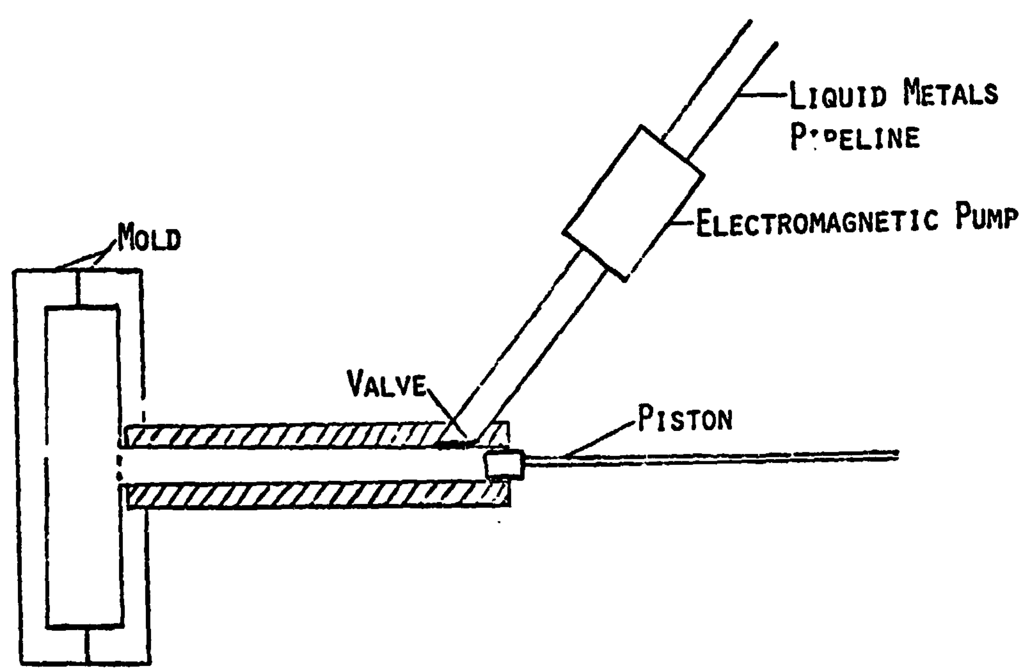


FIGURE 7.14: TRANSFORMER CORE CASTER

SPECIFICATION SHEET

Machine Name: Transformer Core Caster

Function of Machine: To cast transformer cores

Mass of Machine: 11,500 kg

Physical Dimensions: 1 m x 2 m x 10 m

Throughput/Machine (tons/year): 1.1×10^3

Power Requirements (KW/machine): 110

Number of Machines: 1

Number of Operators: .04

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Caster	1	10000	50
Active Cooling System	1	1000	60
Radiator	1	500	0

7.3: RIBBON AND SHEET OPERATIONS

7.3.1 Overview: Figure 7.15 shows a top view of the ribbon and sheet operations section of the components factory.

Slabs of 6063 Al alloy and pure aluminum are received at the rolling mills from the continuous casters (described in Sec. 7.2).

The alloy is rolled to a thickness of 1.77 mm and dispatched as a .74 m wide ribbon to the end trimming and welding area. Here ends of the ribbon are trimmed square by electron beam cutters. The successive ribbons are welded together to form long ribbons, and the long ribbons are wound onto rollers. During winding, teflon sheets are placed between successive layers of aluminum in order to prevent vacuum welding of the ribbon surfaces. The rolls of 6063 alloy are dispatched to the output area to be used as structural member ribbon.

The pure aluminum is rolled to a thickness of 1 mm and dispatched to one of three areas; end trimming and welding (to be dispatched as busbar strips), sheet trimming (to be cut square by electron beam cutters and used in the formation of radiator sheets), or to the ribbon slicer (to be cut into strips for the manufacture of heat pipes).

Ribbon from the ribbon slicer is then either: trimmed in the ribbon trimmer and used as heat pipe ribbon in radiator assemblies; striated, form rolled and trimmed, and used as heat pipe segments in radiator assemblies; formed rolled and trimmed (without striation) for use as radiator pipe segments

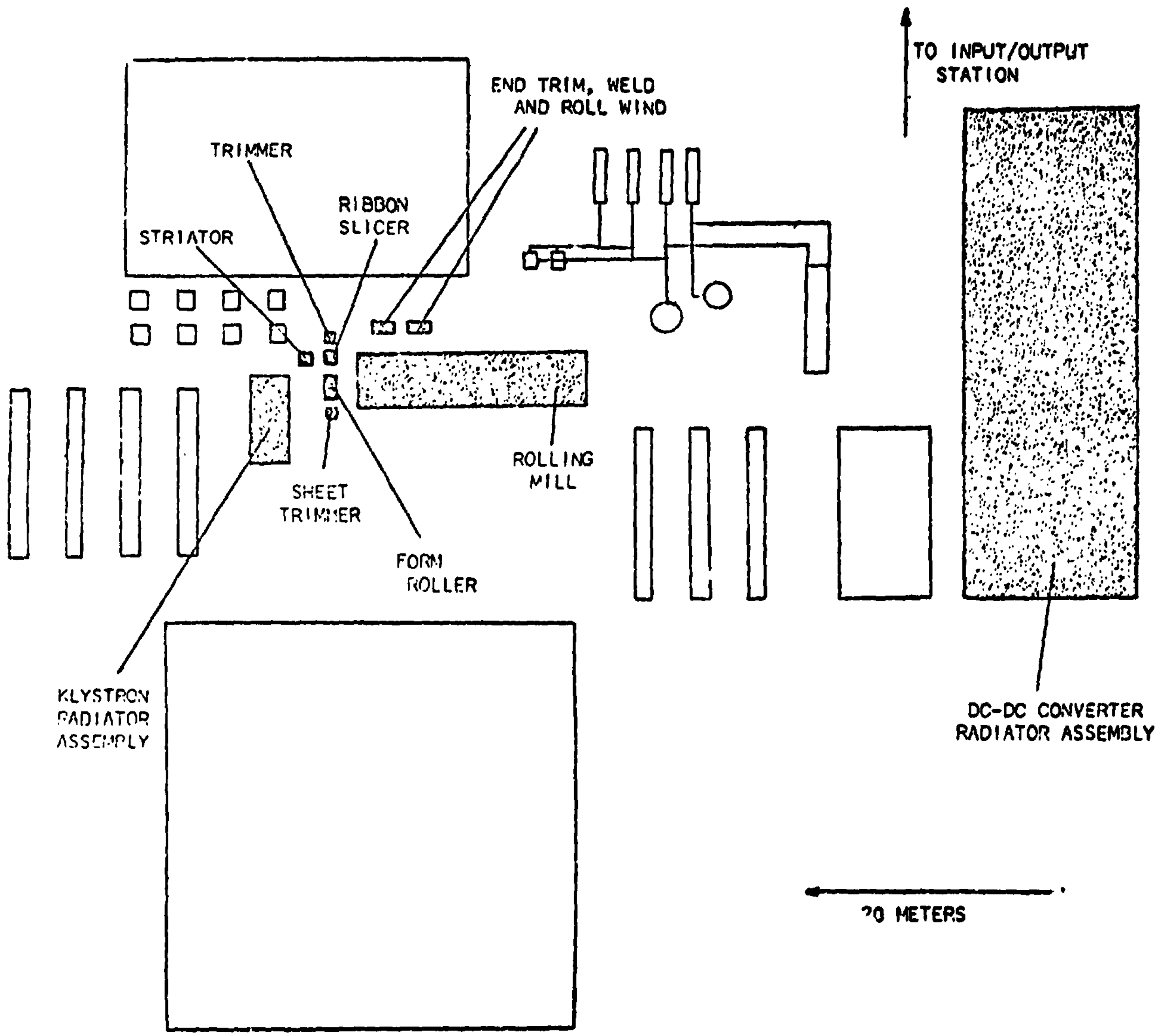


FIGURE 7.15: LAYOUT OF METALS, FURNACES AND CASTERS

in DC-DC converter radiator assembly; or spooled and used as electrical wiring.

Sheets from the sheet trimmer are laid out and electron beam welded together to form radiator sheets for the klystron and DC-DC converter assemblies. Because of the size of the DC-DC converter radiators, they cannot be transported through the factory and are therefore assembled close to the dispatch area to minimize the handling required.

The outputs of this section are then: structural member ribbon, busbar strips, klystron radiators, aluminum wire, and DC-DC converter radiators. The machines used are described below.

7.3.2 Rolling Mill: To produce sheet for use in structural members and other products, it is desirable to cold-roll the stock to give the sheet greater strength. Unfortunately, an attempt to cold-roll aluminum stock to greater than 120% of its original length will produce unwanted cracks in the product. The SMF rolling mill is therefore designed to hot-roll aluminum at all stages but the final one. To facilitate hot-rolling, the mill receives slabs directly from the caster, at 500°C. In the event of a production stoppage at the caster, heating elements at the entry to the rolling mill are put into operation. These consist of electrodes which pass large currents through slabs arriving from storage (see Fig. 7.16).

Once in the mill, slabs first pass through "roughing rollers" which have vertical as well as horizontal rolls designed to maintain the shape of the sheet. Horizontal rolls are 45 cm in diameter; vertical rolls are 20 cm in diameter. Finishing rollers then produce sheets that are close to the desired size. Finally, the sheets may be passed through an active cooling device and cold-rolled at 150°C in the final stage.

The various stages of this rolling mill can be set to different roller spacings, thus producing sheet anywhere from 1 mm to 20 mm thick. In addition, the cold-rolling steps can be omitted if structural strength is not required in the product (in this case the product travels through the cooling jacket and final rolls unchanged).

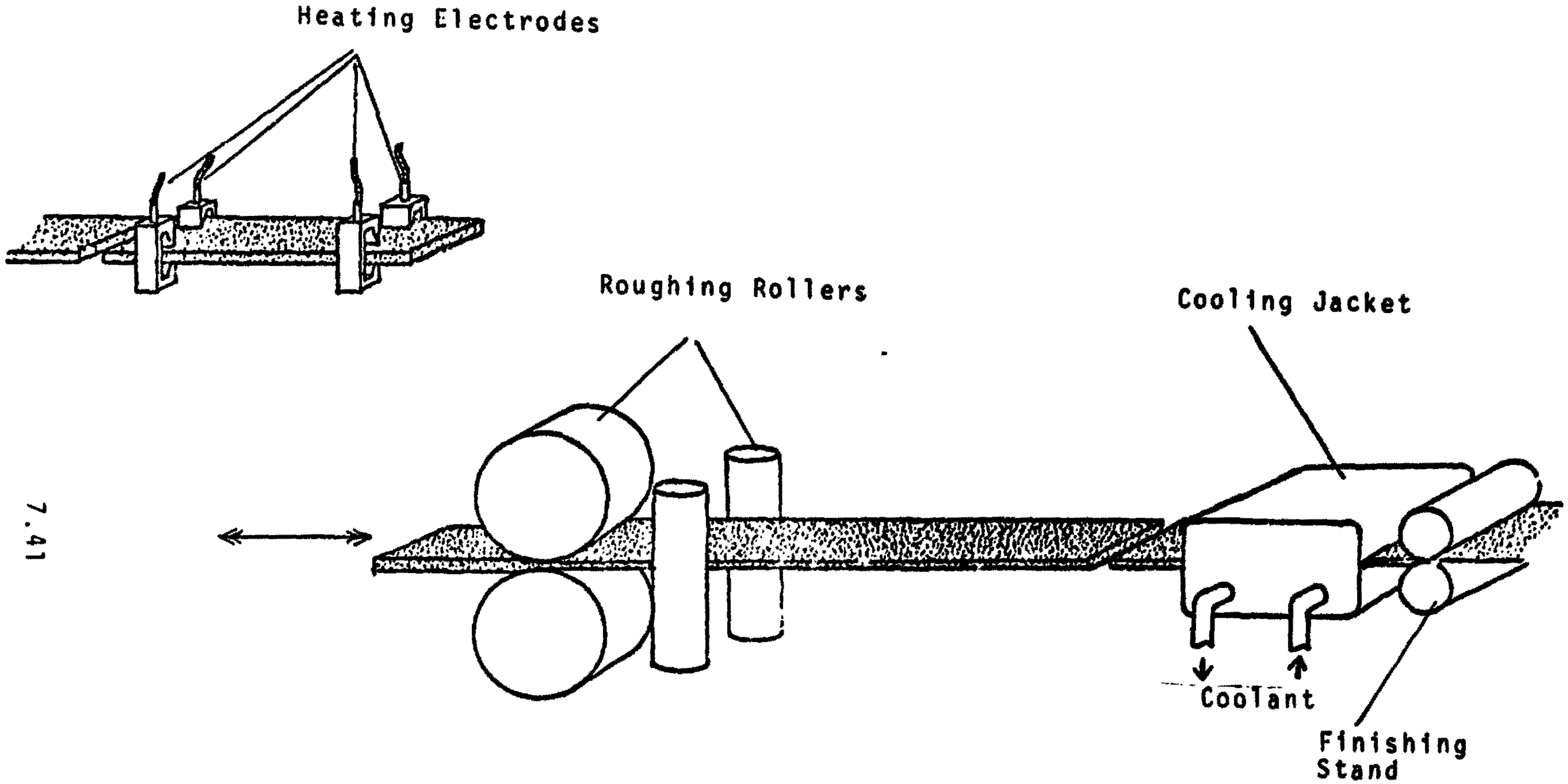


FIGURE 7.16: ROLLING MILL

SPECIFICATION SHEET

Machine Name: Rolling Mill

Function of Machine: Production of sheets from slabs

Mass of Machine: 187,000 kg

Physical Dimensions: 17 m x 2 m x 5 m

Throughput/Machine (tons/year): 3.65×10^4

Power Requirements (KW/machine): 410

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Preheat System	1	·100	10
Roughing Stand	1	105000	225
Cooling System	1	10000	5
Finishing Stand	1	70000	150
Radiatcr	1	100	10
Handling & Control System	1	2000	10

7.3.3 End Trimming, Welding, and Roll Winding: These operations are show in Fig. 7.17. Aluminum ribbon (1 mm thick) or 6063 Al alloy ribbon (1.77 mm thick) are fed from the rolling mill through the end trimmer. The trimmer consists of an electron beam gun which cuts the ends of the ribbon "square" (perpendicular to the ribbon edges). Subsequent ribbons of the same material and gauge are then EB welded end to end. The ribbons produced are wound onto spools with teflon sheets between successive layers of aluminum to prevent vacuum welding. The strips produced by welding are 660 m long in the case of the 1 mm gauge aluminum destined for use as busbars, and of a length suitable for use in a beam builder in the case of the 6063 Al alloy structural member ribbon (1.77 mm thick).

The teflon used in the rolls is returned to the SMF from the SPS assembly site every three months. However, the quantity of structural member strips produced necessitates an initial stock of 3000 rolls.

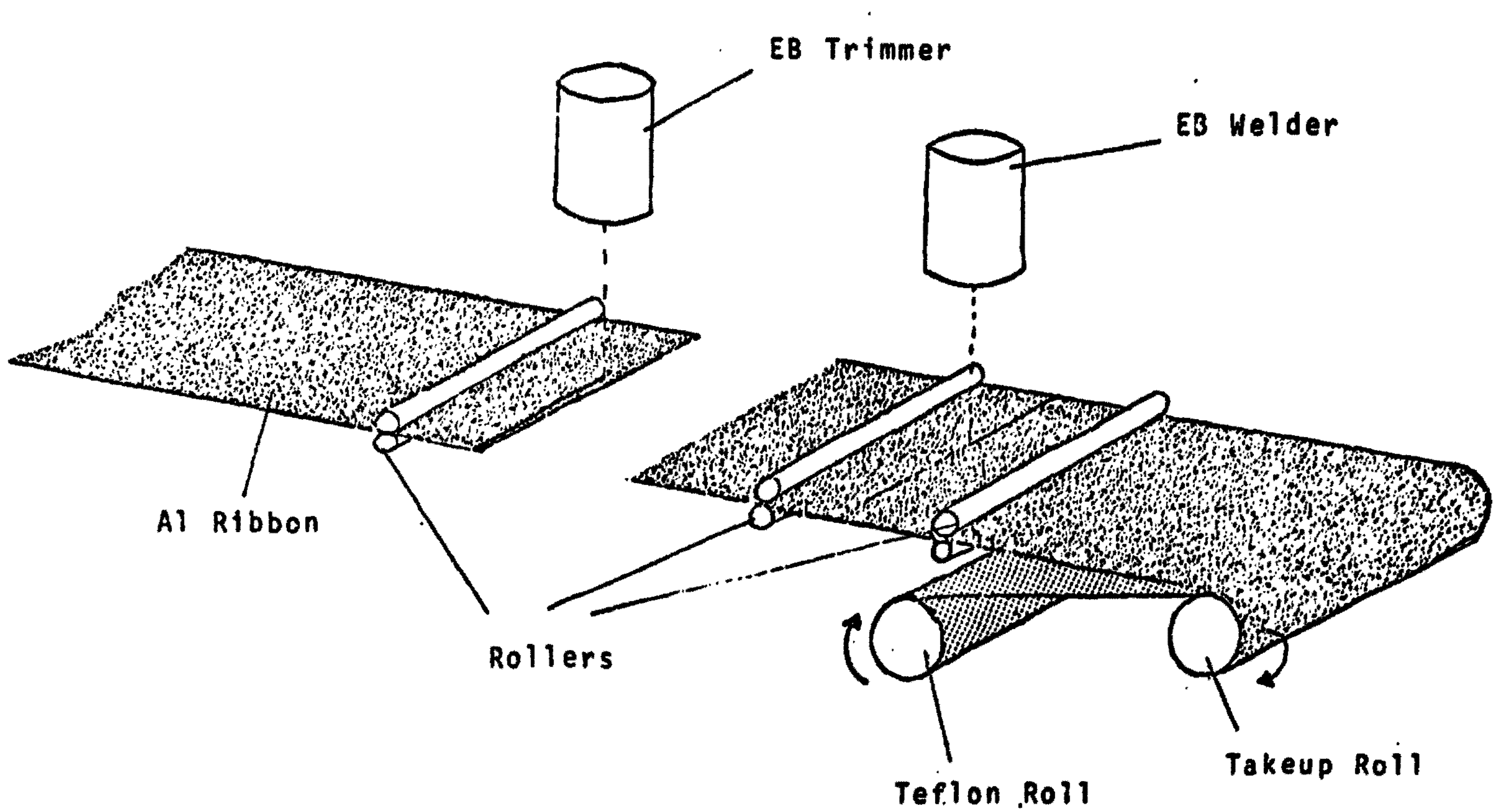


FIGURE 7.17: END TRIM, WELD, AND ROLL WINDER

SPECIFICATION SHEET

Machine Name: End Trimming & Welding & Roll Winding

Function of Machine: Creation of structural members and bus-bars from sheet

Mass of Machine: 840,000 kg

Physical Dimensions: 1 m x 1 m x 2 m

Throughput/Machine (tons/year): 12,700

Power Requirements (KW/machine): 70

Number of Machines: 2

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Trimmer	1	6	10
Focusing Device	1	2	3
EB Welder	1	2	1
Roll Winder	1	500	50
Teflon Rolls	3000	280	0
Handling Equipment	1	100	5
Active Cooling System	1	14	1

7.3.4 Sheet Trimmer: Ribbons to be used in the assembly of radiator sheets (see Secs. 7.39 and 7.3.10) are trimmed to be precisely rectangular (2.15 x .72 m) by an actively cooled electron beam sheet trimmer. The need for precision arises because the sheet pieces are later welded together edge-to-edge.

The ribbon, guided by rollers, first passes through two edge-trimming EB guns which reduce the strip width to 72 cm. The ribbon is then trimmed into 2.15 m long segments by another EB gun. This second gun cuts through the 1 mm sheet sufficiently rapidly to use electronic rather than a mechanical tracking mechanism.

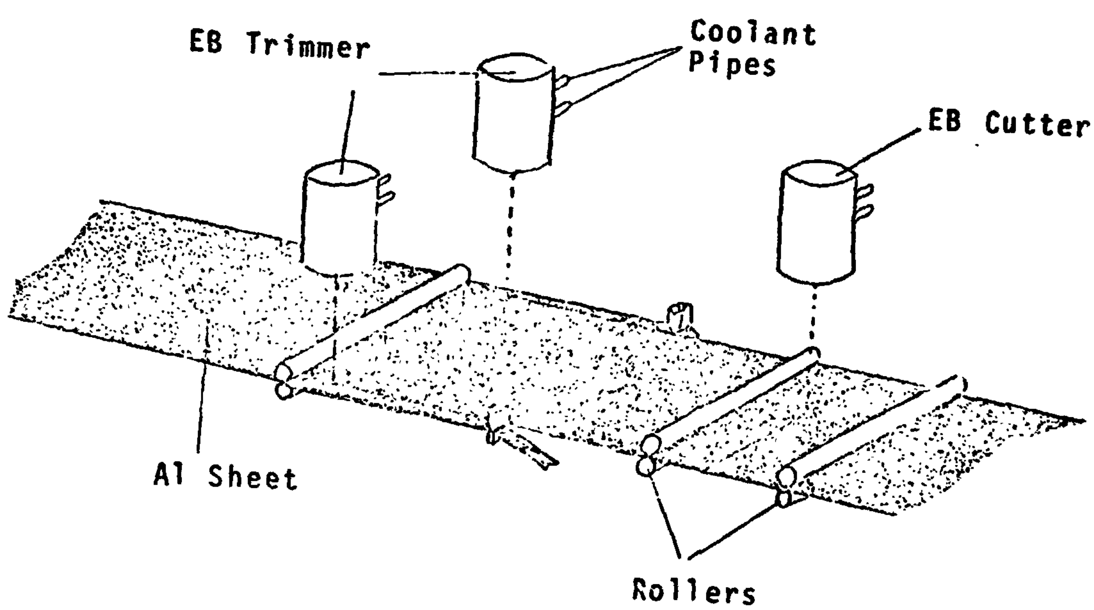


FIGURE 7.18: SHEET TRIMMER

SPECIFICATION SHEET

Machine Name: Sheet Trimmer

Function of Machine: Production of sheets for use in klystron radiators

Mass of Machine: 84 kg

Physical Dimensions: 2 m x 1 m x 1 m

Throughput/Machine (tons/year): 2.4×10^3

Power Requirements (KW/machine): 41.5

Number of Machines: 1

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
EB Cutters	3	6	10
Focusing Device	3	2	3
Handling Equipment	1	30	1
Active Cooling System	1	30	1.5

7.3.5 Ribbon Slicer: The ribbon slicing operation slices narrow strips of 1 mm gauge aluminum for use as electrical wires, and wider strips for heat pipe and rad ator manufacture.

The metal is sliced by being passed through a pair of rollers in a knife-and-slot configuration, which produces wires of varying width (and of square or rectangular cross-section). In order to prevent the cold welding of the aluminum as it is wound, the wire is wound onto spools which allow no contact between successive layers. The square cross-section of the wire produced allows a greater coil density to be achieved on winding.

The strips for heat pipe and radiator manufacture produced by the slicing rollers are then sent to the edge-trim and welding section described in Sec. 7.3.3.

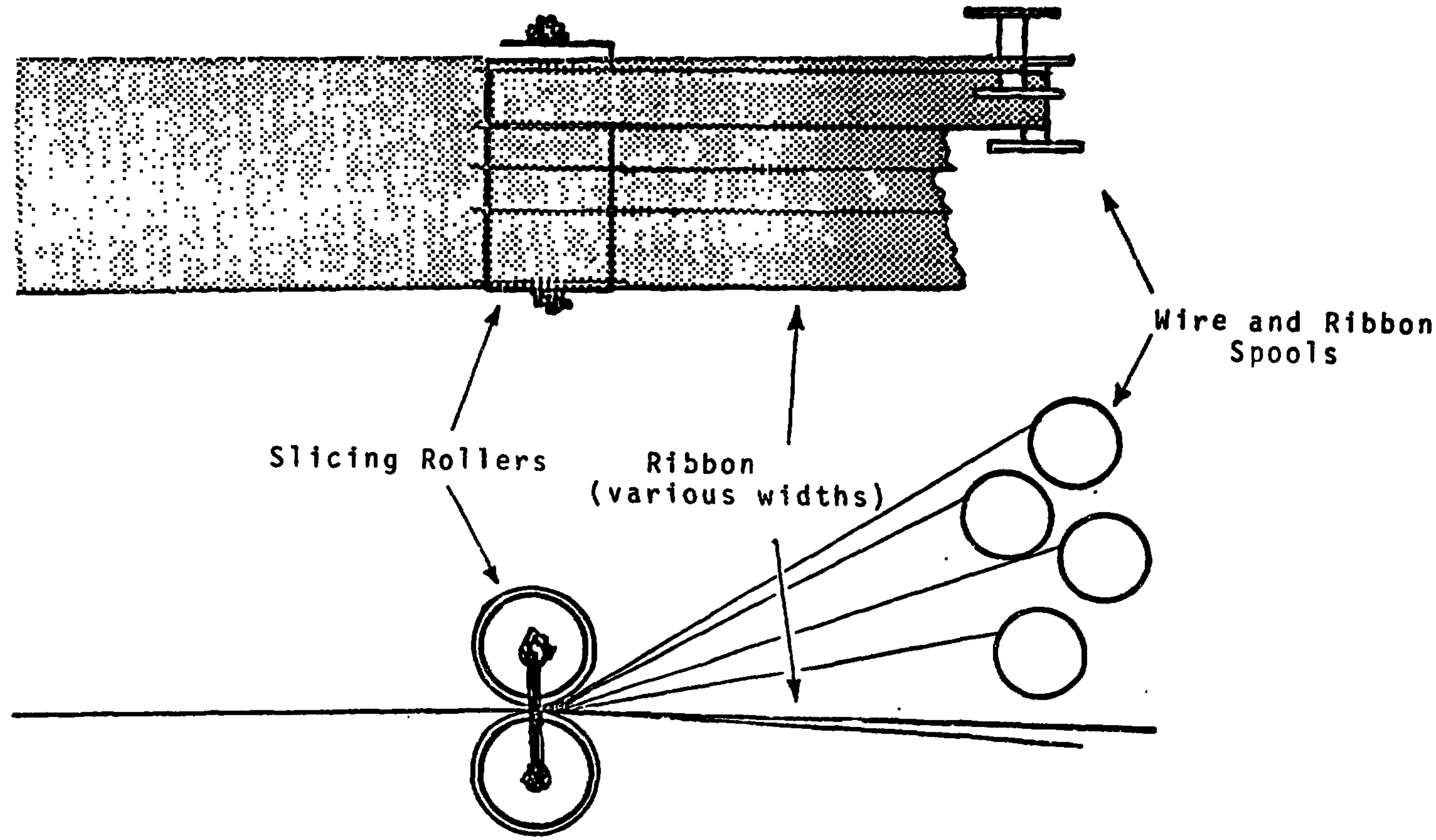


FIGURE 7.19: RIBBON SLICER

SPECIFICATION SHEET

Machine Name: Ribbon Slicer

Function of Machine: Production of wire and of strips for use in heat pipes and radiators

Mass of Machine: 70,000 kg

Physical Dimensions: 1 m x 1 m x 1 m

Throughput/Machine (tons/year): 6.0×10^3

Power Requirements (KW/machine): 231

Number of Machines: 1

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
Rolling Stand	1	70000	225
Handling Equipment	1	30	1
Spool Winder	1	50	5
Spools	100	2	0

7.3.6 Ribbon Trimmer: The ribbon trimmer is designed to square the ends of the heat pipe ribbon (fed from the ribbon slicer and used in klystron heat pipe manufacture). A 'clean' edge cut is required since a sealed edge joint must be formed between the radiator sheet and the ribbon.

A passively cooled electron beam gun is used to cut the ribbon as shown in Fig. 7.20. The ribbon to be trimmed is transported along rollers which position the ribbon so that the 'cut' is made perpendicularly to both edges. The cut ribbons are 1.6 m long, .125 m wide, and 1 mm thick. The power level of the gun is sufficiently high to cut rapidly enough so that a mechnical tracking system is not required.

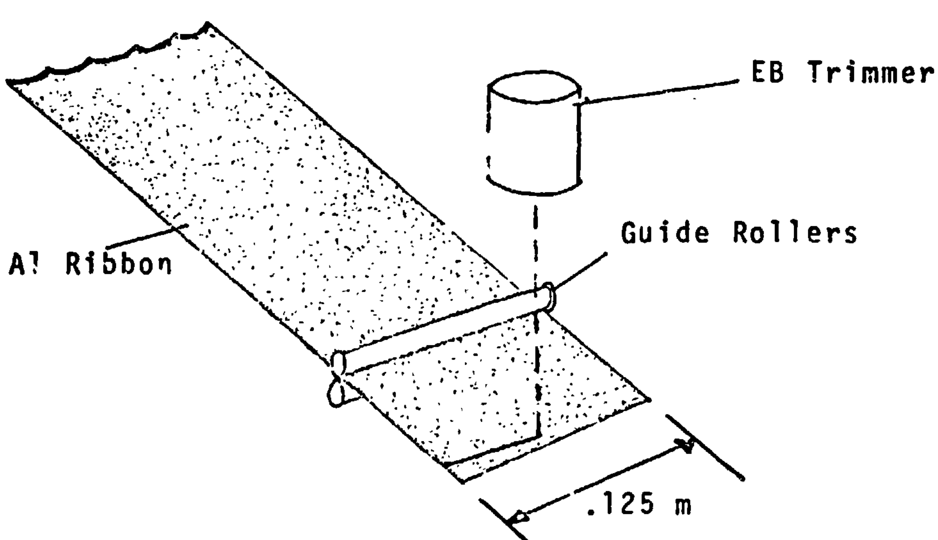


FIGURE 7.20: RIBBON TRIMMER

SPECIFICATION SHEET

Machine Name: Ribbon Trimmer

Function of Machine: To cut ribbon into segments sized for klystron radiator production

Mass of Machine: 30 kg

Physical Dimensions: 1 m x 1 m x 1 m

Throughput/Machine (tons/year): 7.3×10^2

Power Requirements (KW/machine): 4.1

Number of Machines: 1

Number of Operators: 0

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Cutters	1	8	3
Focusing Device	1	2	1
Handling Equipment	1	20	.1

7.3.7 Striator: The striator forms the striations which will become the capillary return paths in the heat pipes for the klystron cooling system. One-millimeter gauge aluminum is passed through the striator as shown in Fig. 7.21. The upper roller is configured to produce striations along the center section of the incoming ribbon, in preparation for form rolling this ribbon into heat pipe segments (discussed in Sec. 7.3.8).

The machine operates as a rolling mill and is conventionally used on Earth in similar operations. One end of the ribbon is left unstriated, in order to provide a flat closed end for the pipes (see Fig. 7.24).

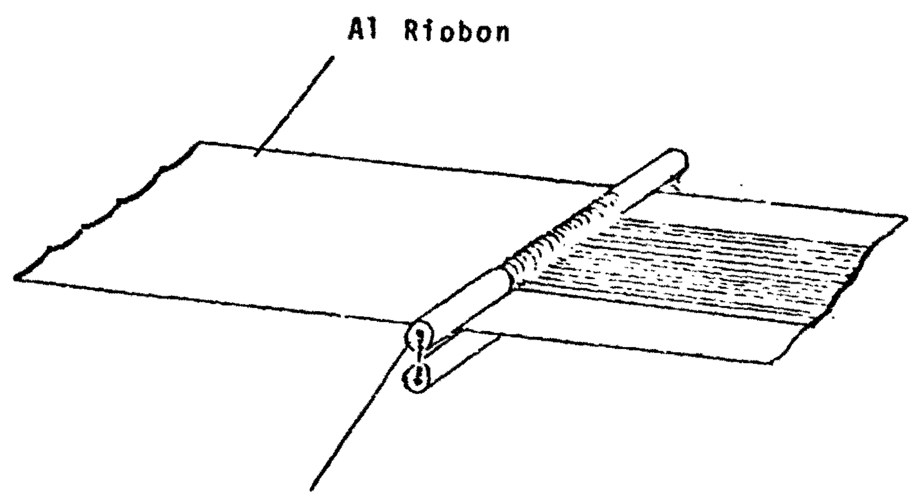


FIGURE 7.21: STRIATOR

SPECIFICATION SHEET

Machine Name: Striator

Function of Machine: Striation of heat pipe strips

Mass of Machine: 20,000 kg

Physical Dimensions: 1 m x 1 m x 1 m

Throughput/Machine (tons/year): 3.2×10^3

Power Requirements (KW/machine): 50

Number of Machines: 1

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
Striator	1	20000	50

7.3.8 Form Roller: The form roller is used to shape both plain ribbon and striated ribbon into 'hat shaped' heat pipe and radiator pipe cross sections (as shown in Fig. 7.22). However, one tip of the striated segments is lest unrolled (the unstriated tip) to provide a flat 'closed' end for the pipes. Plain strips are form rolled along their whole length, to form radiator pipe segments for the DC-DC converter radiators (see Sec. 7.3.10). The form roller assembly also includes an electron beam gun, which is used to trim the pipe segments after rolling.

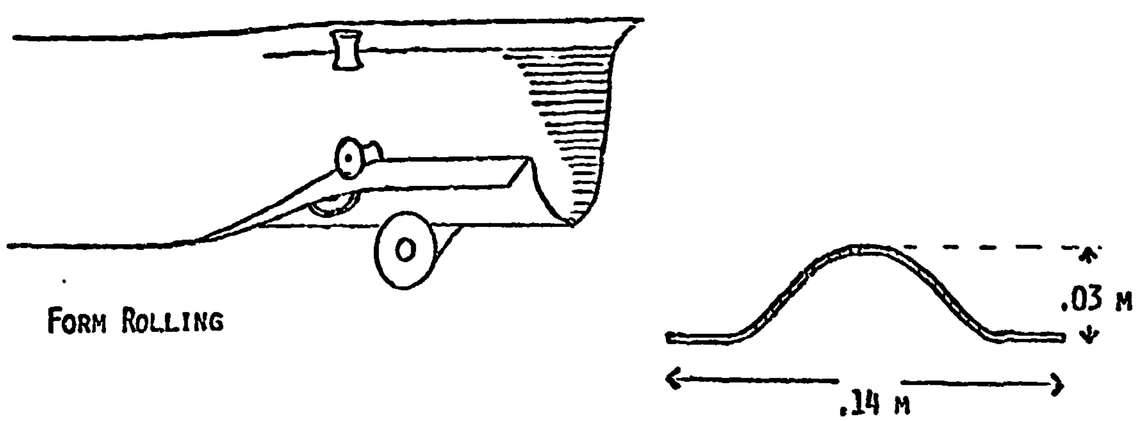


FIGURE 7.22: FORM ROLLER

<u>SPECIFICATION SHEET</u>

Machine Name: Form Roller

Function of Machine: Rolling of heat pipe strips into hat-shaped cross section

Mass of Machine: 3000 kg

Physical Dimensions: 1 m x 1 m x 2 m

Throughput/Machine (tons/year): 3.3×10^3

Power Requirements (KW/machine): 35

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Cutter	1	7	3
Focusing Device	1	2	1
Form Roller	1	3000	30
Handling Equipment	1	30	1

7.3.9 Klystron Radiator Assembly: Figure 7.23 shows the production of klystron radiators. Sheet output from the rolling mills (.72 x 2.15 m, 1 mm thick aluminum sheets) are stored in magazines (separated to avoid vacuum welding). Two sheets are simultaneously fed from the magazines and along guide tracks to an EB welding station. Here, the two sheets are joined at their inner edges to form a plate 1.44 x 2.15 m (the klystron radiator sheet). The radiator is completed by welding into position six heat pipes, stored in magazines alongside the tracks.

Figure 7.24 shows the three principal steps in the attachment of heat pipes to the klystron radiator sheets. The top figure shows an overview of the radiator sheet immediately after it has been welded together. Six heat pipe segments (only one is shown) are moved from the heat pipe segment magazines across the radiator sheets until their form-rolled 'open' ends extend beyond the sheet, and their flat 'closed' ends sit on the sheet. EB welders then weld the segment edges to the sheet.

Next, the open ends of the heat pipe segments are bent over (middle figure). This brings the end of the pipes to the expected location of the klystron (relative to the radiator sheet). Six heat pipe ribbons are then fed from their magazines, and their ends are welded to the radiator-sheet/heat-pipe-segment edge. The ribbons are then bent to fit against

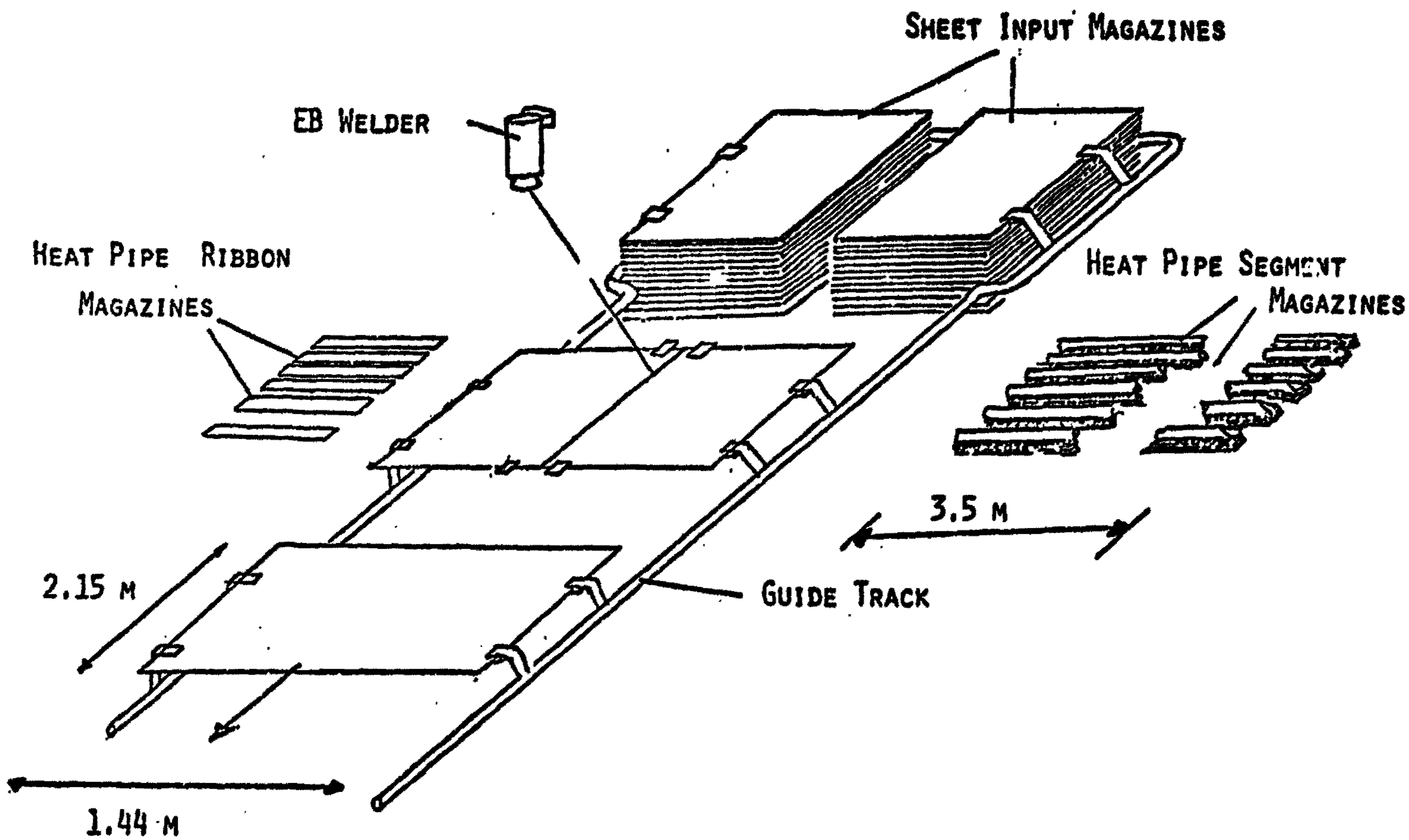


FIGURE 7.23: SHEET LAYOUT AND KLYSTRON RADIATOR MANUFACTURE

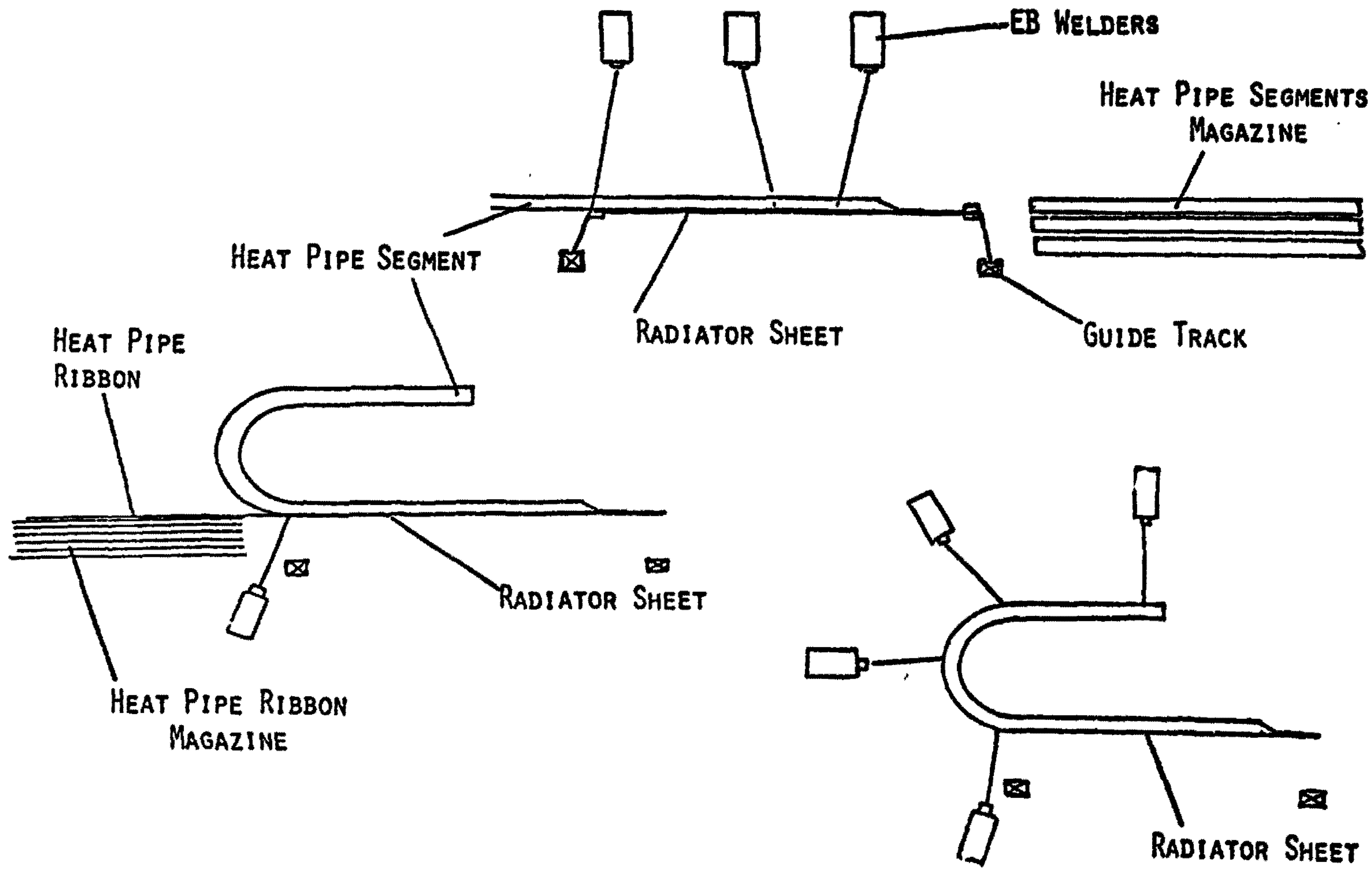


FIGURE 7.24: KLYSTRON RADIATOR ASSEMBLY SEQUENCE

the heat pipe segments, and welded to complete the heat pipes (bottom figure).

The purpose of this assembly sequence is to form heat pipes with one continuous piece along their entire length -- the heat pipe segment. This allows the use of striations along the segment as capillary return paths for the heat pipe fluid, avoiding the need to insert a return wick in the pipe. The study group could not devise a simple, reliable method to connect striations across pipe joints, and so developed this continuous piece design.

Should the heat pipes be replaced by fluid pipes (as in a recent Boeing SPS design iteration), a similar process can produce fluid pipes open at both ends, or a pipe and manifold design can be substituted (such as for the DC-DC converter radiators, see Fig. 7.25).

Klystron-radiator-size sheets are also produced without attachment of heat pipes, and sent to magazines feeding the DC-DC converter radiator assembly (see Fig. 7.25).

SPECIFICATION SHEET

Machine Name: Klystron Radiator Assembly

Function of Machine: Automated assembly of klystron radiators

Mass of Machine: 636 kg

Physical Dimensions: 15 m x 10 m x 3 m

Throughput/Machine (tons/year): --

Power Requirements (KW/machine): 93

Number of Machines: 7

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	49	3	1
Focusing Device	49	1	.5
Sheet Magazine	2	10	.5
Sheet Track & Transport	6	10	.5
Pipe Segment Magazine & Transport	6	10	.5
Pipe Ribbon Magazine & Transport	6	5	.5
Pipe Segment Bender	6	30	1
Pipe Ribbon Bender	6	15	.5

7.3.10 DC-DC Converter Radiator Assembly: Figure 7.25 shows the DC-DC converter radiator assembly system. Sheets of 1 mm thick aluminum (from the sheet layout station) are stored in a sheet magazine. Seven of these sheets are joined to form a strip 10.08 x 2.15 m. Seventeen such strips are joined edge-to-edge to form the DC-DC converter radiator sheet. Although ommitted from the figure for clarity, a number of rollers help the edge clamps to align the edges of the sheets before welding. Also, the EB welders first tack-weld the edges in several places, to avoid separation of the pieces due to thermal effects during the line-welding.

As the radiator sheet grows, manifolds and radiator pipes are welded onto the surface. The function of the manifold (a cast piece) is to spread the hot coolant fluid from on main feed pipe to nine pipes running along the back of the radiator sheet. A similar manifold at the other end of the radiator gathers the cooled fluid from the nine pipes and channels it into one output pipe.

The nine radiator pipes are each made from 10 radiator pipe segments (3.45 m long) with the cross-section shown in Fig. 7.22 but without striations. The pipe segments are positioned on the sheet from nine overhead magazines, and each segment is EB welded into position.

The finished radiator masses 1421 kg, and is too large to travel in the SMF internal transport system. Therefore this assembly station is located near the docking area, and

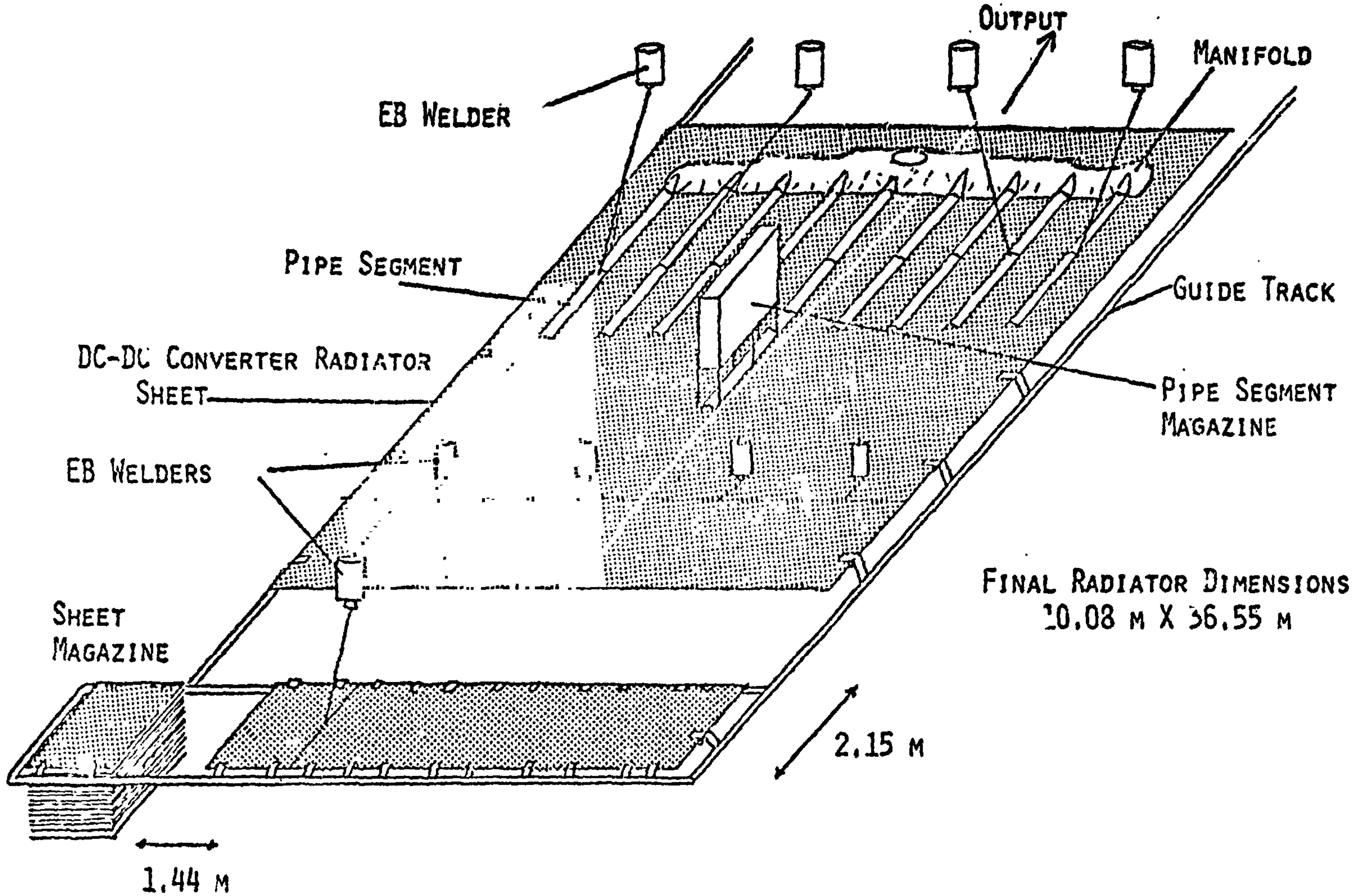


FIGURE 7.25: DC-DC CONVERTER RADIATOR PRODUCER

the long manipulators used for docking and cargo loading and unloading move the finished radiators into the output shipping containers.

SPECIFICATION SHEET

Machine Name: DC-DC Converter Radiator Assembly

Function of Machine: Automated assembly of DC-DC converter radiators

Mass of Machine: 585 kg

Physical Dimensions: 45m x 15m x 3m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 50

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Welder	20	. 3	1
Focusing Device	20	1	.5
Sheet Magazine	1	15	1
Track & Transport	1	30	5
Pipe Segment Magazine	9	10	.5
Manifold Assembler	10	10	1

7.4: INSULATED WIRE PRODUCTION

7.4.1 Overview: Figure 7.26 shows the insulated wire production section of the components factory. Insulating fibers are produced by drawing molten S-glass through a multi-hole die. The strands are then wound onto spools which are in turn loaded onto the winding machinery. Aluminum wire -- produced as described in Sec. 7.2 -- is wrapped with the glass fibers by eight 'weaving' machines. The wire produced is dispatched for use either as DC-DC converter transformer coils, or as klystron solenoid coils.

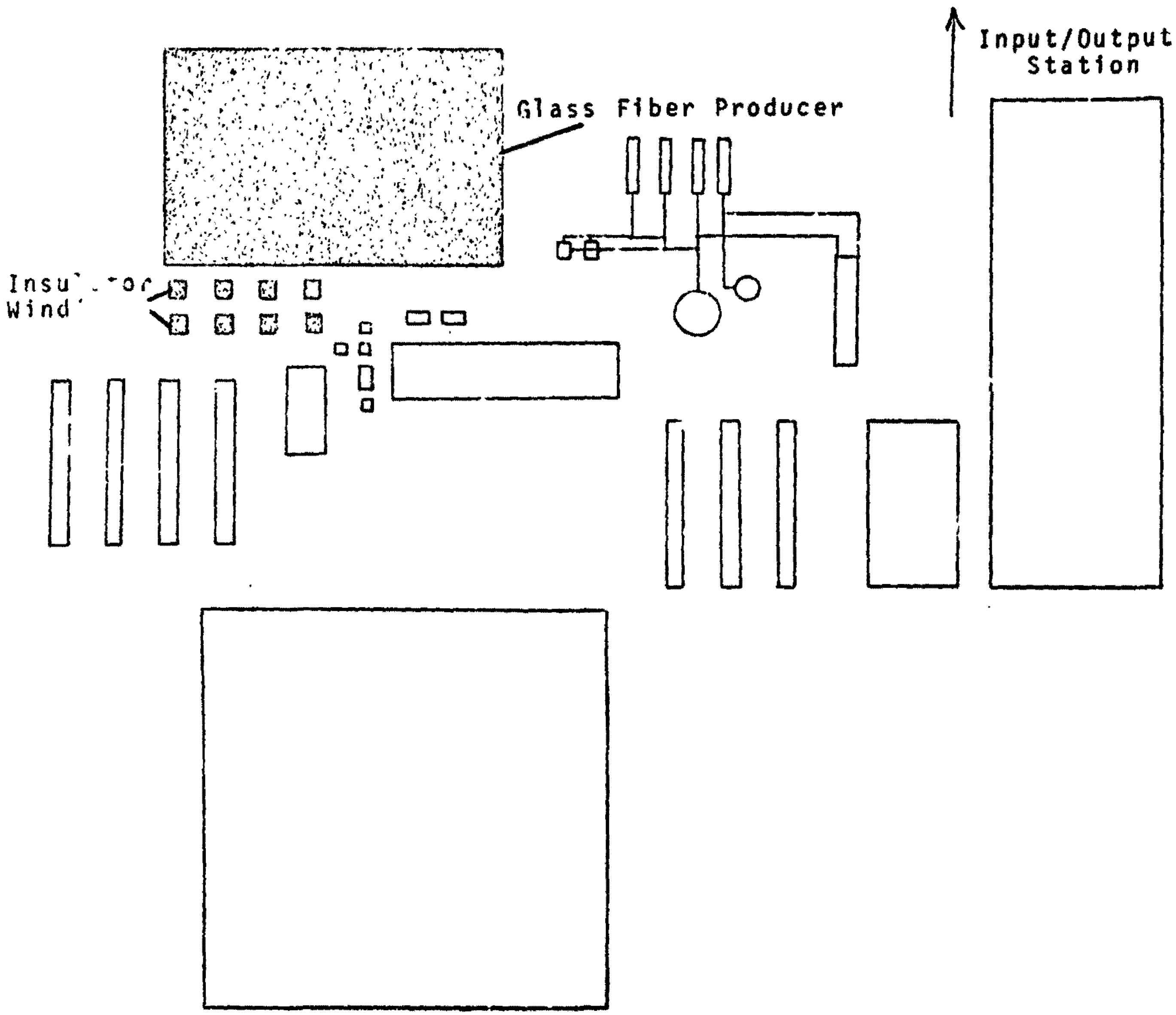


FIGURE 7.26: INSULATED WIRE PRODUCTION LAYOUT

7.4.2 Glass Fiber Producer: The glass fiber producer draws fibers from a melt to produce insulation. The lunar input is in the form of a glass rod 6.4 cm in diameter and 8 m in length. The glass, known as S-glass, is composed of 65% SiO_2, 25% Al_2O_3 and 10% MgO, all of which are available on the moon. The fibers produced are 20 microns in diameter.

The fiber producer consists of a platinum-iridium-osmium alloy tube (2 cm thick) with a 20-hole die at the end (see Fig. 7.27). The tube uses resistance heating coils to heat the glass to about 1700 K. A compressed gas piston is used to drive a plunger into the tube. The fiber producer was sized for output of fibers at 60 m/sec. The piston and compressor masses were based on those of currently available machinery.

The fibers produced are wound onto spools and transported to the insulator winding facility.

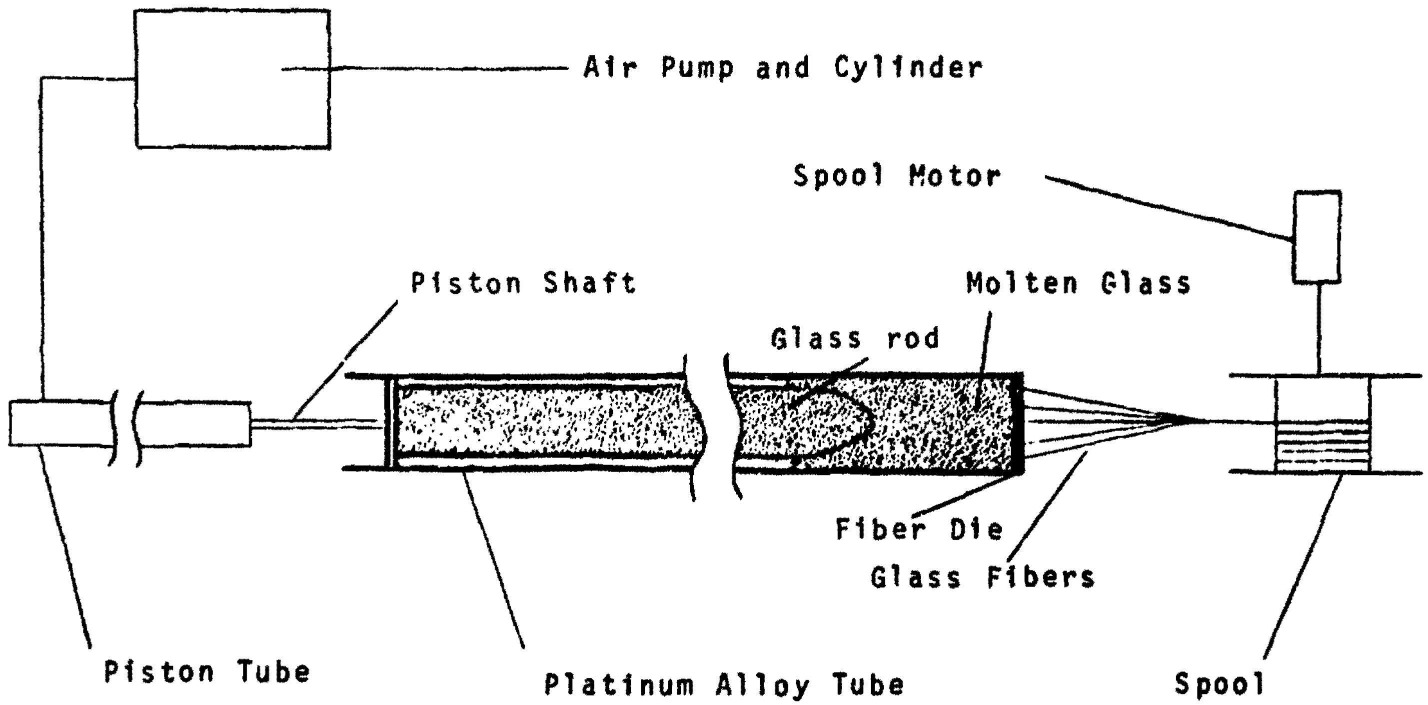


FIGURE 7.27: GLASS FIBER PRODUCER

SPECIFICATION SHEET

Machine Name: Glass Fiber Producer

Function of Machine: To produce glass fibers

Mass of Machine: 400 kg

Physical Dimensions: 20 m x 1 m x 1 m

Throughput/Machine (tons/year): 25

Power Requirements (KW/machine): 9.0

Number of Machines: ȯ1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Platinum Alloy Tube	1	40	8.2
Piston & Piston Tube	1	100	0
Gas Pump	1	30	.5
Gas Cylinder	4	45	0
Spool	6	.5	0
Spool Motor	1	10	.1
Automatic Spool Threader	4	10	.05

7.4.3 Insulation Winder: The wire insulation wrapper draws aluminum wire from a spool and glass fibers from other spools. It then wraps the wire with fibers in a pattern similar to that of the outer wire of a coaxial cable. The insulated wire is then spun onto an output spool and stored.

The cost estimates were based on prices of industrial weavers used for making cloth. The process for making tubular weave is widely used and most machines that weave cloth can weave glass fibers.

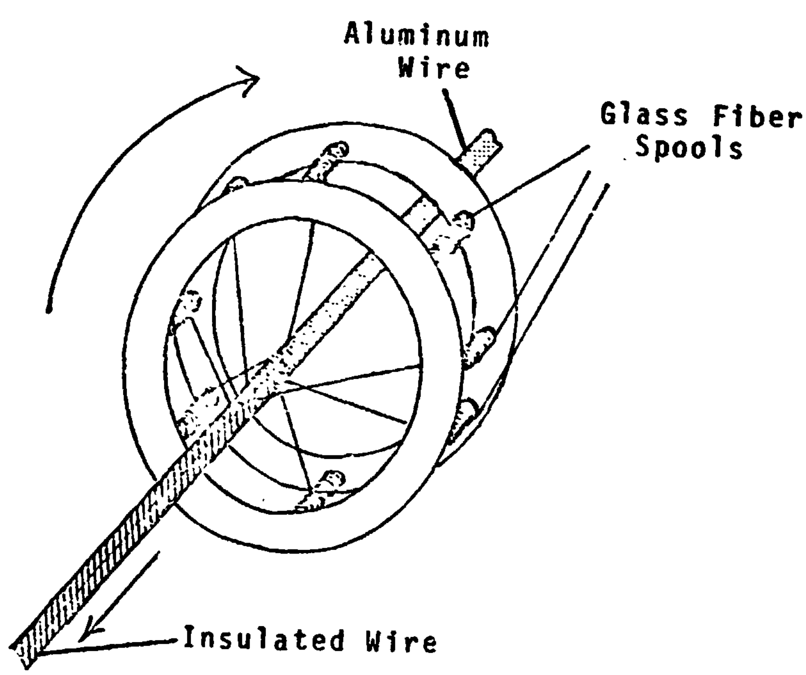


FIGURE 7.28: INSULATION WINDER

SPECIFICATION SHEET

Machine Name: Insulation Winder

Function of Machine: To wrap insulation on wires

Mass of Machine: 500 kg

Physical Dimensions: 1.5 m x 1.5 m x 1 m

Throughput/Machine (tons/year): 430

Power Requirements (Kw/machine): 2

Number of Machines: 8

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Insulation Winder	1	500	2

7.5: DC-DC CONVERTER PRODUCTION

7.5.1 Overview: The DC-DC converter production area is indicated in Fig. 7.29. The converter consists of a SENDUST alloy transformer core (see Sec. 7.2), insulated wire windings (see Sec. 7.4), a radiator (see Sec 7.3), and control circuitry imported from Earth.

In this area, the transformer cores are received from the caster, and cooling channels are drilled through it to allow thermal control of the converter. The insulated wire is next wound onto the limbs of the transformer, and finally, the control circuitry is added. The fitting of the control circuitry is assumed not to be automated because of the combination of the task's complexity and the low output level.

The transformer/circuitry combination, and the DC-DC converter radiator are shipped separately to the SPS construction site because of problems in handling the fully assembled converter.

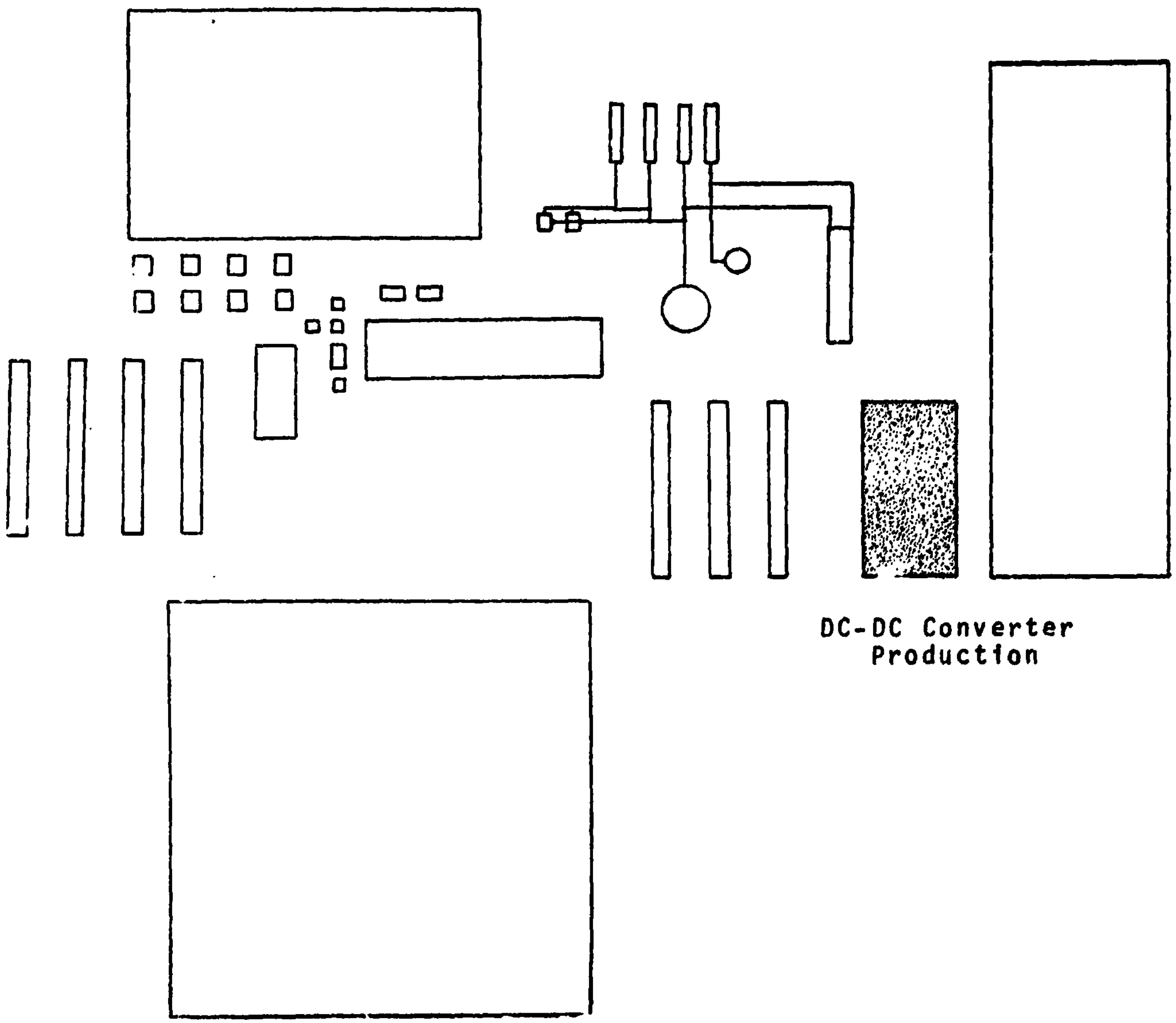


FIGURE 7.29: DC-DC CONVERTER PRODUCTION AREA

7.5.2 DC-DC Converter Producer: A numerically controlled "deep" drill (3 m long bit) is used to drill cooling channels through the transformer core. In order to provide one continuous channel, three interconnecting holes must be drilled (as shown in Fig. 7.30 [a]). The drill features a debris removal system, i.e. liquid injected through the center of the bit is used to carry away metal particles and prevent 'clogging' of the holes. Such machines are in current use in industry.

After drilling, the transformer core is transferred to the coil winding machine. This machine -- again of a type currently used in industry -- uses manipulator arms to wind insulated wire from a spool around the transformer limbs. (See Fig. 7.30 [b]).

Finally, the transformer, complete with windings, is connected manually to the control circuity imported from Earth.

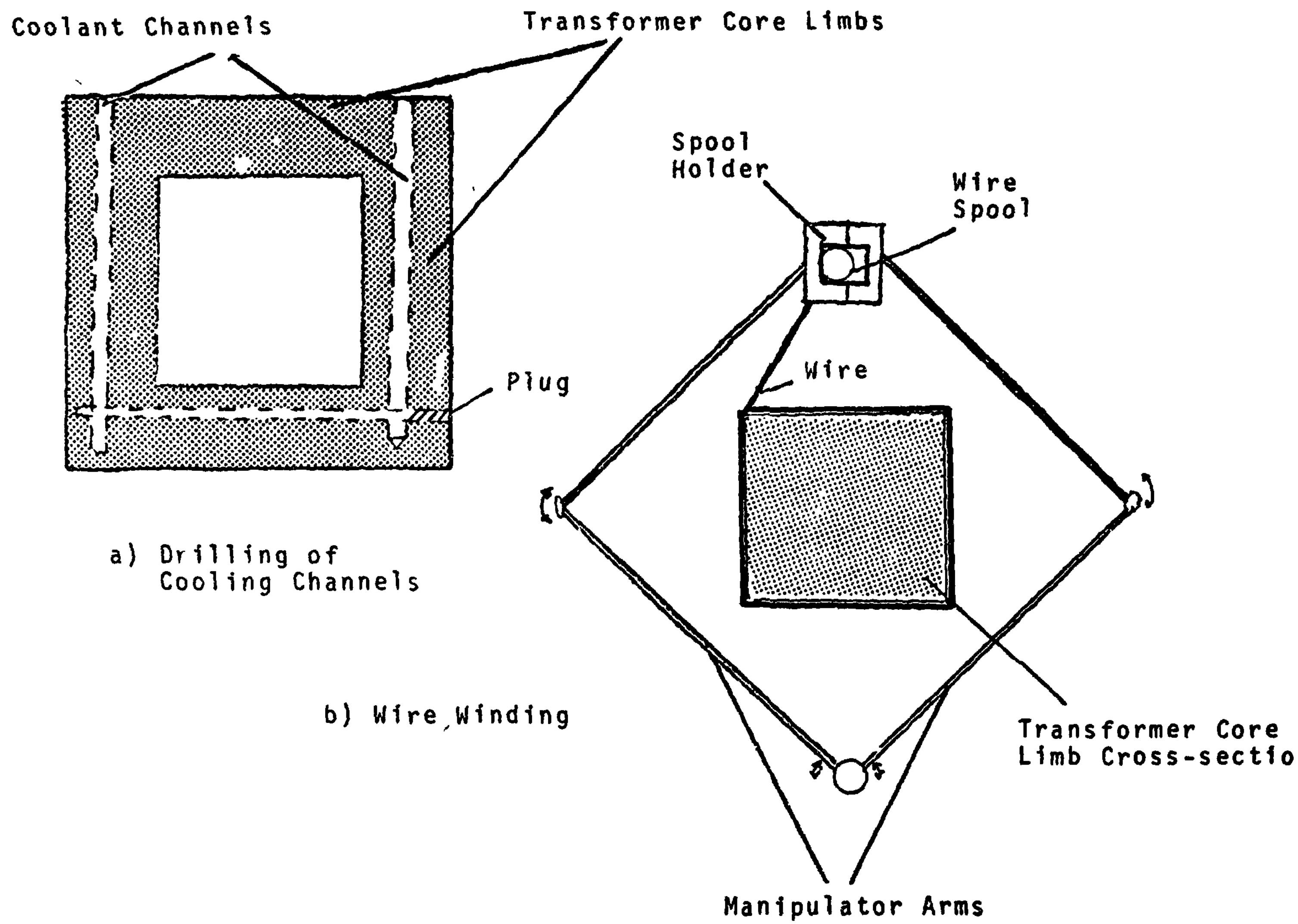


FIGURE 7.30: DC-DC CONVERTER PRODUCTION

SPECIFICATION SHEET

Machine Name: DC-DC Converter Producer

Function of Machine: Manufacture and Assembly of DC-DC converters

Mass of Machine: 4000 kg

Physical Dimensions: 8 m x 15 m x 6 m

Throughput/Machine (tons/year): 2.1×10^3

Power Requirements (KW/machine): 2.5

Number of Machines: 1

Number of Operators: .2

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Coolant Channel Deep Drill	1	2000	2
Winding Machine	1	2000	.5

7.6: KLYSTRON PRODUCTION SYSTEM

The klystron production section is required to be a highly automated facility with a high output rate of complex components. The essential tasks which it must perform are:

- Machining and polishing of cast solenoid core
- Drilling of cooling channels
- Machining of output cavity/waveguide interface
- Winding of solenoid coil
- Fitting of solenoid pole pieces
- Quality control
- Fitting of radiator assembly
- Assembly of gun/collector/housings/control circuitry
- Bakeout and processing
- Testing
- Other design dependent operations

It is anticipated that the aluminum cast solenoid core arriving at the klystron facility from the casting section will be sized to within 0.8% of its nominal design dimensions. The klystron cavities, therefore, must be further machined and polished to come within the tolerance limits of 1.5×10^{-4} mm to 2.0×10^{-4} mm RMS for 2.45 GHz operation. At this stage, provision for cooling channels, drilled transversely in the webs between cavities, should be made. In order to prevent contamination of the core production area by chips (from the machining operations), active dust removal systems should be in operation throughout the plant. Completed core units are subjected to automatic testing of dimensions and surface finish before being transported to the next stage -- any sub-standard units being discarded before fitting of components brought from Earth. Further machining of the cavity, in preparation for fitting of the window after bakeout, is completed before installation of the magnetic circuit.

The magnetic circuit consists of two solenoids (one focusing and one re-focusing solenoid) and two soft-iron pole pieces (to connect the solenoid core and focusing solenoid). The solenoids are wound aluminum wire with a glass wool insulator coating, and the pole pieces are soft-iron annuli, electron beam welded into position at either end of the focusing solenoid to complete a magnetic circuit around the cavities.

The klystron radiators, manufactured elsewhere in the SMF, are at this point connected to the cooling channels. Components originating from Earth, i.e. collector, electron gun, and control systems, are mounted on the tube together with cast aluminum collector and solenoid housings (produced in the SMF). The now completed tube is dispatched to the testing area for bakeout (if necessary) and processing. A final "hot" (cathode on) test of the tube is made before dispatch to stores or to the SPS assembly site. The wastage rate of tubes at the present time is approximately 7% during manufacture -- the study group feels that similar rates (10%) should be achievable using more highly automated manufacturing techniques in the SMF.

Although particular processing stages cannot be listed at the present time, equipment used is experted to include; milling machines, polishers, drills, EB welders, test stations, winding machines and robot manipulators. Since no specific design of the baseline product has been completed, costing of the klystron plant overall (rather than of individual machines) has been conducted. This approach does not involve any attempt to list individual operations and therefore avoids errors arising from the ommission of unforeseen production steps.

The klystron production facility was sized on the basis of a requirement for 204,000 klystrons/year (including a 10% margin for breakage d[illegible] SPS assembly) plus an additional 10% to account for t[illegible] [illegible]ted spoilage (giving a total of 224,400 klystrons/year) [illegible] was assumed that the residence time of a workpiece i[illegible] the machinery was two hours, and therefore that the resident workpiece mass in the machinery would be two hours worth of production (or 3053 kg) at a given time. Since no other information on the specific machinery mass was available, the production machinery mass was estimated to be 100 times the resident mass (i.e. approximately 305 tons). The replacement parts are assumed to account for 5% of the machine mass per year -- giving a figure of approximately 15 tons/year. With an 80% duty cycle, each [illegible]stron production unit within the facility has a working time of 6400 hours/year. Therefore, at 2 hours per klystron it has the capacity to produce 3200 units/year. However, since the final testing is expected to occupy one hour of production time, 2 workpieces may occupy a machine at a given time (one unit being assembled, the other being tested). Therefore, the number of units required is 224,400/(3600 x 2) = 32. Assuming that each unit occupies a 'floor area' of 40 m^2 and a height of 5 m, then the area required f-- klystron production is 1280 m^2. This analysis assumes that a production unit can handle only one workpiece in the production stage and one in the testing stage at a given time. Depending on the klystron design it may be possible to have a higher number of testing units than production units and to have simultaneous production of several workpieces in one machine, thus reducing the facility size.

-all power requirements, procurement costs and dut- cycles were based on an earth-based facility designed by Varian Associates (Ref. 7.2). Repair labor was estimated on the b--is of two crew men per machine section, and crew requirements calculated on the basis that the entire pl would be automatically controlled.

Finally, R&D costs were estimated on the basis of the requirement to develop highly automated close-tolerance machining facilities and to build and test a pilot facility (possibly involving some testing in space).

In the specifications sheet following, the entire facility is listed as <u>one</u> machine, rather than 32 production units. The factory thus agglomerates production stands and common handling and testing equipment.

SPECIFICATION SHEET

Machine Name: Klystron Production System

Function of Machine: To produce klystrons

Mass of Machine: 305 tons

Physical Dimensions: floor area approximately 1300 m^2

Throughput/Machine (tons/year): 1.7×10^4

Power Requirements (KW/machine): 40,000

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Klystron Factory	1	305000	40000

7.7: WAVEGUIDE PRODUCTION EQUIPMENT

7.7.1 Overview: Figure 7.31 shows a "top" view of the waveguide factory. This facility is designed so that each piece of foamed glass (the material from which the waveguides are formed) progresses linearly through the facility to minimize handling of the delicate sheets.

Waveguides for the SPS essentially consist of a closely dimensioned foamed glass box structure coated internally with a thin layer of deposited aluminum. In the baseline SMF dedign, foamed glass is produced by mixing lunar anorthosite and chemical foaming agents, and then thermally cycling the mixture in a mold. The resultant monolithic block of material is sliced into thin sheets using tungsten blade saws.

The sheets are then smoothed on their 'interior' faces by removing surface irregularities with lasers. A 7-micron thick coating of aluminum is then deposited onto the smoothed surface, using direct vaporization. The coated sheets are then cut by laser into strips which will form the sides of the waveguides. Simultaneously, those strips which constitute the 'front' radiating surface (one in four) are slotted, and those strips which constitute the 'back' faces of the waveguides are holed.

Finally, the waveguides are automatically assembled around guides by automatic manipulators. The purpose of the guides is to ensure that the internal dimensions of the

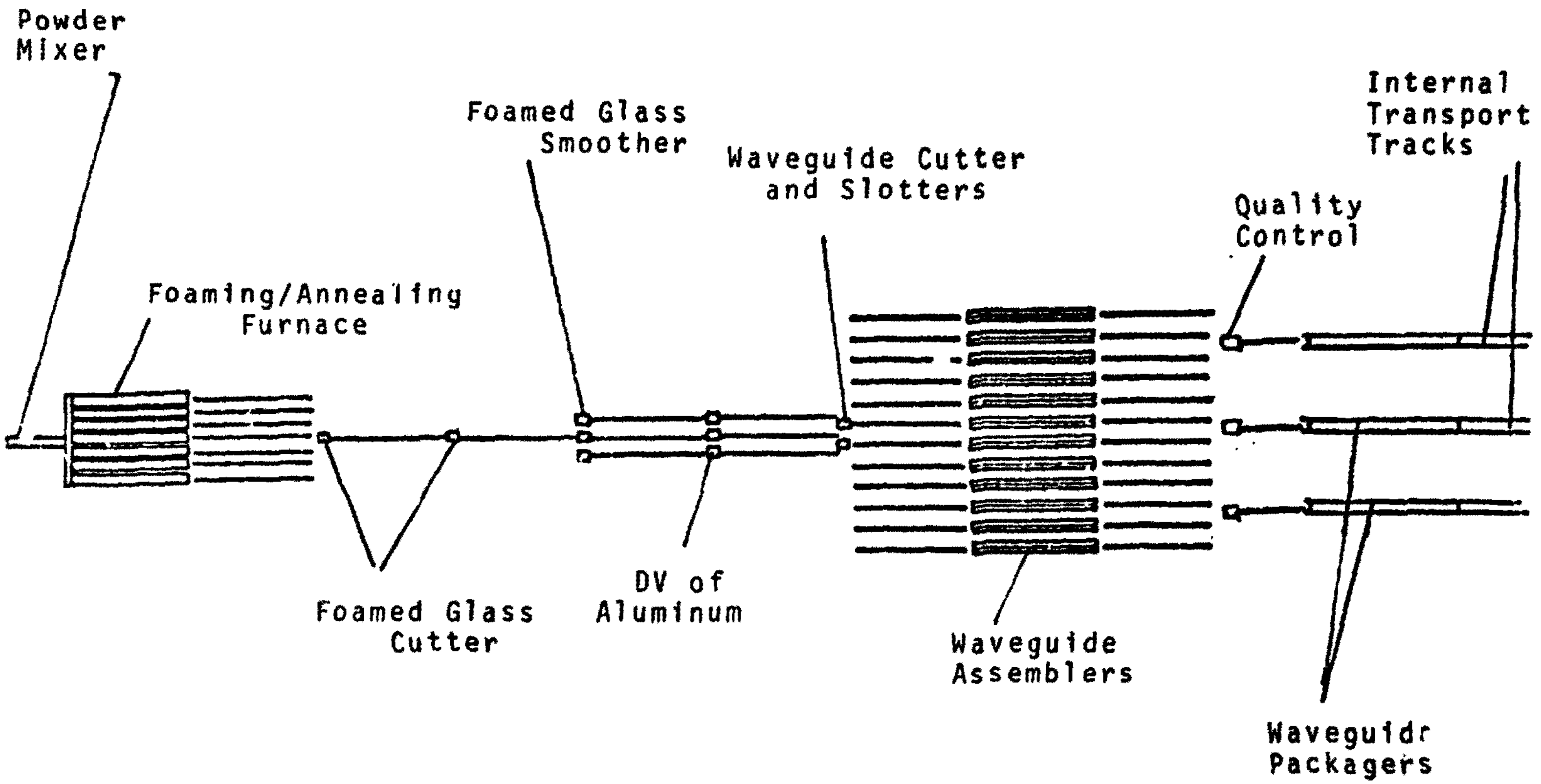


FIGURE 7.31: LAYOUT OF WAVEGUIDE FACTORY

waveguide meet the tolerance requirements by building the box around accurately dimensioned structures. The sides of the box are fused together along adjacent edges by laser beams. Careful handling of foamed glass throughout the production area is required, because of the fragility of the material when in the form of thin sheets.

The completed waveguides are stored in padded racks which are carried by internal transport system to the input/output station.

7.7.2 Glass Foaming Facility: On earth, foamed glass can be manufactured using volcanic ash; similar materials are available on the lunar surface. Lunar anorthosite arrives at the SMF in particles of diameter 5 microns -- the size necessary for the foaming process. Therefore the usual requirement for a ballmill to crush the particles is eliminated.

A flux and chemical foaming agents are added to the glass. (A small amount of grog, which is fired batch material reground to granular form, may also be added to help control the resultant density.) Flux is added to yield more cellulation in the glass and to achieve the proper viscosity for foaming. The viscosity achieved enables the foaming temperature to be lowered to 800 C, which is 750°C less than the normal melting temperature of anorthosite. The flux includes NaOH or Na_2SiO_3 and Na_2O.

The anorthosite and foaming agents must be blended thoroughly in a continuous mixer (Fig. 7.32) to produce an amalgam ready for foaming. The mixer consists of a series of propeller-like blades -- counter-rotating to provide maximum turbulence in the powder -- which are designed to impinge on large numbers of particles and to impart a velocity with both a tangential and axial component (thereby creating flow through the mixer). During mixing, the particles are floating free in vacuum. Each mixing blade has a tip radius of .28 m, and the mixing section is estimated to be 5.4 m long, giving a volume of 1.33 m^3. The residence time of a particle in the

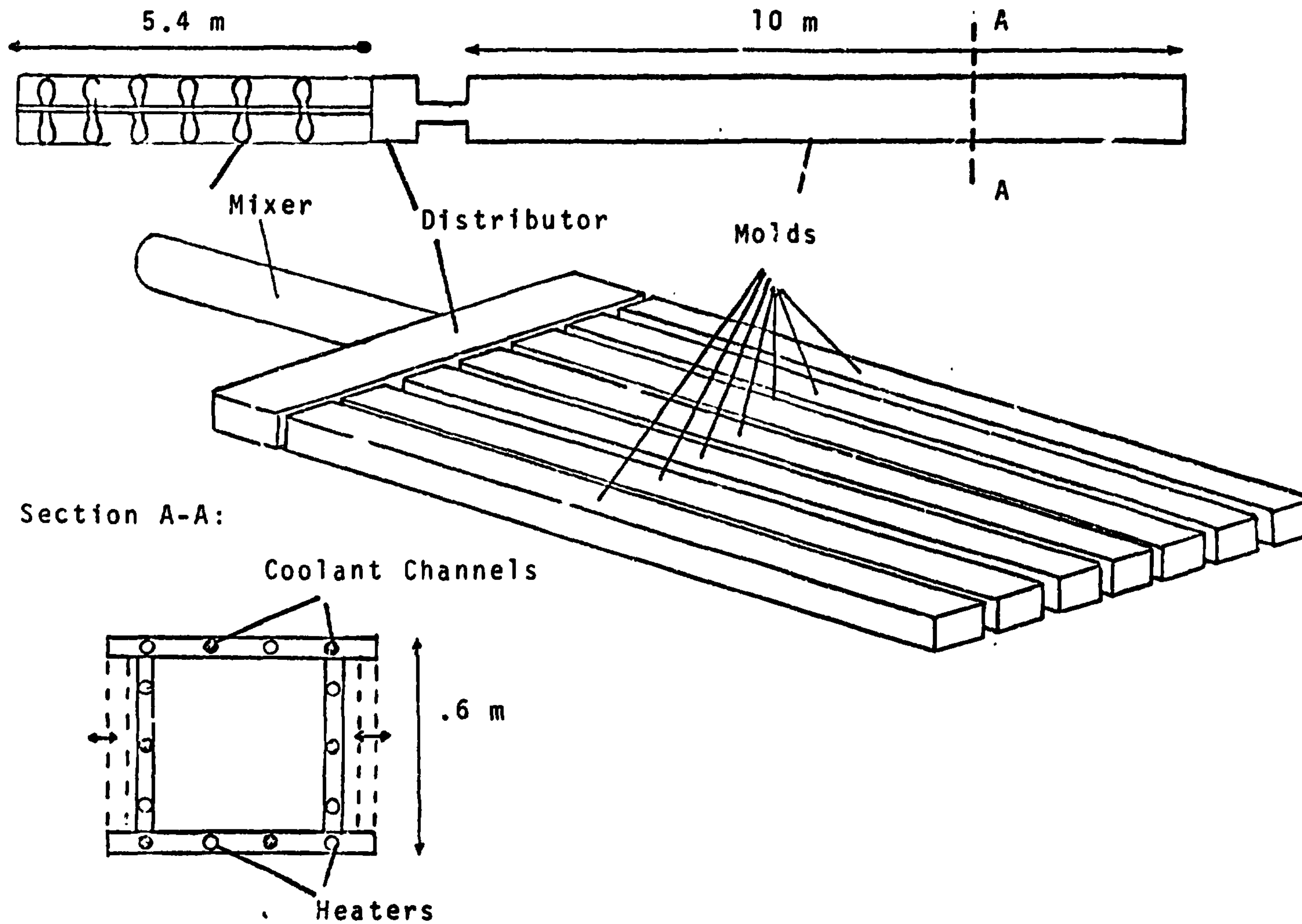


FIGURE 7.32: GLASS FOAMING FACILITY

mixer is estimated to be roughly 20 minutes, at a particle density of 500 kg/m^3, giving a mass throughput rate of 2000 kg/hr.

The foaming mixture is charged into stainless steel molds, and heated (over a period of about 4 hours) to foaming temperature (800°C). Heat is supplied through coils, contained within the molds themselves, at a rate of 1000 kW. On foaming, the mixture expands to about twice its volume as a powder. The foamed glass is then slowly cooled ('annealed') over a period of 8 hours at a rate controlled by a thermal control unit; this unit controls the flow of coolant through channels in the sides of the mold.

The product is a monolithic block of foamed glass (10 x .8 x .6 m) of density 800 kg/m^3. Each block represents roughly two hours worth of production (at 2000 kg/hr) and is sized so that the longest waveguide may be formed from a single sheet. At the conclusion of the cooling cycle, the glass is removed from the mold by a manipulator system.

The molds are each charged (sequentially from the mixing unit) for 2 hours out of every 14. The powder is initially compacted by bring the mold sides toward the center. Heat is supplied directly from heaters in the walls of the mold, as the walls move outwards to their full .8 m displacement as foaming occurs. This allows more even heating during the foaming operation. Additionally, the walls are moved outwards again after annealing, to ease the removal of the foamed glass blocks after cooling.

SPECIFICATION SHEET

Machine Name: Glass Foaming Facility

Function of Machine: Production of foamed glass for waveguide manufacture.

Mass of Machine: 228,000 kg

Physical Dimensions: mixer: blade radius 28 cm, length 5.4 m
mold (internal) 10 x .60 x .80 meters

Throughput/Machine (tons/year): 1.8×10^4

Power Requirements (KW/machine): 7600

Number of Machines: 1

Number of Operators: 1

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Mixer	1	75000	35
Thermal Control Unit	7	850	80
Mold	7	21000	1000

7.7.3 Foamed Glass Cutter: The blocks of foamed glass produced in the glass foaming facility must be cut into sheets of 2.5 mm thickness before being coated with the layer of conducting aluminum. This slicing operation is achieved in two stages, by tungsten-blade saws. In the first cutting operation, the 10 x .8 x .6 m foamed glass block is sliced into 8 blocks 10 m x .8 m x 7.35 cm. These smaller blocks are then fed one by one into a 20 blade saw whose output is 21 sheets 10 m x .8 m x 2.5 mm. The sheets produced are dispatched to the smoothing area.

The cutting section must, in addition to the sawing equipment, include conveyors for handling of the foamed glass blocks. The delicate foamed glass sheets are handled between soft conveyors in order to minimize damage.

Kerf removal is achieved by imparting an electrostatic charge to the debris via the saw blade. An oppositely charged belt is run past the cutting area to carry away the particles to a disposal area.

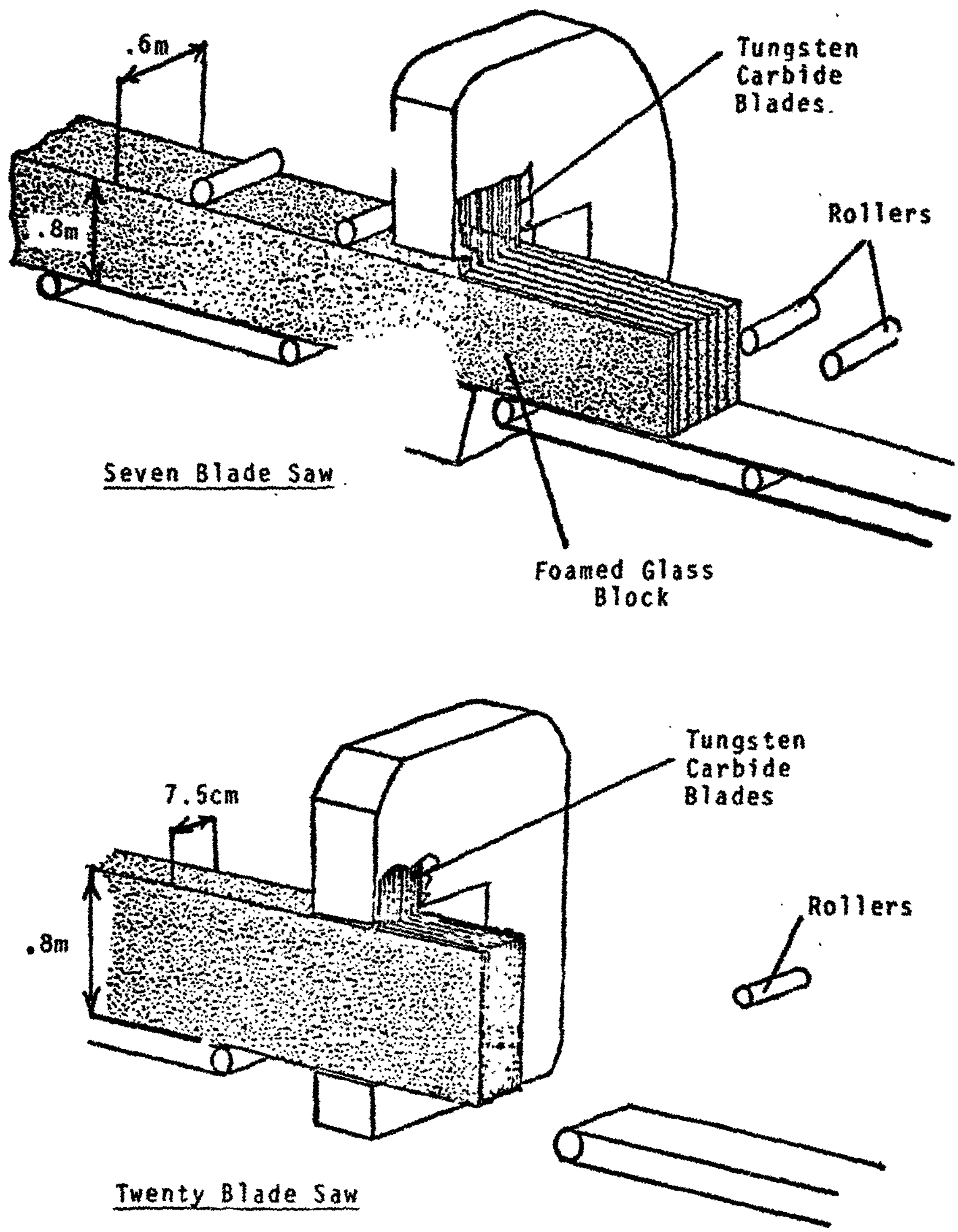


FIGURE 7.33: FOAMED GLASS CUTTER

SPECIFICATION SHEET

Machine Name: Foamed Glass Cutter

Function of Machine: To cut foamed glass blocks into sheets 10 m x .8 m x .0025 m

Mass of Machine: 5900 kg

Physical Dimensions: 24 m x 2 m x 3 m

Throughput/Machine (tons/year): 1.3×10^4

Power Requirements (KW/machine): 23

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Eight Blade Saw	1	1700	5
Twenty Blade Saw	1	4000	12
Handling Equipment	1	170	5
Kerf Removal System	1	20	.5

7.7.4 Foamed Glass Smoother: The faces of the foamed glass sheets leaving the cutting area have surface irregularities which must be removed before deposition of aluminum. A good finish is required on the surface to be coated in order to ensure that the coating itself is smooth. (An irregular inner surface would lead to a loss in the waveguide efficiency.)

The waveguide smoothing operation uses two pulsed lasers (see Fig. 7.34) to burn off any surface irregularities. One laser is positioned so that the beam passes across the surface of the foamed glass sheet which is travelling at 0.1 m per second. This laser burns off material protruding above the plane of the foamed glass surface. A second laser sweeps the surface from directly above to fuse any remaining irregularities. This laser's beam is focused to a wider spot than the first laser's, since its function is to fuse rather than vaporize.

Each of the lasers has a beam power of 1 kW which, after allowing for an efficiency of 10%, require an input power of 10 kW. CO_2 lasers are used because their operating wavelengths are suitable for cutting glasses.

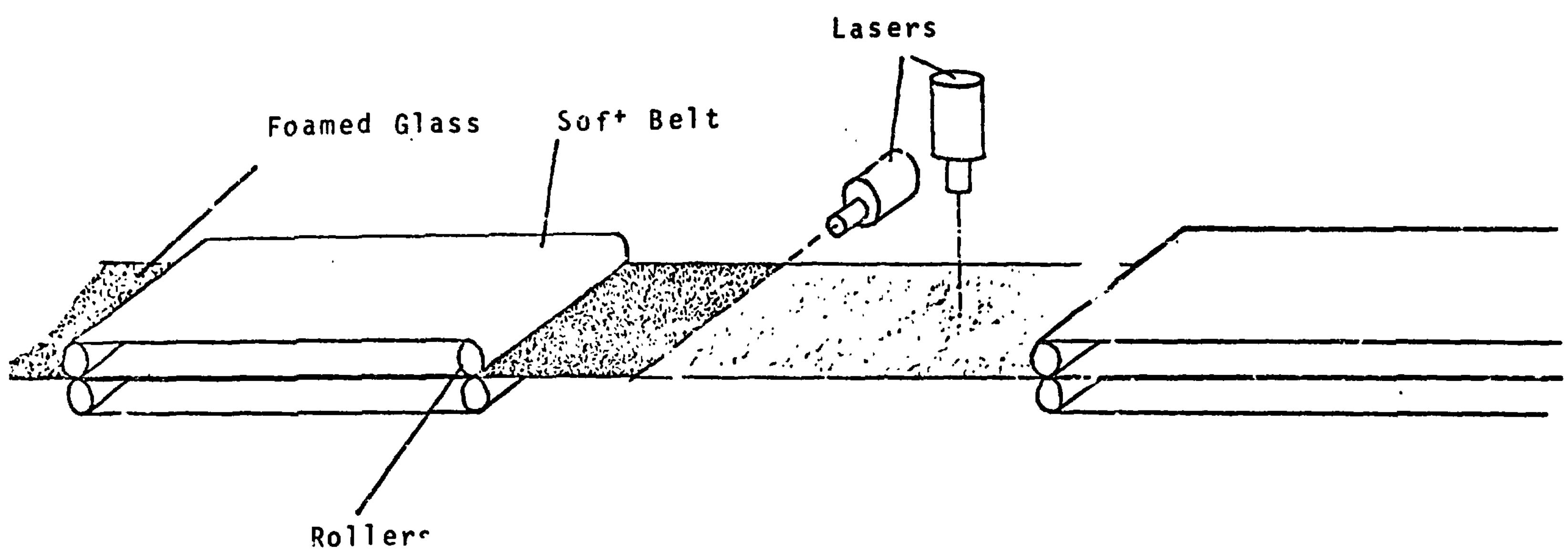


FIGURE 7.34: FOAMED GLASS SMOOTHER

SPECIFICATION SHEET

Machine Name: Foamed Glass Smoother

Function of Machine: To smooth rough surface of foamed glass

Mass of Machine: 8250 kg

Physical Dimensions: 12 m x 2 m x 3 m

Throughput/Machine (tons/year): 4.3×10^3

Power Requirements (KW/machine): 25

Number of Machines: 3

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Laser	2	4000	10
Radiator Pump	1	40	1
Conveyor System	1	210	5

7.7.5 Direct Vaporization of Aluminum Coating: In order to operate as waveguides, the internal surfaces of the foamed glass assembly must be coated with a 6.7 micron thick layer of aluminum. The reference SMF design uses an electron beam direct vaporization technique to deposit the aluminum at a rate of 50 microns per minute.

As shown in Fig. 7.35, the slabs of aluminum are positioned above the deposition surface, and are subjected to bombardment by a focused electron beam. The aluminum vaporizes and travels to the deposition surface (the foamed glass sheet). The Al is deposited at 50 microns/minute. Therefore, for a travel speed of .1 meters/sec, the deposition section must be .8 meters long.

This process and equipment is similar to the direct vaporization used in solar cell production. Such equipment is discussed in greater detail in the solar cell production equipment descriptions (see Sec. 7.8.3). Cost and sizing of the waveguide coating equipment is based on the solar cell factory designs.

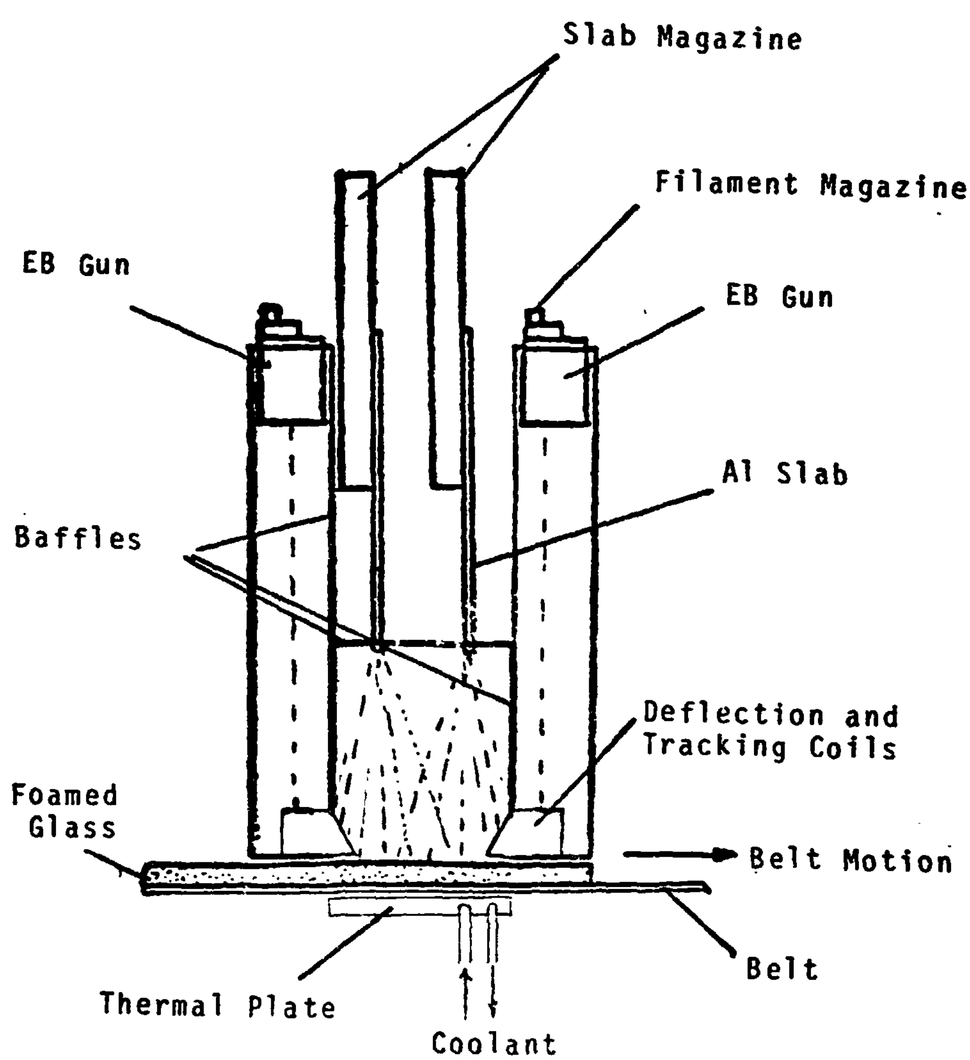


FIGURE 7.35: DV OF ALUMINUM COATING

SPECIFICATION SHEET

Machine Name: Waveguide DV of Aluminum

Function of Machine: To deposit internal conducting surface on foamed glass waveguides.

Mass of Machine: 1000 kg

Physical Dimensions: 12 m x 2 m x 3 m

Throughput/Machine (tons/year): 4.3×10^3

Power Requirements (KW/machine): 87

Number of Machines: 3

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	5	17	17
Gun Cooling System	5	20	.3
Slab Feeders	5	50	.01
Baffles	4	.25	0
Belt and Cooling System	1	500	2

7.7.6 Sheet Cutter and Slotter: After the aluminum coating is applied, waveguide sheets are cut into strips 9.8 cm and 6.0 cm wide (see Fig. 7.36). Eight strips, four of each width, are cut from each foamed glass sheet by lasers. These strips will form the sides of the waveguides.

Next, holes in the 'back' faces and slots in the 'front' faces of the waveguides are cut to allow the microwaves to enter and be radiated during waveguide operation. The radiating slots must be made to tolerances of $\pm$ .0127 mm in alignment, $\pm$ .058 mm in length, and $\pm$ .058 mm in spacing. Half of the 9.8-cm-wide strips are slotted lengthwise in two parallel rows -- these will form the radiating surface. The other half of these strips are holed to form the inlet ports for the microwaves. These holes and slots are cut by the pulsed 1 kW lasers. Finally, another laser crosscuts the 10 m strips to the lengths required for the various waveguides.

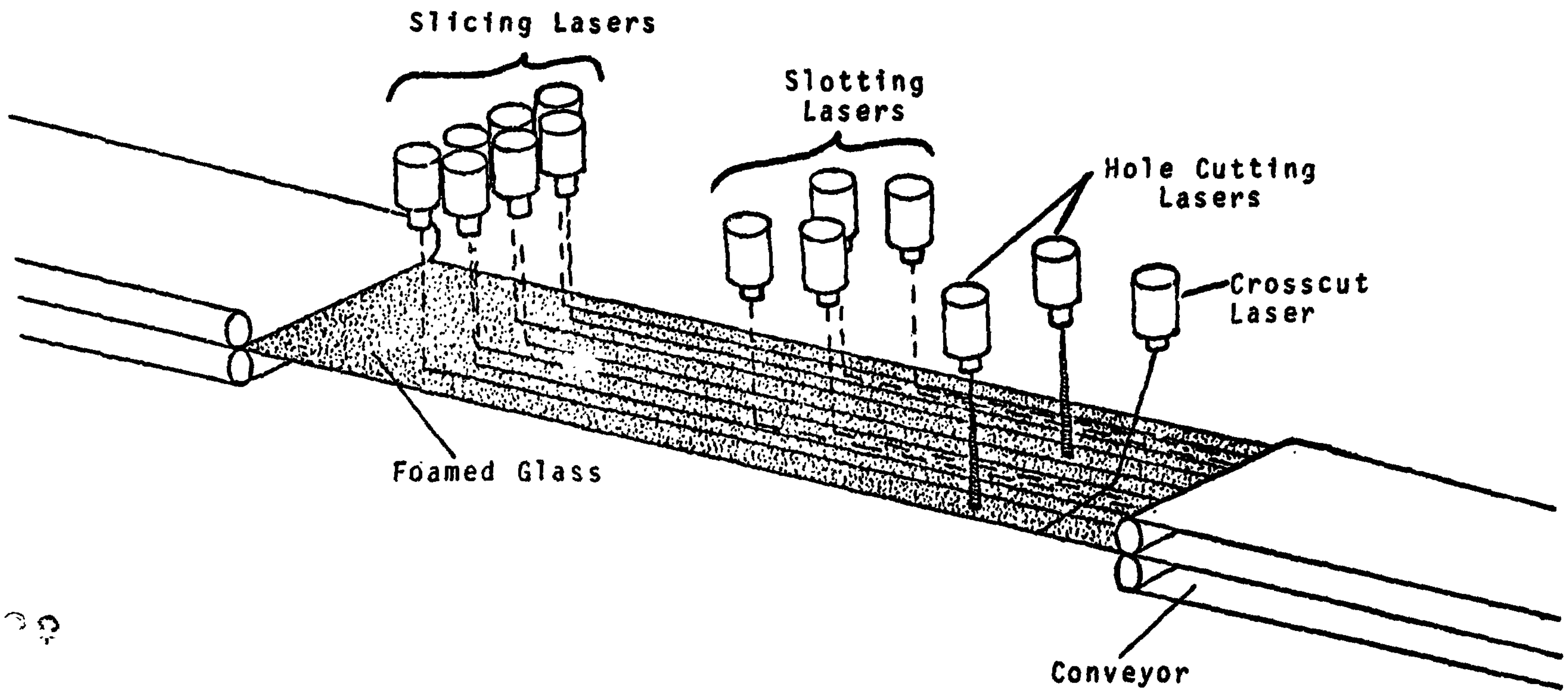


FIGURE 7.36: SHEE CUTTER AND SLOTTER

SPECIFICATION SHEET

Machine Name: Sheet Cutter and Slotter

Function of Machine: To cut and slot foamed glass sheets

Mass of Machine: 56000 kg

Physical Dimensions: 12 m x 2 m x 3 m

Throughput/Machine (tons/year): 6.5×10^3

Power Requirements (KW/machine): 21

Number of Machines: 2

Number of Operators: 0

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
Laser	14	4000	10
Radiator and Pump	1	20	1
Conveyor System	1	170	5

7.7.7 Waveguide Assembler: The waveguide assembly system is shown in Fig. 7.37. Manipulator arms maneuver the strips of foamed glass into position around a set of guides whose purpose is to ensure the dimensional accuracy of the waveguide cross-section.

Three sides of the 'box' are formed around the internal guides (as shown in the figure). The fourth side is then guided into position with the internal guides removed. Once in place, the edges of adjacent sheets are fused together by a 1 kW pulsed laser beam. The completed waveguides are removed from the mold and dispatched to the waveguide packaging area.

Twelve assembly stations are provided in the reference SMF design. The previous production sections produce enough completed strips to produce three 10-meter-long waveguides every minute. However, the actual waveguides must be produced in a variety of lengths. Assuming that on the average each 10-m length is cut to produce two waveguides, and that the assembly time for each waveguide is two minutes, twelve assembly stations are required.

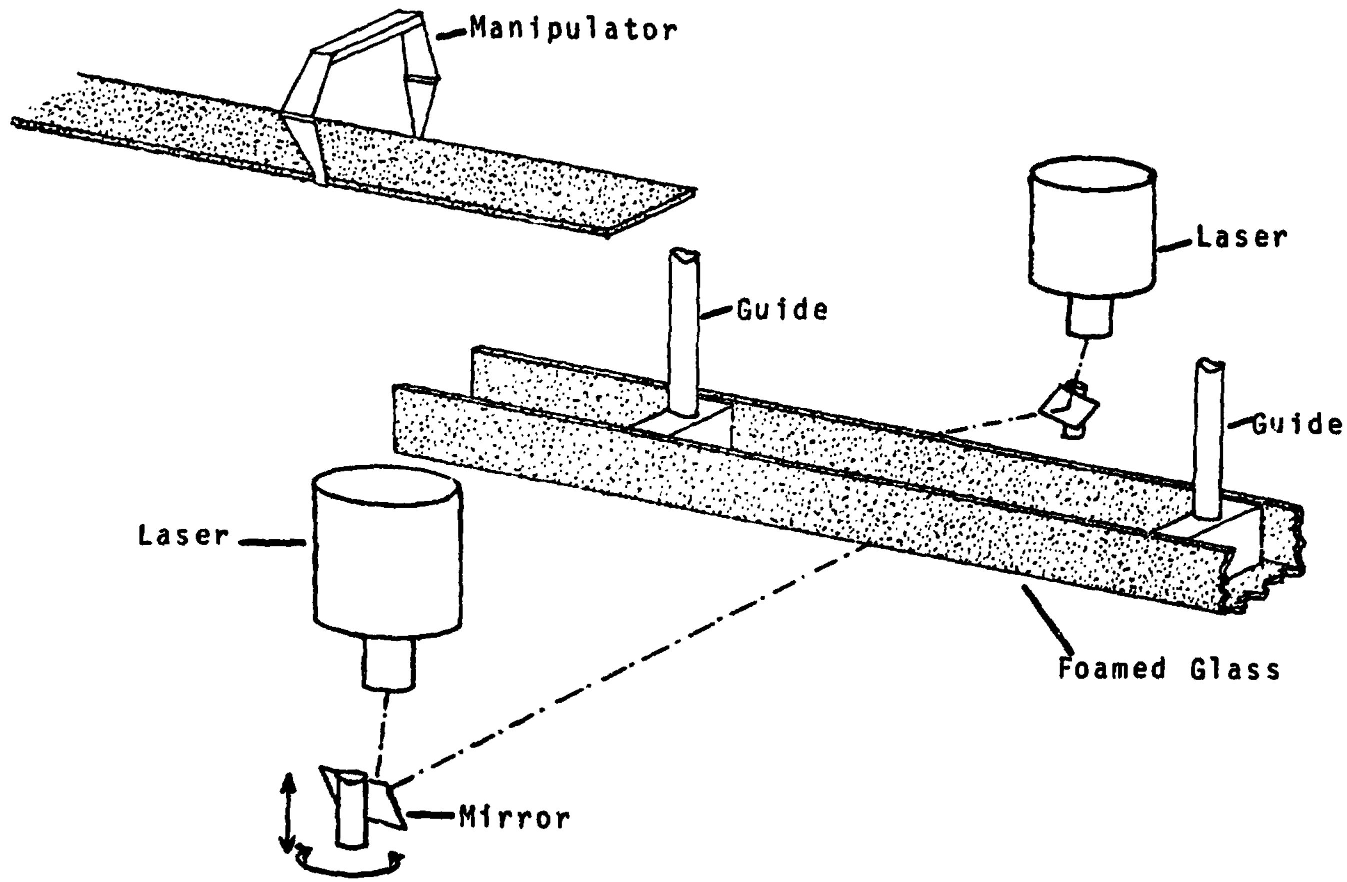


FIGURE 7.37: WAVEGUIDE ASSEMBLY

SPECIFICATION SHEET

Machine Name: Waveguide Assembler

Function of Machine: To assemble foamed glass sheets into waveguides

Mass of Machine: 24100 kg

Physical Dimensions: 20 m x 2 m x 3 m

Throughput/Machine (tons/year): 1.1×10^3

Power Requirements (KW/machine): 9

Number of Machines: 12

Number of Operators: 6

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Assembly Arms	8	10	1
Interior Guides	2	15	0
Laser	4	4000	10
Radiator and Pump	1	80	4

7.7.8 Waveguide Packager: The packager system is used to remove completed waveguides from the assembly station and to place them into containers ready for dispatch to the output or storage areas.

Manipulator arms are used in the physical handling of the foamed glass between assembly and packaging. The waveguides are packaged into racks which connect two transporter carts -- as shown in Fig. 7.38. Because of the fragility of the waveguides special precautions in their handling -- such as lined containers -- are required.

Each waveguide is subjected to testing, before being dispatched, as a quality control measure. These tests include optical geometric tolerance testing to check slot positioning and alignment, and hot tests using a microwave source to obtain a measurement of the radiated output quality. The testing station is situated between the final assembly and output stations.

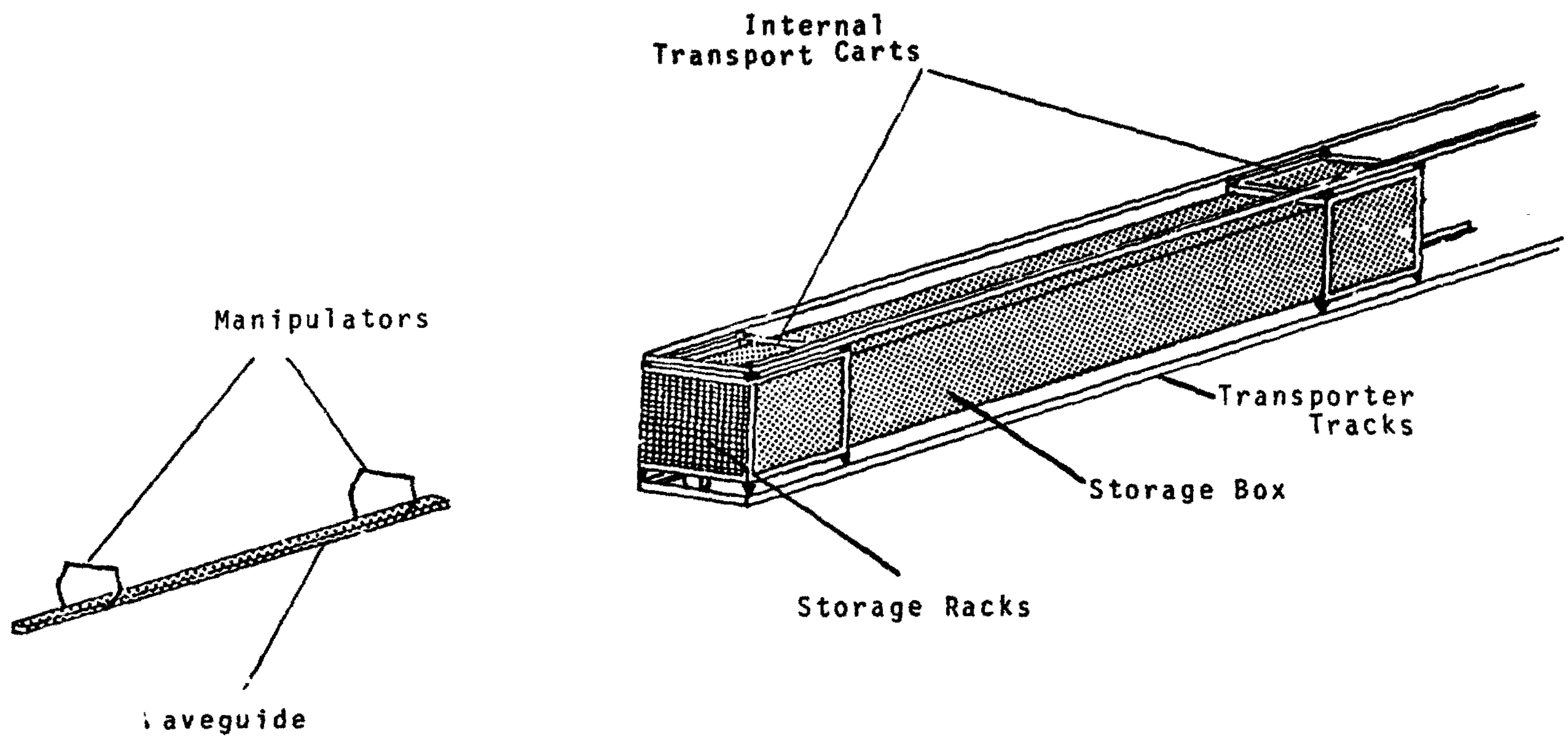


FIGURE 7.38: WAVEGUIDE PACKAGER

SPECIFICATION SHEET

Machine Name: Waveguide Packager

Function of Machine: To package waveguides in preparation for transportation to storage

Mass of Machine: 8650 kg

Physical Dimensions: 22 m x 2 m x 3 m

Throughput/Machine (tons/year): 4.3×10^3

Power Requirements (KW/machine): 0

Number of Machines: 3

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Handling Equipment	1	100	5
Waveguide Box and Racks	850	10	0
Quality Control Equipment	1	50	5

7.8 SOLAR CELL FACTORY

7.8.1 Overview: Figure 7.39 is a "top" view of the solar cell factory (repeating Fig. 7.5). The factory consists of two major structural sections: one containing the zone refining, mask and masking strip cleanup, and interconnect deposition sections; and the other, the deposition and assembly sections for the production of the cell arrays. Each of these structural units is attached to the central mast at discrete points, with vibration damping systems built into the joints. These joints also carry flexible power feeds and internal transport tracks.

The solar cell factory is a planar structure, i.e. its thickness (into the paper in Fig. 7.39) is on the order of 10-20 meters. In addition, there are heat-waste radiators roughly 30 meters above and below the plane of the factory. These radiators are in a plane parallel to that of the factory, and are therefore omitted from the figure, since they would obscure the production sequences. These radiators are discussed further in the individual equipment descriptions and in Sec. 7.8.24.

The deposition and assembly section of the factory consists of parallel production lines ("strips") running perpendicular to the central mast (from bottom to top in Fig. 7.39). Each production strip is 1.1 meters wide, the width of a solar panel. The strips are clustered in groups of 14

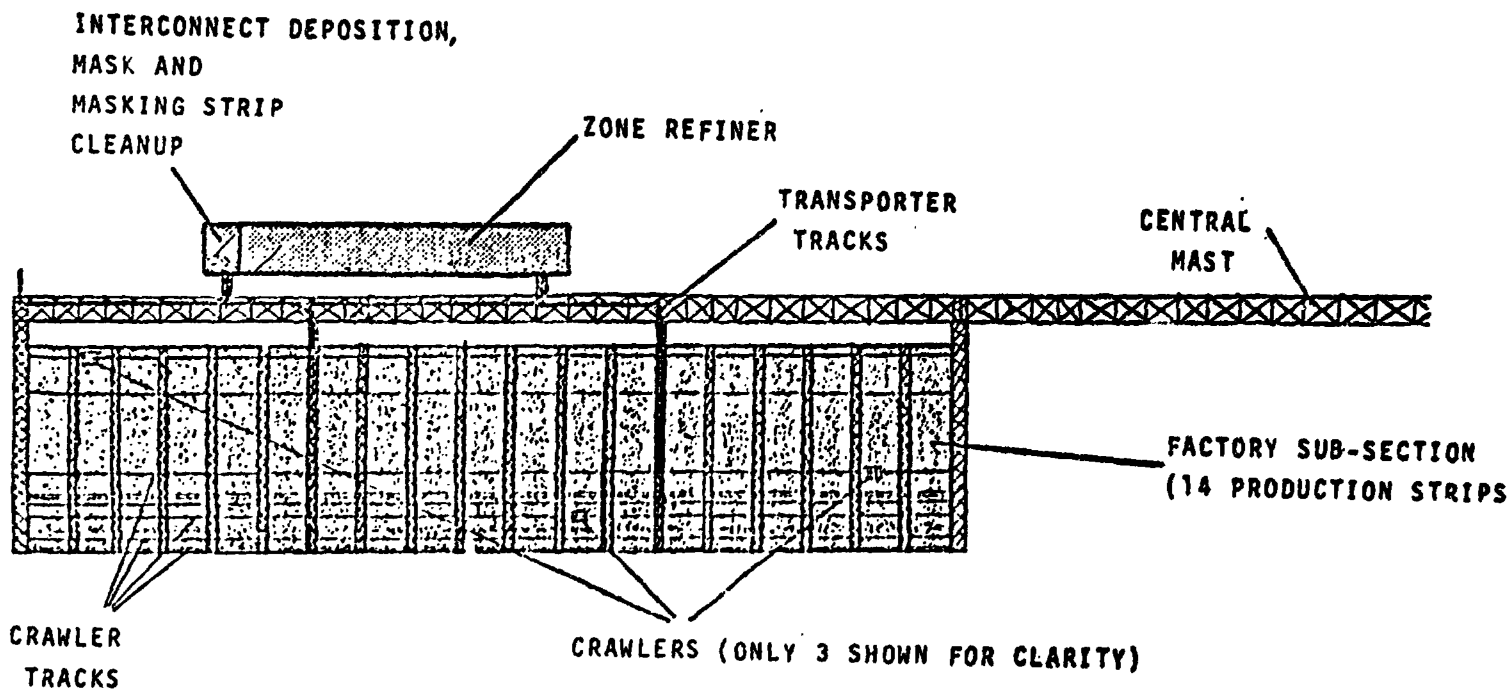


FIGURE 7.39: LAYOUT OF SOLAR CELL FACTORY

("subsections). Therefore one factory subsection produces arrays of solar cells 14 panels wide.

One such subsection is shown in greater detail in Fig. 7.40. Each production strip is 104 meters long (from front to right rear in the figure). The astronaut figure is included next to the near corner for size comparison. The early stages of solar cell production are deposition processes onto belts. These belts move independently, allowing single-belt shutdowns for maintenance and repair. In each 14-strip subsection, the later array assembly stages are equipped with devices to insert spare solar panels into inoperative strips. The subsection output is therefore unaffected by single-strip failures. The factory output is boxed arrays of connected solar cell panels ("packages"), each containing an array 14 panels wide by 541 panels long (15.5 m x 633 m, unfolded).

Thus solar cells are progressively built up (layer by layer) as they move through the successive processes. The study group chose this continuous production line design for maximum automation, and for minimum handling of the fragile solar cell layers. Equipment for the successive processes sits either above or below the moving solar cell strips. The deposition and assembly sections of the solar cell factory are designed to be entirely free of direct human operations, since the factory is unpressurized, the solar cells are extremely fragile, and the production equipment is hot (both

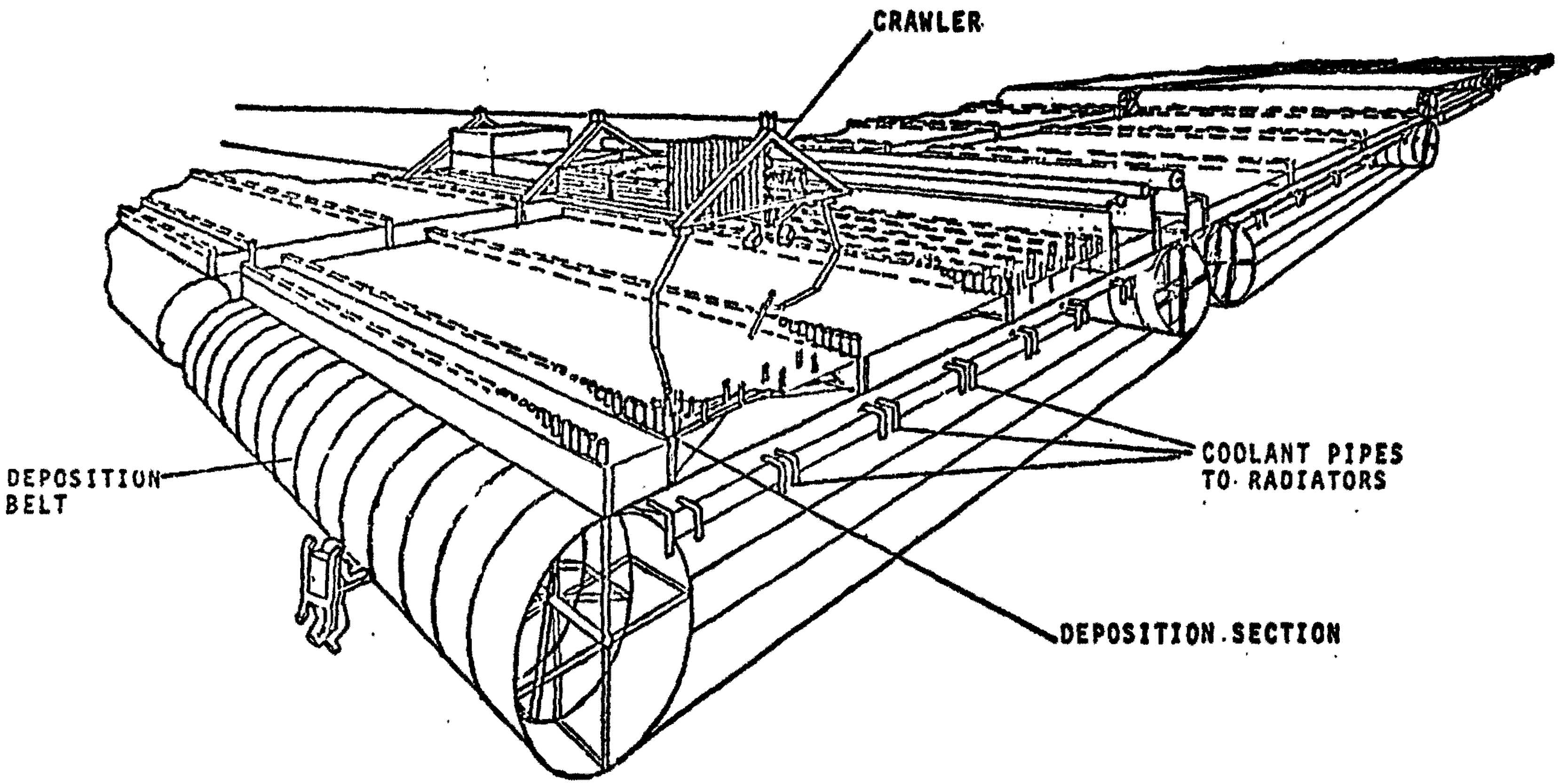


FIGURE 7.40: SOLAR CELL DEPOSITION AND ASSEMBLY: PERSPECTIVE VIEW

in the thermal sense, since many of the radiators are at 475°K or higher, and in the radiation sense, since electron beam guns put out x-rays). Operations within the solar cell factory are either automatic, robotic, or remote-controlled.

Although open to vacuum, the individual processes generate low pressures of deposition vapors, and are therefore protected from each other by baffles (thin sheets) to avoid contamination of product and equipment. Hence the 'box' appearance of the deposition sections in Fig. 7.40.

Also shown in Fig. 7.40 is a "crawler". Such crawlers move along guide tracks which run over (or below) each process, extending across the factory. Crawler tracks are shown as horizontal lines across the deposition and assembly sections in Fig. 7.39. The crawlers feed, maintain, and replace components of individual processes across the strips (for example, crawlers dedicated to the support of the aluminum rear contact deposition move along one track across the width of the factory). The crawlers pick up input materials and replacement parts from the internal transport system. Internal transport tracks cross the crawler tracks at several locations across the factory. Crawlers and internal transport devices are discussed in Chap. 8, "Support Equipment Specifications".

Onsite repairs in the deposition and assembly sections are performed by free-flying teleoperators. These are described in Chap. 9, "Maintenance and Repair".

Figure 7.41 is a side-view schematic of a production strip, showing the successive deposition and assembly processes and the dimensions of their sections. The solar cell strips travel through the process sections (from left to right in the figure) at .85 m/minute. The individual processes are discussed in the following sections of this chapter. In addition, these sections include descriptions of zone refining (Sec. 7.8.4), mask cleanup (7.8.11), interconnect deposition (7.8.14), and masking strip cleanup (Sec. 7.8.18).

The total number of production strips is computed by assessing the effect of the duty cycles of deposition and assembly sections on the maximum production capability. These calculations are discussed in Chap. 10, "Line Item Costing". The total number of strips in the reference SMF is 266, grouped in 19 clusters.

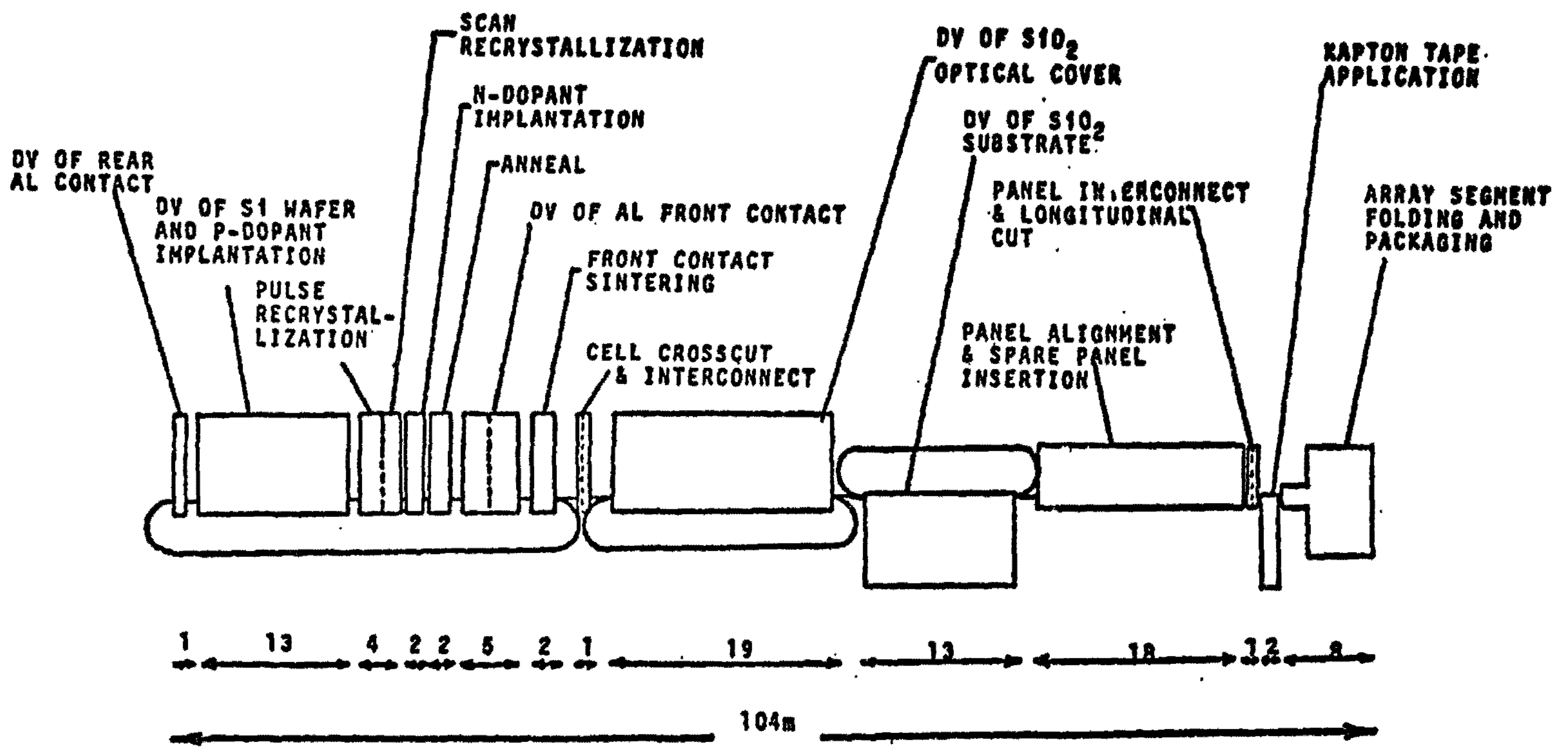


FIGURE 7.41: SOLAR CELL DEPOSITION AND ASSEMBLY: SIDE VIEW SHEMATIC

7.8.2 Thermal Belt: The thermal belt (see Fig. 7.42) serves as a deposition surface for the aluminum rear contact, silicon wafer, and aluminum top contact of the solar cell. It also carries the solar-cell wafers through recrystallization processes. The belt runs trhough 33 meters of deposition chambers and other production equipment, then curves around a 4.5 meter diameter roller and returns to the start of the production line. The belt's length is therefore 81 meters; each belt is 1.1 meters wide, the width of a panel of solar cells. Modeling the belt as 5 mm-thick copper yields a belt mass of 4000 kg.

To provide thermal control of the deposition surface during the process steps, the belt travels over fixed thermal control plates. These cool the belt, as required by the processes above. Heat is extracted by liquid sodium passing through the plates. To avoid stoppage of several belts by single failures, each belt has its own set of thermal plates, with their own thermal control systems. (Given present knowledge, the precise thermal requirements [e.g. surface temperature, thermal gradient, CTE] of the belt surface are unknown; an exact belt design is therefore difficult. An alternative to the belt-and-plate design in the reference SMF is a recently invented rod-and-sprocket belt made of stainless steel [Refs. 7.3, 7.4]. This belt may prove more reliable in space applications.)

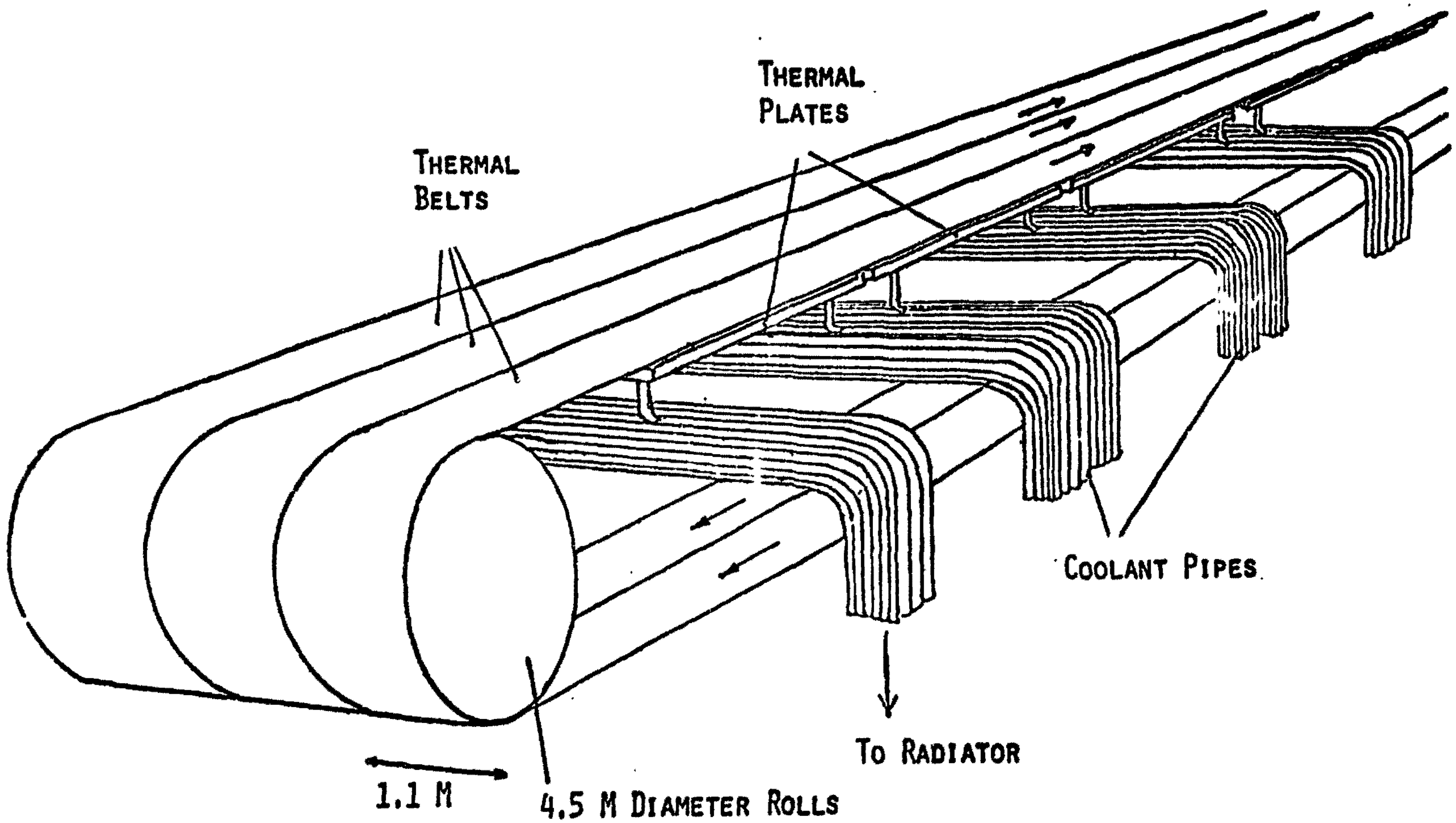


FIGURE 7.42: THERMAL BELT

The belts are grouped in sets of 14, with the belts in each group 1 mm apart, forming a nearly continuous deposition area. (Each group of belts produces 'packages' of solar cells, arrays 14 panels wide.) Between groups, the belts are separated by an open space 3 meters wide. Since the returning belts in a group also form a nearly continuous surface, power cables and coolant pipes to the group's thermal plates are routed to the gap between groups and out of the belt system. The coolant pipes carrying sodium at .5 m/sec are then routed to 1 mm thick aluminum sheet radiators. The 4.5 meter gap between the upper and lower belt surfaces contains the needed thermal plates, power feeds, piping, and structural supports. The three-meter gap between groups of belts, besides allowing entry and exit of power feeds and coolant pipes, also provides access to the inside of the thermal belt system for teleoperators.

Similar thermal belts are also used in the deposition of SiO_2 optical covers and substrates. These belts are listed as components of those processes, however. The thermal belt in this section is described separately because it is shared by several processes. For all the thermal belts in a deposition strip, about 2.2 tons of liquid sodium will be required, assuming a coolant flow rate of .5 m/sec through 100-meter-long pipes. Individual coolant requirements for each machine are listed under their sections. Pipe masses were assumed to be 15% of the coolant mass, based on a case example design. For each thermal belt, the mass of thermal control equipment is estimated at 200 kg. In addition, drive equipment to turn the belt rollers is estimated at 1000 kg per strip.

At the end of the belt, when the deposition surface curves down around the 4.5-meter-diameter roller, the 1.1 meter wide strip of deposited material (rear contact, silicon wafer, and top contact) is peeled from the thermal belt and travels on through more production steps.

SPECIFICATION SHEET

Machine Name: Thermal Belt

Function of Machine: To serve as deposition surface for several processes.

Mass of Machine: 5250 kg

Physical Dimensions: 38 m x 1.1 m x 5 m (not including radiators)

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 45

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Belt	1	4000	0
Drive/Motor	1	1000	20
End Rollers	2	50	5
Thermal Control	1	200	20

7.8.3 DV of Al Rear Contact: The solar cell production process begins with the direct vaporization of the 2-micron thick aluminum rear contact. The process is illustrated in Figs. 7.43 and 7.44. As shown in the figures, aluminum atoms are boiled off slabs by electron beams, and the atoms are deposited onto the thermal belt.

The electron beam (EB) guns fire beams of electrons into magnetic deflection and tracking coils near the surface of the belt. These coils deflect the beams upward and track them (2 mm spot) along the underside of the Al slabs, vaporizing the material. This geometry allows the positioning of the slabs 50 cm from the belt. At the deposition pressure of roughly 10^{-6} Torr, this distance is the mean free path of the atoms, and the Al therefore deposits with a minimum of atomic collisions.

This geometry also allows the thermal belts to be edge to edge, since neither equipment nor electron beams need to cross the belt surface. Neighboring belts therefore benefit from some of the vaporized material, improving the evenness of the deposition.

In this reference design, the thermal belt speed is set at .85 meters/minute, and the Al deposition rate at 4 microns per minute. The required deposition length is therefore .43 meters.

The aluminum slabs used in the process are produced at

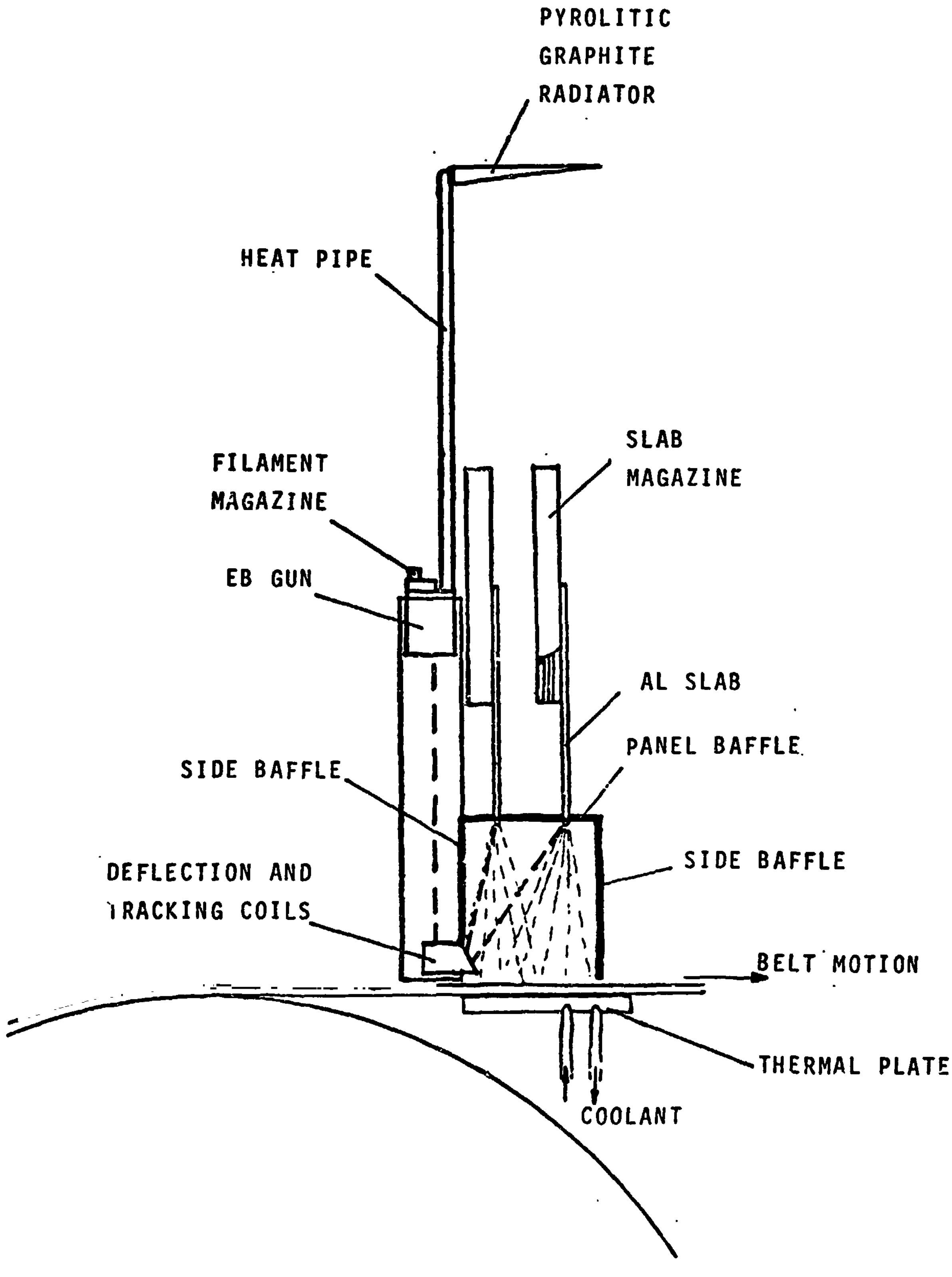


FIGURE 7.43: DV OF AL REAR CONTACT: SIDE VIEW

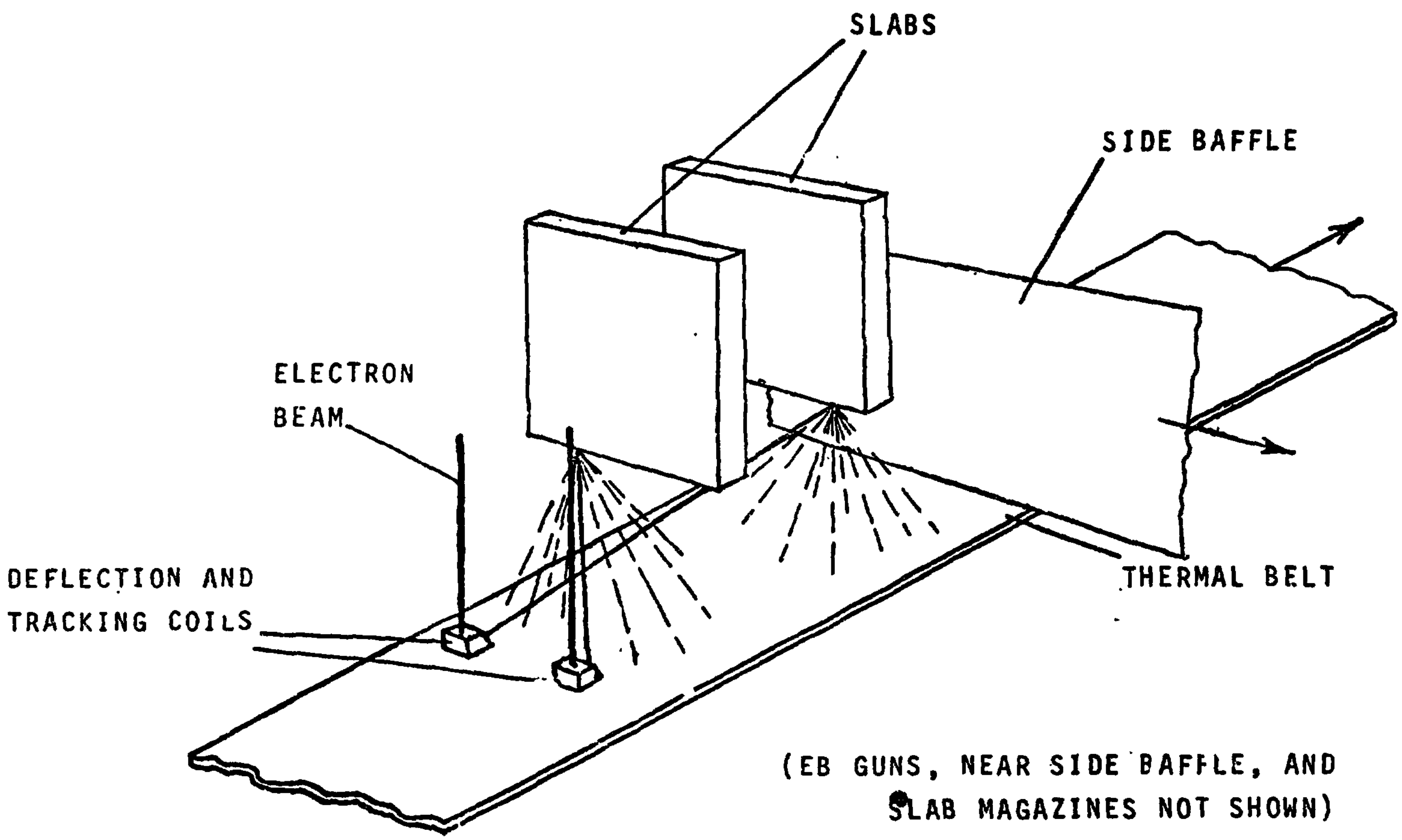


FIGURE 7.44: DV OF AL REAR CONTACT; OBLIQUE VIEW

the SMF by the continuous caster, and are therefore 2 cm thick and 70 cm high. Their length is set at 1 m, so that they fit across the 1.1-m-wide belt, with room at their ends for slab feeding mechanisms. The slabs are fed from magazines sized to hold 4 reserve slabs each.

Assuming that the deposition is 67% efficient (2/3 of the slab material ends up on the belt), slabs are used up at the rate of one every 165 hours (6.9 days). New and old slabs vacuum-weld themselves together at their edges as their boundary approaches the vaporization surface. Therefore an old slab is completely vaporized as a new one takes its place.

The remaining 1/3 of the slab material is vaporized and lost either to baffles or to open space. Although the deposition process does not require a pressure vessel (the lower the pressure, the better the deposition), the vaporized Al can contaminate neighboring equipment and processes. Therefore the deposition section is surrounded by baffles. These thin sheets of material serve as line-of-sight barriers to the Al vapor, shielding the EB guns, deflection coils, and slab feeding mechanisms.

The baffles are of two types. "Panel" baffles are those shielding the slab feeding mechanisms. They are made from 100-micron thick teperature-resistant material, e.g. glass cloth. (Although the reference SMF brings baffles from Earth, glass cloth baffles could also be manufactured at the SMF by machines similar to the electrical insulation winders.) Each strip's rear contact deposition section has a separate panel baffle; this baffle has two slits through which the slabs are fed into the deposition chamber. Estimating the deposition rate onto the panel baffles of .35 microns/minute, and allowing a 2500-micron layer of aluminum to accumulate before baffle replacement, each panel baffle is replaced every five days. Panel baffles are held in place by double tracks so that new baffles can be inserted before the old ones are removed, thus avoiding production stoppages.

The other type of baffle is the "side" baffle. Side baffles are positioned across the ends of the deposition section, shielding the EB guns and the next process in the production line. These baffles extend down to within a millimeter of the deflection coil output port or thermal belt surface. Unlike the panel baffles, side baffles are shared by the 'DV of rear contact' sections of all 14 strips in a solar cell factory subsection. Each side baffle is a 100-micron thick sheet of material (e.g. glass cloth) which is slowly unwound from a 310-meter roll at the edge of the 14-strip subsection. The baffle is guided across the 14 strips, it is discarded as process waste. Estimating a .7 micron/minute deposition on the side baffles (higher than the panel baffle because of the geometry of the deposition) and allowing a 500-micron buildup before discard, one roll of baffle lasts 10 days. Since new rolls can be attached directly to old ones, replacement of side baffles does not stop production.

The use of rolls of side baffles is possible because the side baffle surface is uninterrupted (i.e. no slits are required, as in the panel baffles). There are no baffles between strips, since deposition on neighboring strips is beneficial to the process.

Electron beam guns are described in some detail in Sec. 7.2.7. Unlike the slab cutter, however, for the EB guns in the solar cell factory, the 100° to 170° bending of the electron beam places the filament in the EB gun out of sight of the impact point, avoiding filament deterioration problems. Filaments are replaced every 40 hours by an automatic reload mechanism from a 20-filament magazine mounted on the gun. The reloader uses two filament cartridges, thus stopping the gun for only a few seconds during reload. This operation therefore does not stop production.

The total input power to each EB gun used in the DV of the aluminum rear contact is 3.1 kW. Focusing and deflection requires 20% of this power Of the remainder, 50% is wasted as heat in the EB gun, and the other 50% is the beam power. Electron scattering and thermal waste in the slab wastes 30% of this beam power, leaving (.8)(.5)(.7) = 28% of the original input power to vaporize the slab (including the vapor wasted on the baffles). At this efficiency, one 6.2 kW EB gun is sufficient to deposit the Al at 4 microns per minute. However, since the solar cell material cannot be routed from one strip to another during the deposition processes, failure of the EB gun would halt the entire production line. Therefore two 6.2 kW guns are used, for redundance; these guns operate at 3.1 kW during normal operations.

The latent heat of vaporization released by the aluminum vapor when it deposits onto the belt requires an active cooling system to prevent intersolution of solar cell layers and eventual melting of the belt. Assuming 40% of the nominal input power to the guns [equivalent to the beam power = (6.2 kW)(.8)(.5) = 2.5 kW] must be removed through the belt, and that the liquid sodium (heat capacity 1340 joules/kg°K at 475°K) enters at 400°K and leaves at 600°K, then each strip's 'DV of rear contact' section requires .01 kg/sec of liquid sodium to keep the thermal belt below 750°K. If the sodium flows at .5 m/sec through 100 meters of piping (out of the thermal belt, to a radiator roughly 30 meters away, and back), then 1.9 kg of sodium is required for each section. The waste heat is radiated away from a 1.1 m^2 sheet of aluminum (1 mm thick), located below the returning portion of the thermal belt. Although each strip has its own thermal plate and pump, piping and radiators for the 'DV of rear contact' sections of the 14 strips in a subsection could be combined, since the duty cycles of these components is virtually 100%. The pump, piping, fittings, radiators, and control system for one strip's 'DV of rear contact' thermal control are estimated at 20 kg.

Of the 60% of the input power remaining, it is assumed that 10% is lost in escaping vapor and baffle radiation. The remaining 50% must be dealt with in the electron beam gun. A heat pipe conducts waste heat from the gun to a pyrolytic graphite radiator above the deposition section. The radiator is rectangular, has an area of .25 m^2, and operates at 720°K when wasting 3.1 kW. The heat pipe is long enough to allow handling of input slabs by manipulators without removing the radiators. The pyrolitic graphite radiators are modeled on those suggested by Raytheon for amplitrons (Ref. 7.5), and are estimated to mass 10 kg (including heat pipe).

SPECIFICATION SHEET

Machine Name: DV of Al Rear Contact

Function of Machine: To DV aluminum onto the thermal belt

Mass of Machine: 164 kg

Physical Dimensions: 1 m x 1.1 m x 3 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 6.2

Number of Machines: 266

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
EB Gun	2	20	3.1
Filament Magazine	2	.04	0
Slab Feeder	2	50	.01
Panel Baffles	1	.05	0
Side Baffles	2	.05	0
Side Baffle Guide	2	2	.01
Cooling System	1	20	.004

7.8.4 Zone Refiner: The reference SMF receives metallurgical grade silicon in slabs 1.2 m x .42 m x .04 m. These slabs are zone refined in a separate facility to reach semiconductor grade purity. The study group assumed that the Si from the Moon would be sufficienctly pure that 10 zone refining passes would be sufficient to reach the needed 99.999% purity.

The zone refiner is shown in Fig. 7.45. Slabs travel one after another through the machine at a speed of 2.5 cm per minute. Each slab passes through ten heating coils spaced 40 cm apart; each heating coil uses magnetic induction to create a molten zone in the silicon slab. Behind each coil is a gas-jet ring which sprays cooling argon onto the slab sufficiently close to the induction coil to create a 670°K/cm thermal gradient. Under those conditions the silicon at the liquid/solid interface will recrystallize at 2.5 cm/minute, and each melt zone will therefore be stationary relative to the heating coil and gas-jet ring. Each zone "travels" down the silicon as the slab moves through the machine. The leading and trailing ends of the slab are not melted, to preserve the structural integrity of the slab. In addition, a separate set of magnetic shaping coils preserves the rectangular cross-section of the slab during the process, resisting each melt zone's tendency to assume a circular cross-section in zero-g.

Thus each slab enters the zone refiner at 2.5 cm/minute,

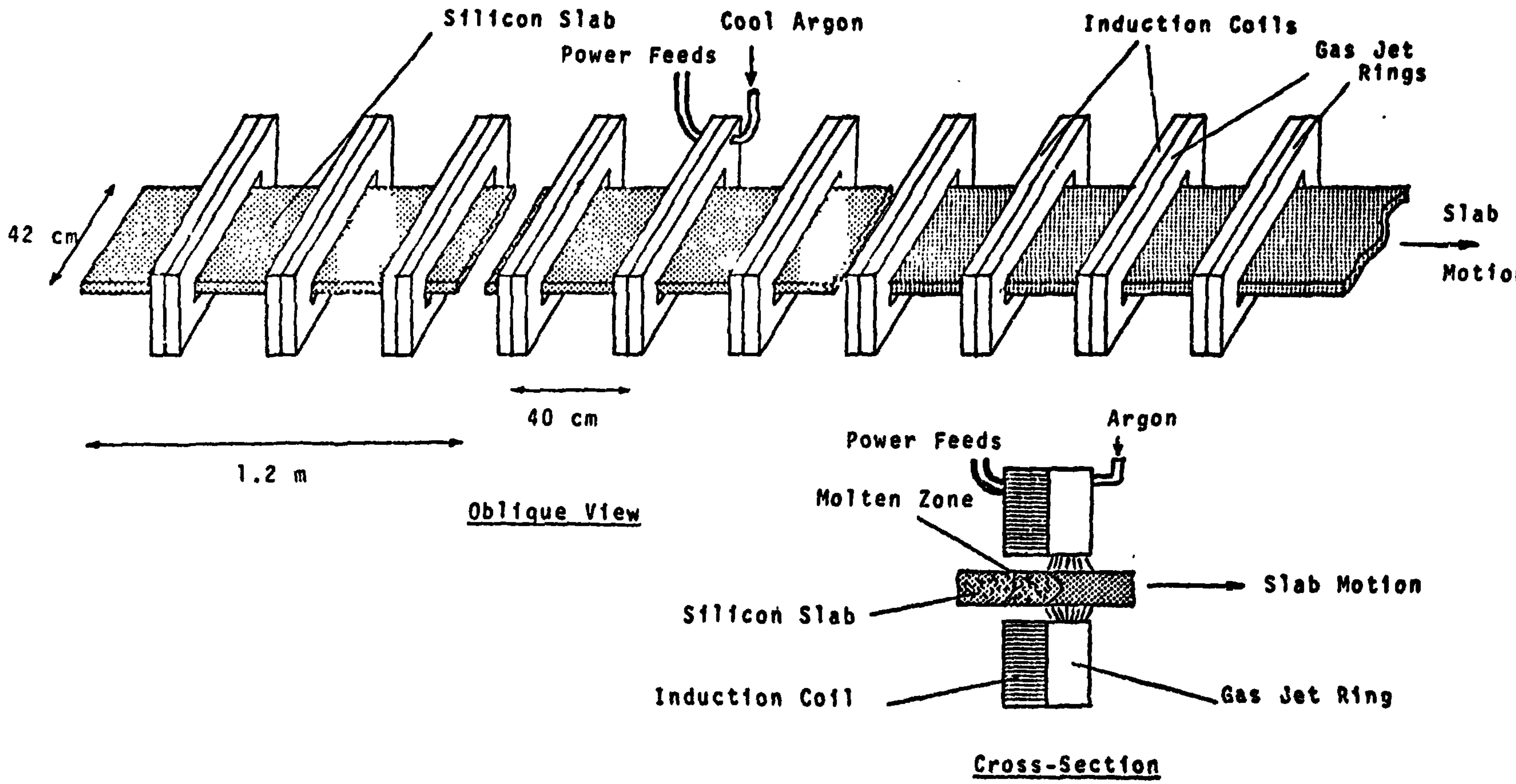
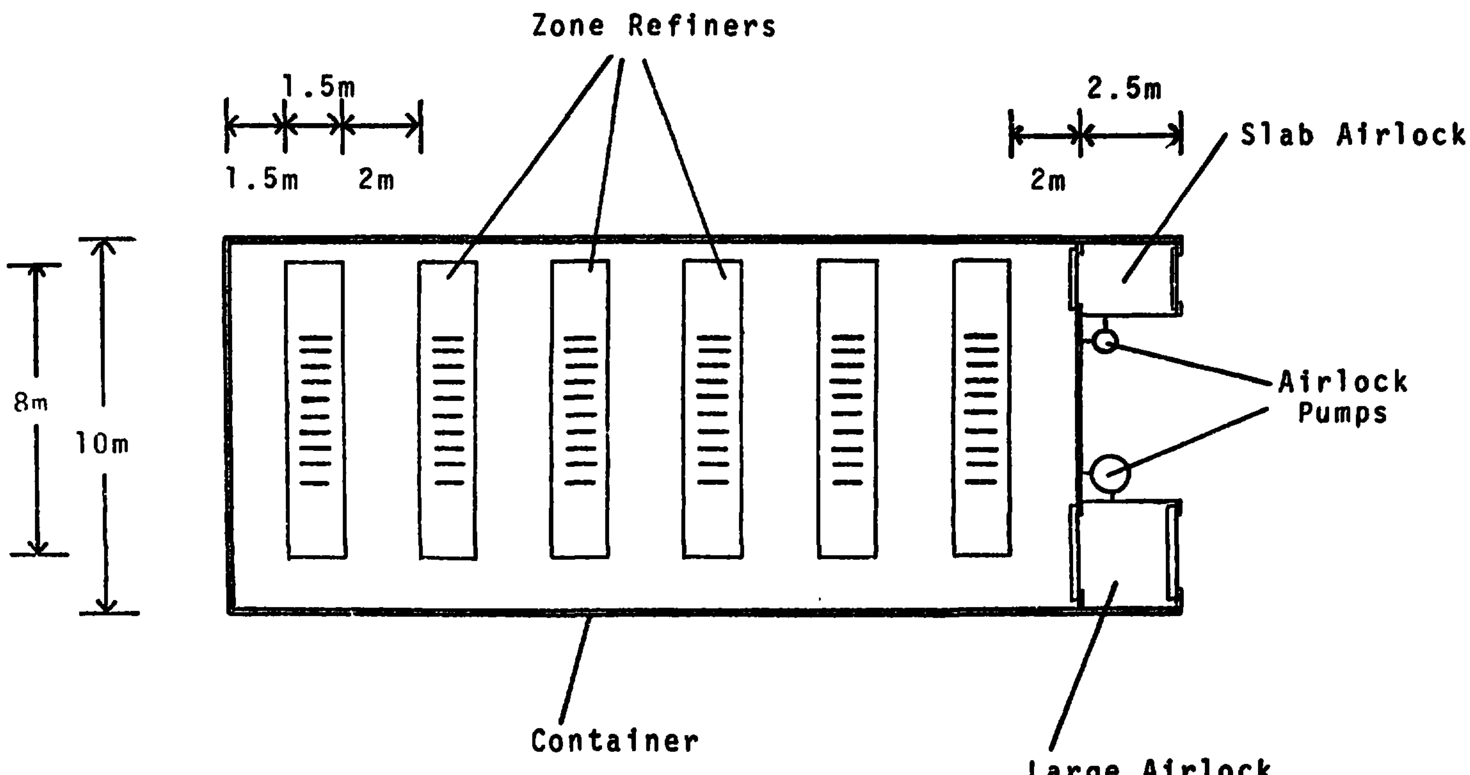


FIGURE 7.45: ZONE REFINER



(Handling equipment not shown)

FIGURE 7.46: CONTAINER FOR ZONE REFINERS

supported and moved by a set of clamps. Shortly after the leading edge passes through the first coil, that coil is turned on and creates a melt zone. That coil stays on until shortly before the trailing end of the slab reaches it (time of operation, 46 minutes); its molten zone therefore travels through the central 1.15 meters of the 1.2 meter-long slab. Successive coils operate in the same fashion. Since the coils are 40 cm apart, the slab can have as many as three molten zones within it at one time. To maintain its structural integrity, the slab is passed through the coils by a series of clamps which grasp and ungrasp the middle and ends of the slab so that sections between melt zones are not left freely suspended. The clamps also serve as heat sinks to help preserve the gradients near the melt zones.

Passage of one slab through the ten heating coils takes 190 minutes. With a 10-cm gap between slabs, the machine processes each slab in 194 minutes. After the ten melt zones have traveled through the slab, almost all of the impurities have been crystallized in the trailing end of the slab. Allowing a 10-cm gap between slabs, each zone refiner outputs one slab every 52 minutes. Each machine therefore produces 9500 slabs per year (95% duty cycle), and 60 machines are required to refine the 570,000 slabs of silicon required for the production of one 10-GW SPS per year.

To avoid loss of the argon sprayed by the gas-jet rings, the zone refiners are enclosed in pressure-tight containers. Each 25 m x 10 m x 5 m container holds six zone refiners (each 1.5 m x 8 m x 2 m), as shown in Fig. 7.46. Each container also includes two airlocks for introduction and removal of slabs and entry and exit of repair crews. The containers are sized to allow access space for space-suited repair workers around the refiners. Hot argon is pumped from the containers to radiators for cooling, and the cool argon is returned to the gas jet rings.

Slabs entering and leaving the container are handled by automatic manipulators. After refining, the silicon slabs are first placed into racks designed to hold the semiconductor grade slabs without contaminating them. Once full, a rack of slabs is passed out through the air lock and taken to a cutting area. There four 128-kW EB guns cut off 10 cm from each end of the slab (the impure ends) and trim 1 cm from each side edge to provide a flat surface for vacuum welding during deposition processes. This trim is required because the magnetic shaping coils cannot maintain a completely rectangular shape. The final slab dimensions are 1.0 m x .40 m x .04 m.

The ten pressurized containers and the EB cutting sections are arranged into a flat shape 120 m x 25 m x 5 m, with radiators above and below the equipment.

SPECIFICATION SHEET

Machine Name: Zone Refiner

Function of Machine: Refines input metallurgical grade Si slabs to semiconductor grade

Mass of Machine: 2200 kg

Physical Dimensions: 8 m x 1.5 m x 2 m (zone refiner only)

Throughput/Machine (tons/year): 350

Power Requirements (KW/machine): 300

Number of Machines: 60

Number of Operators: 0

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
Induction Coil	10	35	25
Gas Jet Ring & Pump	10	10	1
Rod Clamps & Drive	1	150	.2
Handling Equipment	1	50	.5
Active Cooling System for Coils	1	200	.3
Radiator	1	33	0
Container and Airlocks	1/6*	6000	0
EB Cutter	1/15*	40	128
Cooling for EB Guns	1/15*	100	.1
Packing Containers	2	2	0
Magnetic Containment Coils	10	30	3
Active Cooling System for Argon	1/6*	30	1

(*number of components/number of refiners)

7.8.5 DV of Silicon Wafer and P-Dopant Implantation: The next step in the buildup of solar cells is the deposition of 50 microns of polycrystalline silicon (see Fig. 7.47) onto the aluminum rear contact. The details of this deposition equipment are similar to the DV of aluminum rear contact (see Sec. 7.8.3). Zone refined slabs of silicon (1.0 m x .4 m x .04 m) are vaporized at the rate of one every 3.2 days (magazine holds six extra slabs). The total deposition length is 10.63 m assuming a 4 micron/minute deposition rate. To avoid too oblique an angle when the electron beam strikes the slab (a shallow incidence angle would result in electrons bouncing off the slab), the deposition is divided into two sections each 5.3 m long. The shallowest angle of incidence is therefore 11°.

The EB guns are mounted vertically in clusters of five at the beginning and end of each section. Each of the 7.3 kW guns is assigned a particular slab. In each 5-gun cluster, if one gun goes off, the other four increase their power levels by 25% to compensate for loss of DV power. Pyrolitic graphite radiators (14.6 kg each) cool the guns at a temperature of 640°K. The total input power to the machine is 146 kW based on a DV power of 408 kW needed to raise silicon from 60°K to its boiling point at the required rate.

Side roll baffles (identical to those described in DV of Al rear contact) are used up every 55 hours (estimating

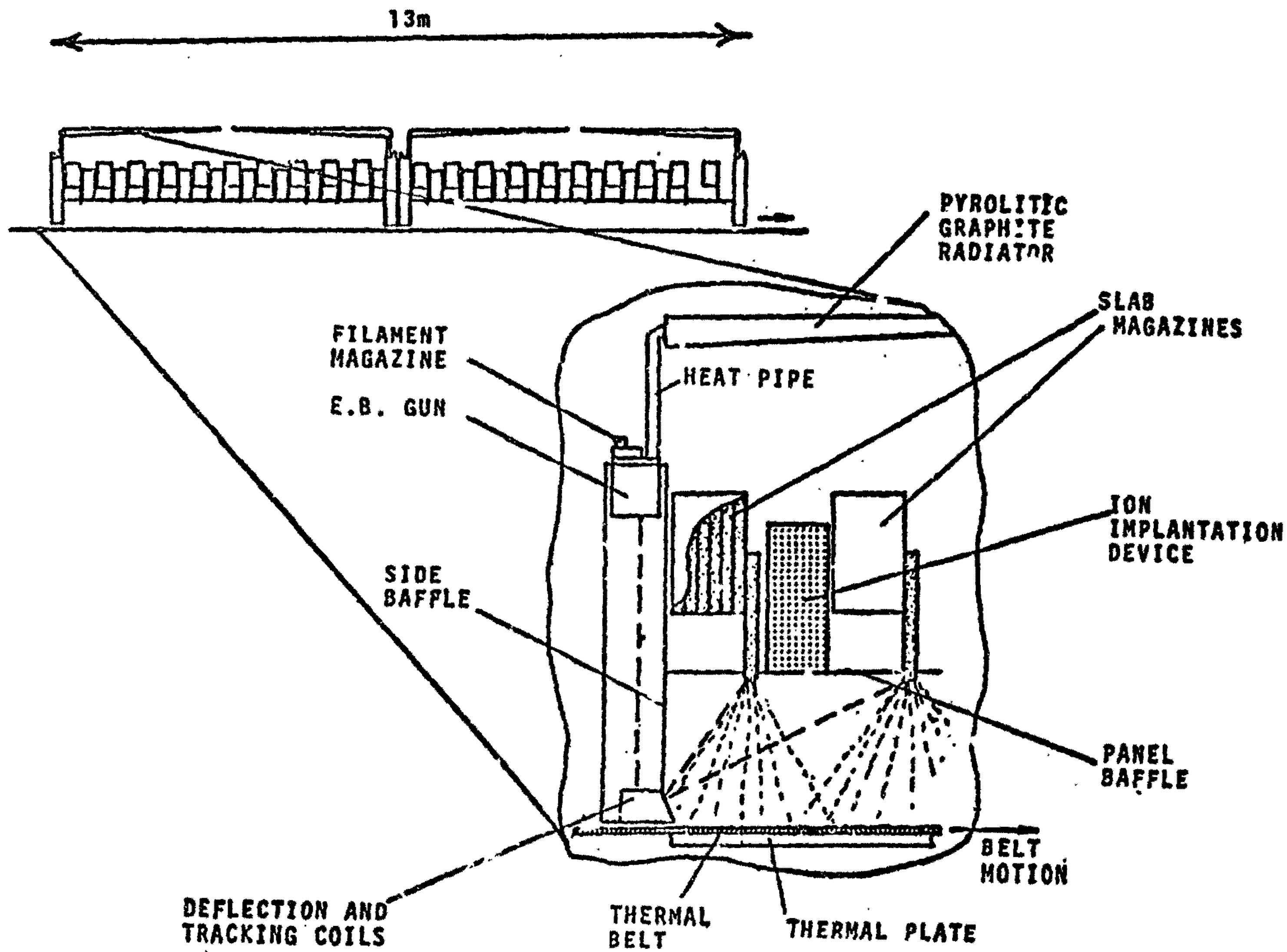


FIGURE 7.47: DV OF SILICON AND P-DOPANT INPLANTATION

3 microns/minute depositon on the side baffles). Panel baffles between the slabs are replaced every 27 hours (1.5. microns/minute deposition).

The temperature of the deposition surface is actively controlled to prevent intersolution of the aluminum and silicon and to control the crystalline structure of the silicon layer. To cool the thermal plates under the belt, liquid sodium is routed through the plates, to a radiator roughly 30 meters below the thermal belt, and back to the thermal plate (total travel distance is 100 meters). To remove 40% of the total input power [(.4)(146 kW)= 58.4 KW] .22 kg/sec of liquid sodium is required for each strip (400°K input, 600°K output). Assuming a flow rate of .5 m/sec in the piping, 43.6 kg of liquid sodium are required for each strip. The heat is wasted to space by a 25.2 m^2 aluminum sheet radiator (average temperature is 475°K). Since this area is 2.2 times the deposition area, the radiator extends beyond the silicon deposition section.

Ion implantation of the p-dopant (boron) occurs during the first 45 microns of silicon deposition. Beginning just after the first slab, 18 ion implantation devices are interspersed between slab feeders. Each device implants boron atoms (at 10^{18} atoms/cm^3) throughout a depth of 2.5 microns. There are no ion implantation devices after the last two slab feeders to allow a 5 micron layer of undoped silicon which will later be implanted with phosphorus. Roughly 150 kg/year of boron (shaped into 2 kg rods) is needed. The ion implantation device is identical (except for lower accelerating voltage) to that described in the section on ion implantation of the n-dopant, phosphorus (Sec. 7.8.8).

SPECIFICATION SHEET

Machine Name: DV of Si Wafer and P-Dopant Implantation

Function of Machine: To DV silicon onto the rear Al contact and to ion-implant p-dopant in the Si

Mass of Machine: 2810 kg

Physical Dimensions: 13 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 178

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	20	25	7.3
Filament Magazine	20	.04	0
Slab Feeder	20	60	.01
Panel Baffles	4	25	0
Side Baffles	4	.05	0
Side Baffle Guide	4	2	.01
Boron Ion Implanter	18	50	1.75
Cooling System	2	50	.038

<u>7.8.6 Pulse Recrystallization</u>. After the 50 micron wafer of polycrystalline silicon has been deposited, the grain size is increased by a two-step recrystallization process. The first step is a pulsed-beam recrystallization (see Fig. 7.48) which transforms the original silicon crystallites into full-film-thickness columnar grains. The process uses electron beam guns delivering pulsed streams of high-energy electrons.

The beam has an average electron energy of 55 KeV, a pulse length of 200 nanoseconds, and a pulsed beam fluence of 6.3 J/cm^3 (1 kW EB gun output). Pulsing is accomplished by a plasma diode and an energy storage capacitor, and electrons are returned to the gun via a metal brush sweeping across the surface of the silicon near the beam impact area.

The pulsed-beam recrystallization zone in each strip is cooled by .007 kg/sec of liquid sodium (400°K input, 600°K output) flowing through a thermal plate below the belt. Estimating a total pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, 1.5 kg of sodium is required for each strip. The radiator is an .9 m^2 aluminum sheet radiating at an average temperature of 475°K. In addition, the two 1.8 kW EB guns are cooled by pyrolitic graphite radiators (5.7 kg each) at a temperature of 450°K.

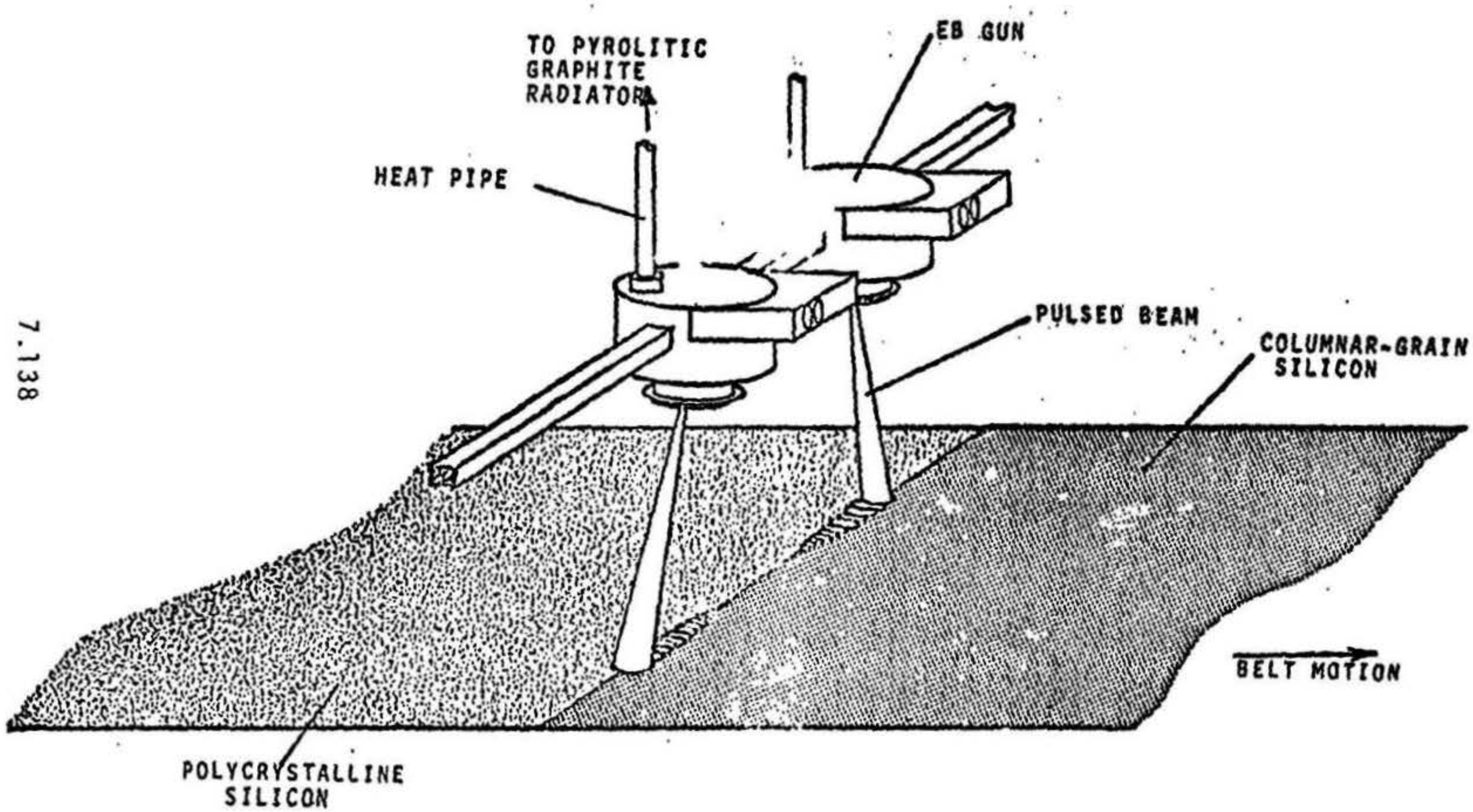


FIGURE 7.48: PULSED BEAM RECRYSTALLIZATION

SPECIFICATION SHEET

Machine Name: Pulse Recrystallization

Function of Machine: To recrystallize the silicon layer, causing the growth of columnar grains in the layer

Mass of Machine: 40 kg

Physical Dimensions: 2 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 3.6

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	2	10	1.8
Filament Magazine	2	.04	0
Cooling System	1	20	.004

7.8.7 Scan Recrystallization: The second step in the recrystallization process is a fast-scan electron beam solid phase recrystallization (see Fig. 7.49) to grow the columnar grains to a diameter of 100-200 microns. This is done with triode guns which have accelerating voltages of 100 KeV, fast-scan velocities of 100 m/sec with a 55 mA current, and an estimated beam diameter of .25 mm.

Since the belt speed is 1.42 cm/sec, 56.8 scans across the strip must be done per second. The gun must therefore sweep a total of 62.5 meters in one second ((1.1 meter wide strip), well within the scanning capacity of 1000 m/sec.

The electron beam power required is .35 kW (5.5 kW for 1000 m/sec scan speed). Electron current loop return and belt cooling are accomplished in the same ways as for pulse recrystallization. The scan zone is cooled by .003 kg/sec of liquid sodium per strip (400°K input, 600°K output) flowing through a thermal plate beneath the belt. Estimating a total pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, .52 kg of liquid sodium is required for each strip. The radiator is a .31 m^2 aluminum sheet (average temperature 475°K). The two .6 kW EB guns are also cooled by 2.0-kg pyrolitic graphite radiators at 340°K.

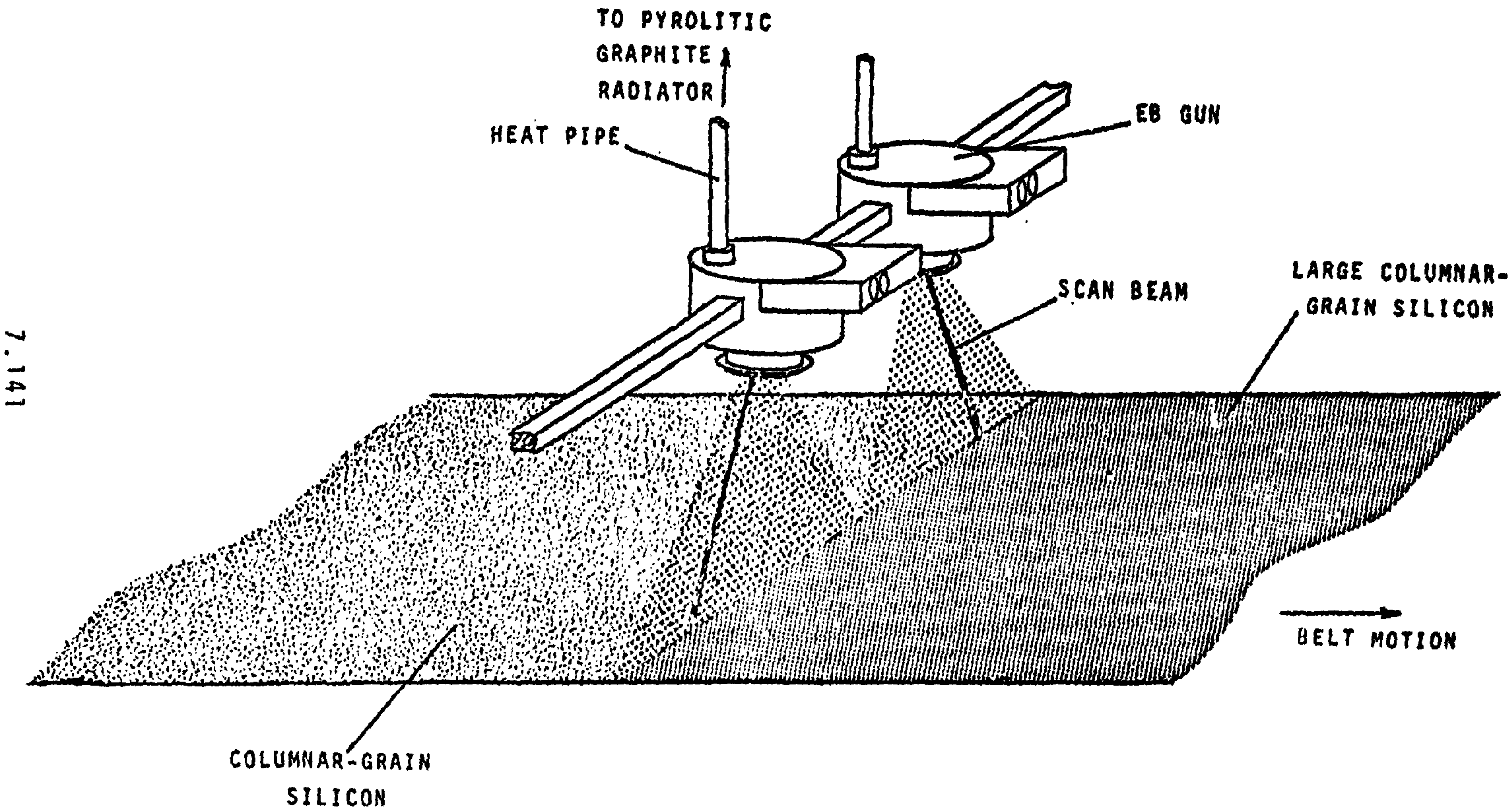


FIGURE 7.49: SCAN RECRYSTALLIZATION

SPECIFICATION SHEET

Machine Name: Scan Recrystallization

Function of Machine: To enlarge the diameter of the columnar grains in the silicon layer

Mass of Machine: 15 kg

Physical Dimensions: 2 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 1.2

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	2	5	.6
Filament Magazine	2	.04	0
Cooling System	1	5	.002

7.8.8 N-Dopant Implantation: In order to obtain an n-p junction between phosphorus and boron, an electron beam irradiated ion implantation device is used ee Fig. 7.50). The device consists of an electron beam gun, a 2 kg rod of phosphorus which is automatically fed down form a 10 rod magazine, a permanent U-magnet for deflecting the electron beam, an acceleration grid, and electromagnetic coils for defleting the ion beam.

The electron beam is deflected by the magnetic field to strike the flat end of the rod. A tenuous phosphorus cloud is produced which is ionized by the incoming electron beam. The positively charged ions are accelerated through a grid with a high negative potential and scanned across the width of the strip by powerful electromagnets. The ions impact and penetrate the silicon, implanting themselves into the layer.

Fifty kilograms per year of phosphorus are required for the entire factory. There are implanted at a density of 10^{18} atoms/cm^3. While ion implantation devices today implant to depths of less than 2 microns, a 5 micron depth should be possible with a high accelerating voltage implant device, given some development. The power level of such a gun and associated systems is estimated at 1.75 kW, and its mass (including a pyrolitic graphite radiator) at 50 kg.

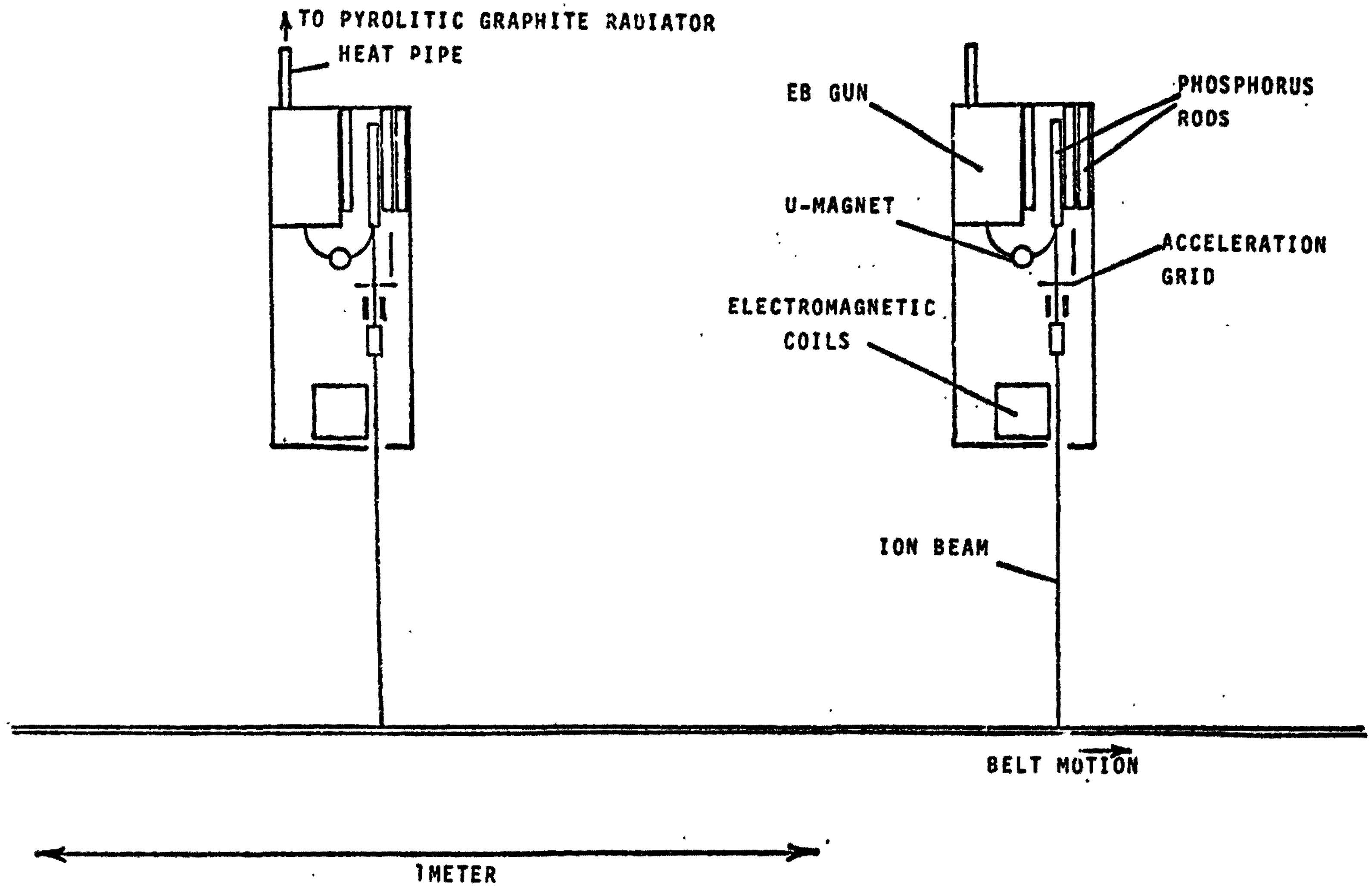


FIGURE 7.50: N-DOPANT IMPLANTATION

SPECIFICATION SHEET

Machine Name: N-Dopant Implantation

Function of Machine: To implant phosphorus into the top 5 microns of the silicon wafer

Mass of Machine: 100 kg

Physical Dimensions: 2 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 3.5

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Phosphorus Ion Implanter	2	50	1.75

7.8.9 Anneal: The ions bombarding the silicon in ion implantation produce crystal lattice defects in the top layers. This leads to a more amorphous structure in the bombarded zone, requiring repair of the lattice damage to restore the efficiency of the cell.

The implanted silicon is annealed by a series of .1 microsecond electron beam pulses with mean electron energy of 20 KeV (see Fig. 7.51). Although the energy transferred to the silicon is only 1.0 J/cm^2 (.2 kW average beam power), the pulse duration is short enough to momentarily elevate a 2 micron thickness of the silicon close to its melting temperature (1400°C). This penetration is enough to recrystallize and anneal the damaged layer. The silicon drops back down to the ambient temperature within a few microseconds.

The anneal zone is cooled by .001 kg/sec of liquid sodium per strip (400°K input, 600°K output) flowing through a thermal plate beneath the belt. Estimating a total pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, .3 kg of liquid sodium are required for each strip. The radiator is a .17 m^2 aluminum sheet at an average temperature of 475°K. The two .4 kW EB guns are cooled by .8 kg pyrolitic graphite radiators at 310°K.

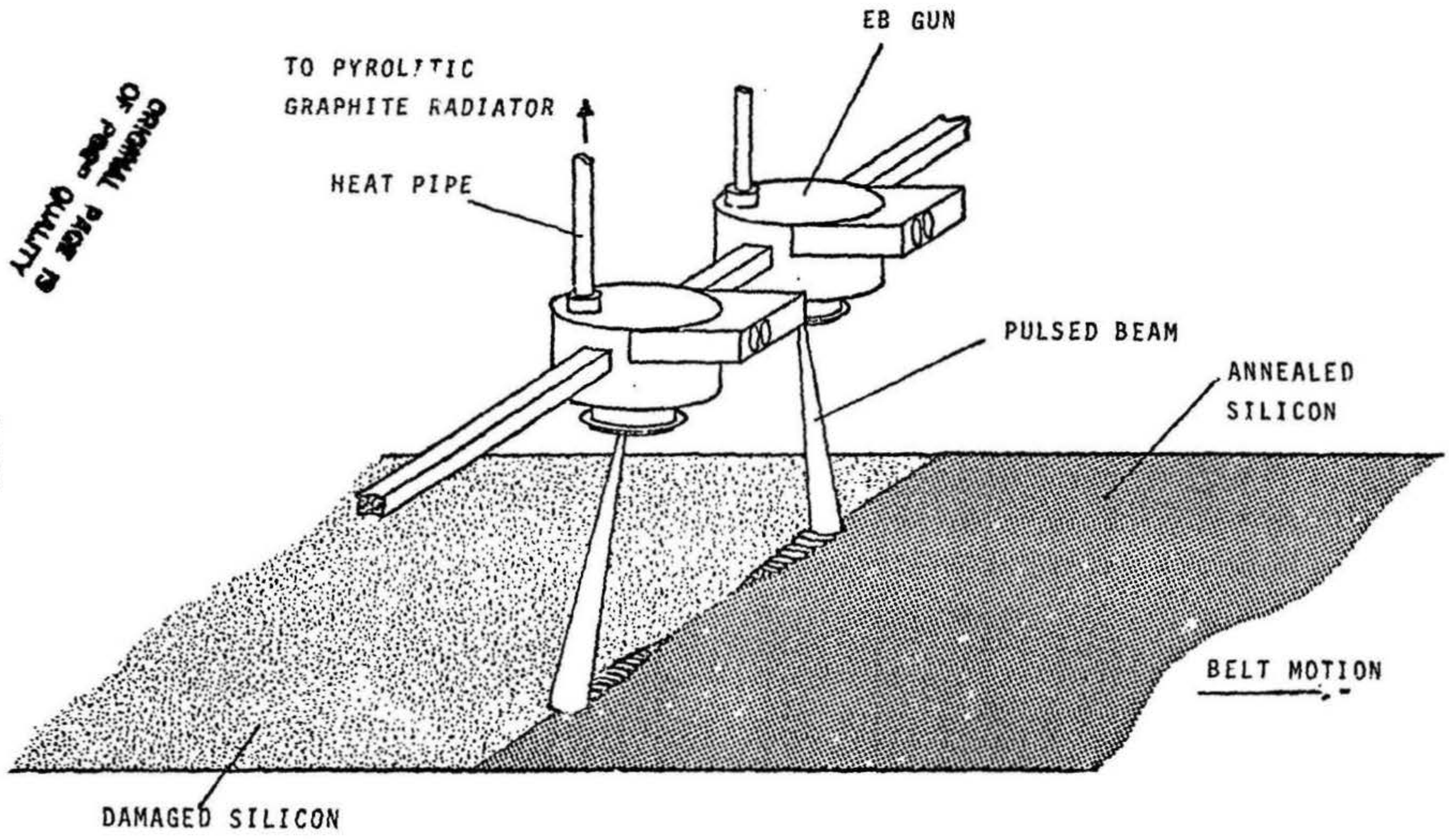


FIGURE 7.51: ION IMPLANTATION DAMAGE ANNEAL

SPECIFICATION SHEET

Machine Name: Anneal

Function of Machine: To anneal out the ion implantation damage in the silicon wafer

Mass of Machine: 15 kg

Physical Dimensions: 2 m x 1.1 x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): .8

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Guns	2	5	.4
Filament Magazine	2	.04	0
Cooling System	1	5	.001

7.8.10 DV of Front Al Contact: To produce power from a solar cell an electrical contact must be placed on top of the silicon wafer. This contact must provide conducting paths over the surface of a cell, yet not prevent incoming sunlight from impinging directly onto the silicon surface. The top contact is therefore a comb-like pattern, consisting of 1 micron thick aluminum grid fingers, each 50 microns wide, altogether covering 5-7% of the cell surface. The fingers all lead into a collector bar at the edge of the cell which gathers the current.

These patterns are vapor deposited through shadow masks (each one strip wide) positioned near the silicon surface and moving with the belt at the same speed of .85 m/min (see Fig. 7.52). The aluminum is direct vaporized (in the same fashion as the aluminum rear contact) to a depth of 1 micron. To alleviate structural problems in a single shadow mask for the entire pattern, the deposition is done in two steps: first the grid fingers are deposited through a mask, then the collector bars are deposited through another mask. For each deposition step, the deposition rate is 2 microns/minute, and the deposition length is .43 m.

The masks are unwound from rolls, travel with the solar cell strip during contact deposition, and are rewound on take-up rolls. Aluminum is deposited on the masks as well as the solar cells, so the used rolls are taken to a separate facility for brush cleaning. Assuming the roll will last for two

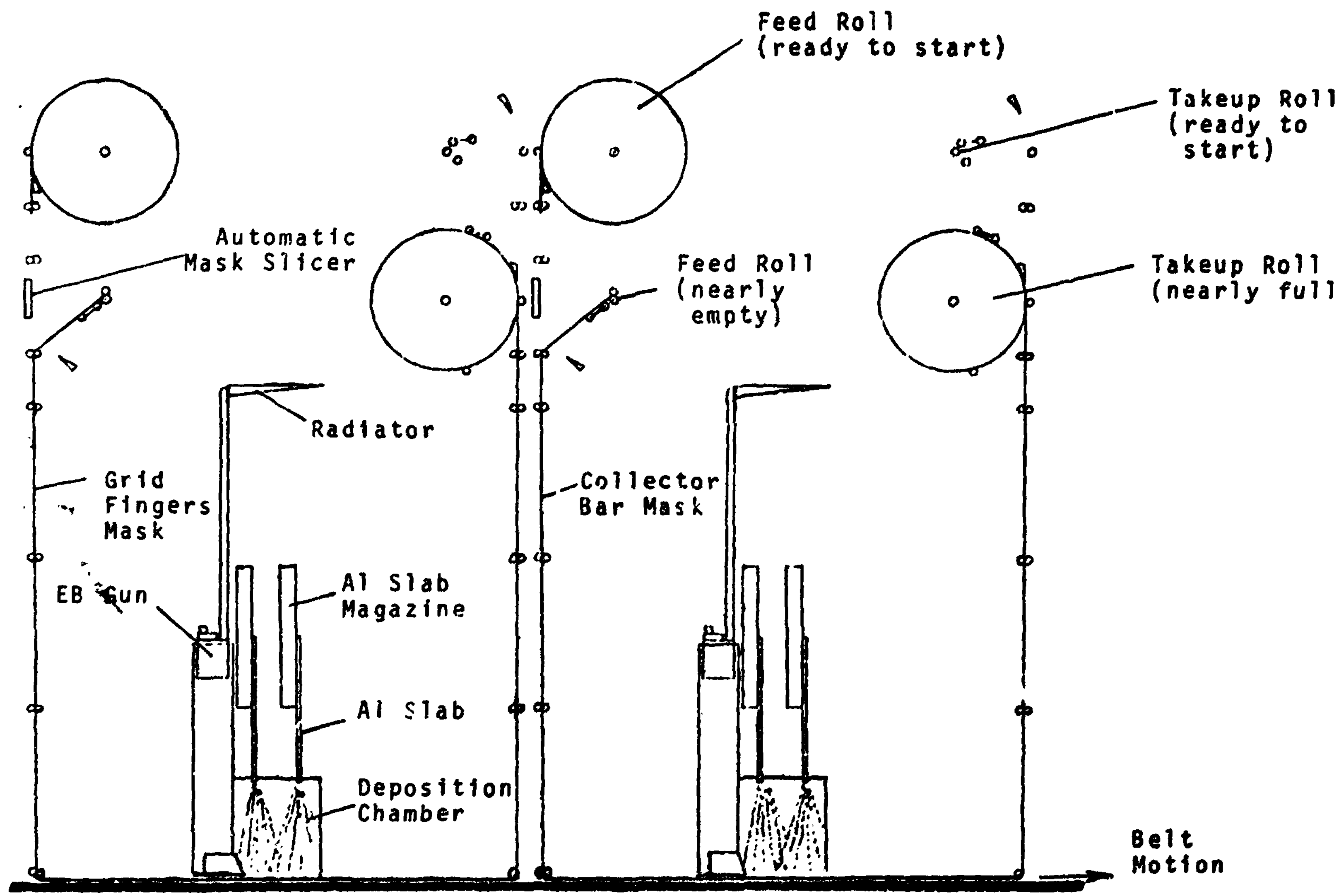


FIGURE 7.52: DV OF ALUMINUM FRONT CONTACT

633 meter-long solar cell array segments, the .5 mm-thick mask would be 1266 m long (with a roll radius of about .5 m) and last about one day. The mask material must be strong enough to be used and cleaned without deformation, resistant to vacuum, radiation, and temperature, and inert to aluminum. Materials such as kapton and teflon are possibilities, but further research is needed to verify their suitability. Assuming a material with the density of teflon, each roll would mass roughly 300 kg.

To avoid production stoppages, the masks are switched from one roll to another by automatically splicing the lead end of the new roll to the tail end of the old one. The splice is undone at the takeup roll and the lead end is threaded onto an empty roller.

The geometry of each deposition chamber is the same as for the DV of the Al rear contact (see Sec. 7.8.3). Since the deposition rate is 2 microns/minute, each of the four EB guns uses 1.6 kW, and wastes heat through a 5.1 kg pyrolitic graphite radiator at 610°K. Each slab lasts 13.8 days, and the panel baffles last 10 days. The 310-meter side baffle rolls last 20 days.

The thermal belt is cooled with liquid sodium (.01 kg/sec, 400°K input, 600°K output) flowing through thermal plates. Estimating a pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, 1.9 kg of sodium is required for each strip. The radiator is a 1.1 m^2 aluminum sheet.

<u>SPECIFICATION SHEET</u>

Machine Name: DV of Al Front Contact

Function of Machine: To DV 'grid-fingers' Al patterns onto the siliccn wafer

Mass of Machine: 1120 kg

Physical Dimensions: 5 m x 1.1 m x 5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 8.4

Number of Machines: 266

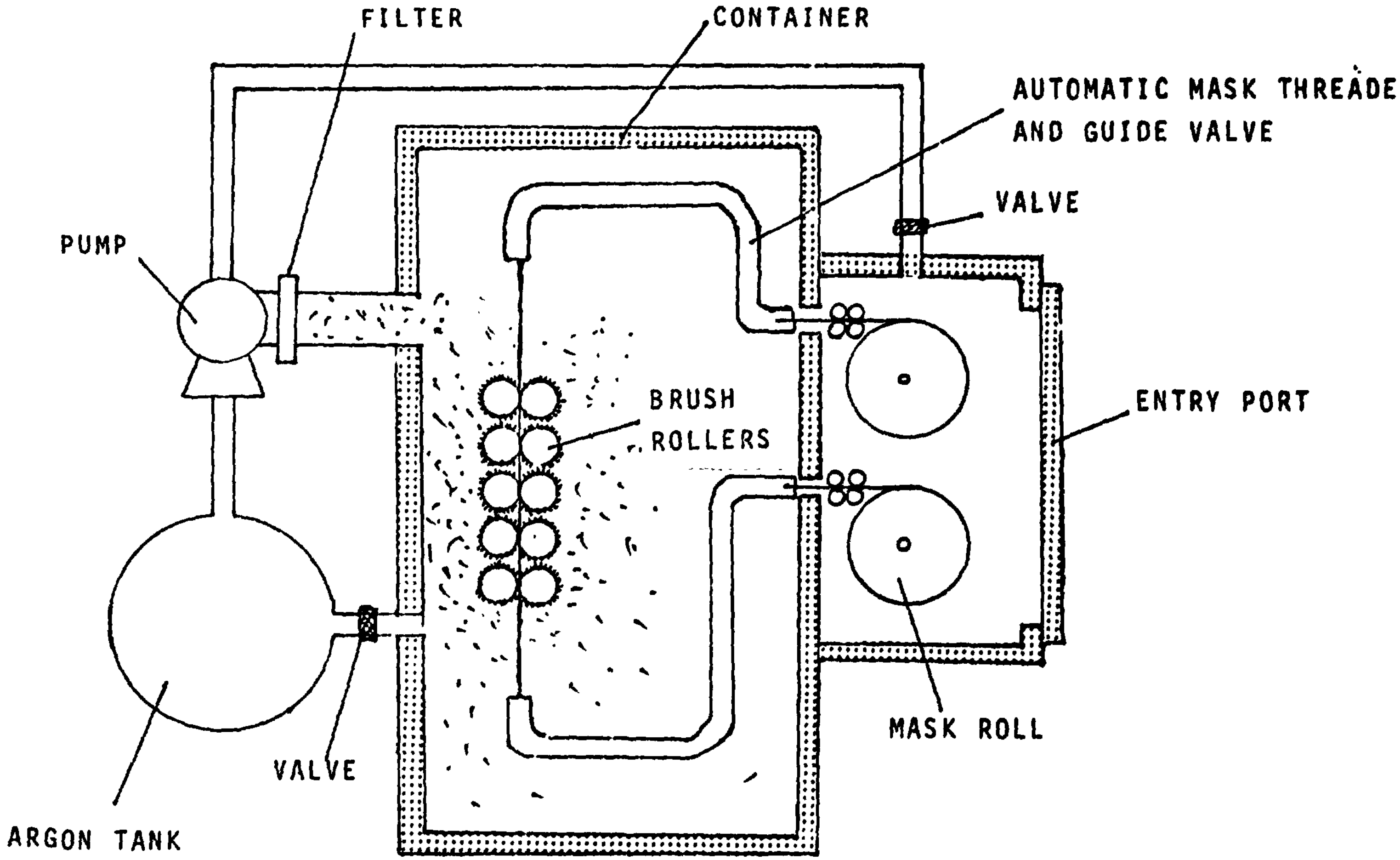
Number of Operators: 0

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Guns	4	10	1.6
Filament Magazine	[redacted]	[redacted]	0
Slab Feeder	4	50	.01
Mask	2	300	0
Mask Guide and Rollup	1	250	2
Panel Baffles	2	.05	0
Side Baffles	4	.05	0
Side Baffle Guide	4	2	.01
Cooling System	2	10	.002

7.8.11 Mask Cleanup Device: As shown in Fig. 7.53 cleaning of the teflon shadow mask (used in deposition of the solar cell top contacts) is performed within a pressurized chamber to allow gas suspension and filtration of the aluminum particles brushed from the masks. An aluminum-coated roll of mask is loaded into an evacuated outer chamber (the two-chamber design reduces pumping requirements). After the chamber is sealed and filled with argon, the mask is automatically threaded through cleaning rollers and back to a takeup roller.

The mask is then wound from one roll to the other at 28 meters/minute (one roll in 45 minutes) while the brushes remove the aluminum. The aluminum flakes are suspended in the argon and filtered out by a gas recircualtion system. Once the mask is cleaned, the inter-chamber slits are closed and the roll chamber is evacuated. The cleaned mask is removed and another used mask is inserted. The entire cycle is estimated at 1 hour per mask, and therefore 25 mask cleaning machines are required for the factory.



<u>FIGURE 7.53: MASK CLEANUP</u>

SPECIFICATION SHEET

Machine Name: Mask Cleanup Device

Function of Machine: To remove deposited Al from teflon shadow mask

Mass of Machine: 200 kg

Physical Dimensions: 6 m x 6 m x 2 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 16

Number of Machines: 25

Number of Operators: 0

Components:

Components	Number/ Machine	Mass (Kg)	Power Required (KW)
Mask Threader	1	20	1
Brushers and Drive	10	5	1
Gas Circulation Pump	1	10	5
Filter System	1	1	0
Container	1	130	0

7.8.12 Sintering of Front Al Contact: After the aluminum top contact has been vapor deposited on the silicon, an electron pulse sintering step is necessary to produce good mechanical and electrical behavior at the aluminum-silicon interface. The pulse-induced transient temperature is much lower than that necessary for implantation damage anneal. If the interface temperature is raised above the eutectic temperature of aluminum and silicon (851°K), an alloyed interface results producing good electrical contact. The brief thermal transient ensures that the intersolution of the contact and the silicon is quenched before more than a shallow interface can result.

An electron beam pulse gun (see Fig. 7.54) similar to the one used in annealing (Sec. 7.8.9) is used. Its average beam power of .1 kW is less than that used for annealing because of the lower energy required to reach the eutectic temperature.

The sintering section is cooled by .0007 kg/sec of liquid sodium per strip. Estimating a total pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, .15 kg of liquid sodium are required for each strip. The radiator is a .09 m^2 aluminum sheet at an average temperature of 475°K. The two .2 kW EB guns are cooled by .6 kg pyrolitic graphite radiators at 260°K.

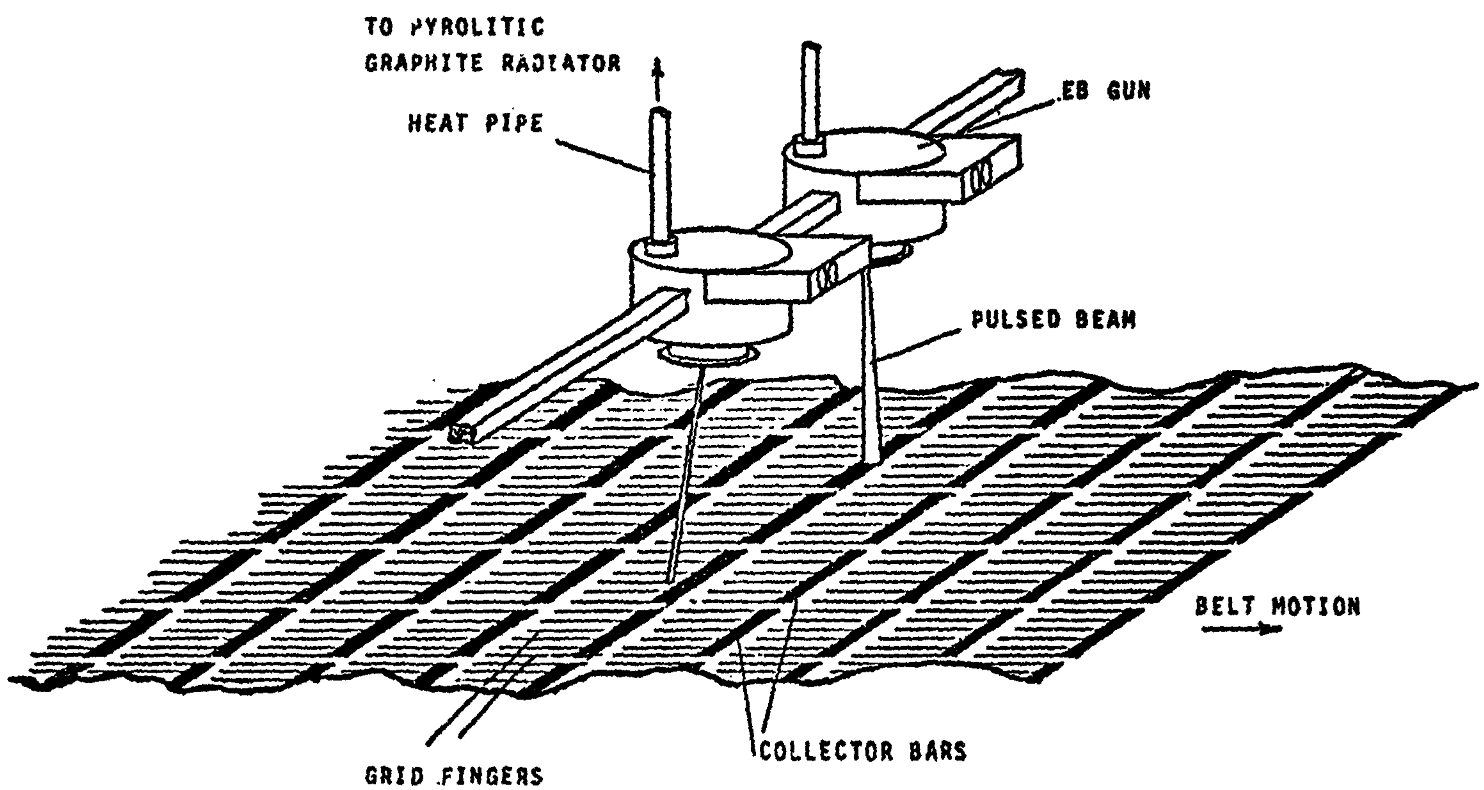


FIGURE 7.54: FRONT CONTACT SINTERING

SPECIFICATION SHEET

Machine Name: Front Contact Sintering

Function of Machine: To sinter the Al front contact/silicon wafer interface

Mass of Machine: 15 kg

Physical Dimensions: 2 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): .4

Number of Machines: 266

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
EB Gun	2	5	.2
Filament Magazine	2	.04	0
Cooling System	1	5	.001

7.8.13 Cell Crosscut: Immediately following contact sintering, the solar cell strip is peeled from the thermal belt and travels straight on, guided by rollers. The thermal belt curves around its end roller and returns to the start of the production line. The solar cell strip is then cut crosswise by a laser, forming 6.4 cm x 110 cm sections (see Fig. 7.55). These sections will be interconnectd in groups of 18 to form panels, and later cut length-wise (along the strip) to form individual solar cells. Each 6.4 cm x 110 cm section will become 14 solar cells.

The cutting speed is 25 cm/sec (110 cm in 4.5 sec), using a continuous wave (CW) Nd:YAG laser with a 50-watt beam power (2.5 kW input at 2% efficiency).

A laser was chosen over EB guns for cell cutting because of anticipated problems in returning electrons to the gun, specifically those electrons which open the kerf and travel through the solar cell material. The use of lasers also avoids putting electrical surges through the cells, which could degrade the cell properties.

A solid state Nd:YAG laser was chosen over the more efficient CO_2 gas laser (2% vs 15%) for three reasons: a power intensity a hundred times greater can be achieved with a YAG laser (smaller kerf) because of the small angle of resolution that can be achieved with its ten times shorter wavelength (1.06 microns); CO_2 laser radiation is reflected strongly by

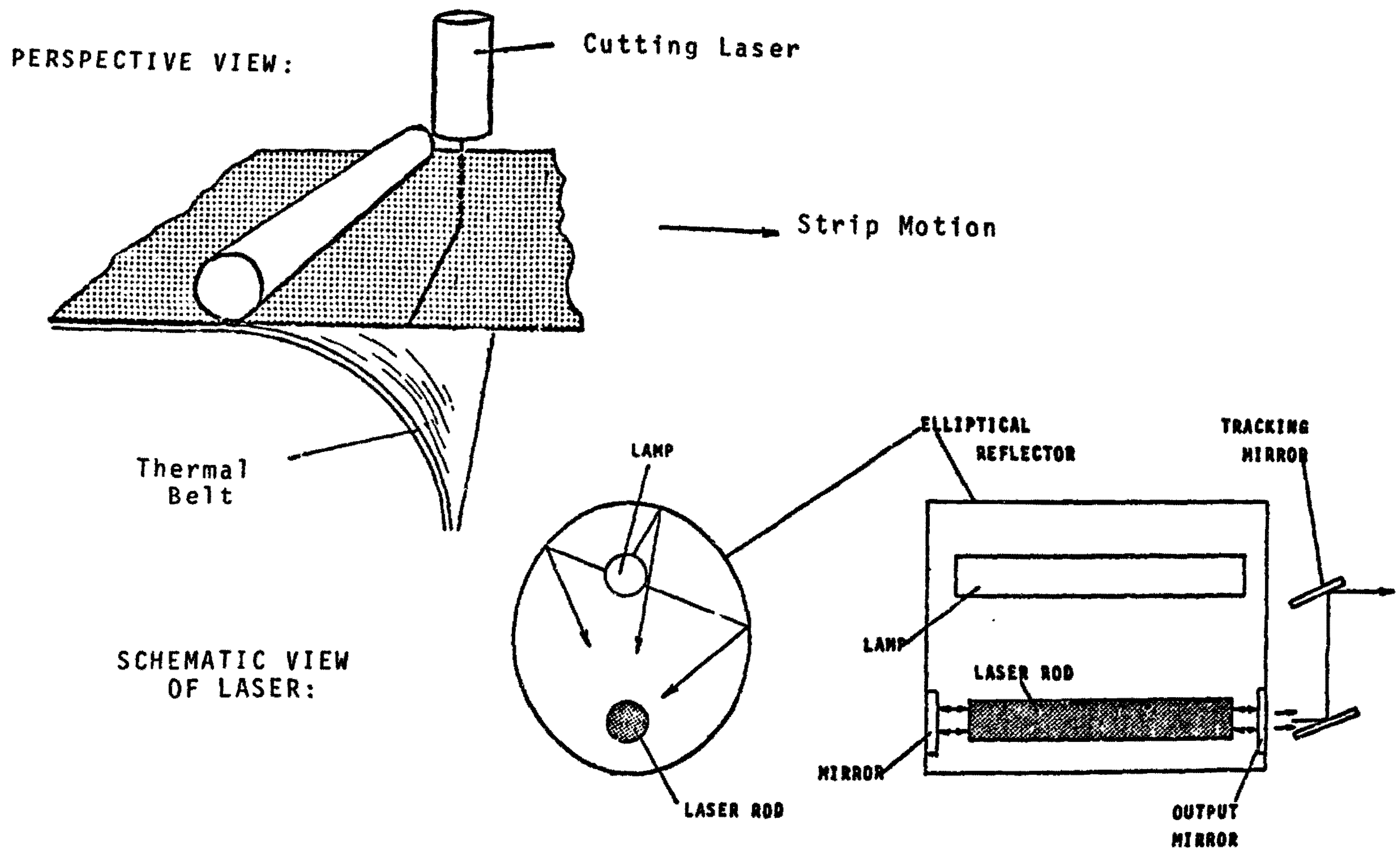


FIGURE 7.55: CELL CROSSCUT

aluminum, which might cause delamination problems when cutting through the aluminum rear contact; and CO_2 lasers are larger (up to 10 times) than YAG lasers and their gaseous laser medium is more difficult to maintain than solid state laser rods.

YAG lasers are used today in the scribing and breaking of solar cells. Solar cells at the SMF, however, will need to be cut completely through, requiring more power. If vaporization is achieved fast enough, little heat is conducted into the cells, resulting in a narrow heat affected zone and no physical distortion of the cell material. Increasing the cutting speed also tends to decrease the degradation of those layers in the cutting region for which penetration requires relatively more input power to achieve vaporization. The waste heat (98% of the input power) will be radiated to space at a temperature of 410°K by an 8.0 kg pyrolitic graphite radiator connected tothe top of the laser.

Figure 7.55 also depicts the basic laser operation. The laser rod, consisting of the host material, neodymium-doped yttrium aluminum garnet (Nd:YAG), is placed along one focus of an elliptical reflector cavity. A krypton flash lamp placed at the other focal axis optically excites the laser material (these lamps are replaced every 200 hrs by an automatic refill mechanism with a 20 lamp magazine.) The resulting coherent beam of radiation emanating from the partially reflecting output mirror is mechanically deflected and focused, using mirrors and lenses, onto the cell surface. The position of the focus is set by the focal length of the final lens (usually 35-50 mm) which must be protected from the metal vapor by a shielding gas. An oxygen canister attached to the laser's side provides this modest oxygen requirement. The focusing becomes more critical with thickness and melting point and requires $\pm$.1 mm 3-D positioning accuracy for reflective metals. A metal shield beneach the cutting zone obstruct the laser beam once it cuts through the cell.

Some of the system controls needed for the laser are position of deflection mirrors, focal lens-to-work distance for kerf compensation, shielding gas flow, laser head temperature, and beam power. Reference 7.6 discusses numerical control of lasers used for cutting in the textile industry.

SPECIFICATION SHEET

Machine Name: Cell Crosscut

Function of Machine: To crosscut the solar cell material strip every 6.4 cm

Mass of Machine: 22 kg

Physical Dimensions: .5 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 2.5

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Laser	1	20	2.5
Krypton Lamp Magazine	1	.1	0
Guide Rollers	2	.5	0
Shield	1	1	0

7.8.14 DV of Interconnects: For cell and panel interconnects, the reference SMF requires 1.05 meter-wide, 50-micron thick aluminum strips, with lengths totalling 5.1 x 10^6 meters per year. Each 633-meter-long solar cell array segment produced by the factory requires 27.6 m of cell interconnects and 1.6 meters of panel interconnects. The 3 mm x 50 micron x 1.05 meter interconnects are produced by direct vaporization in a separate facility. Eleven hundred tons of aluminum are supplied to this process (in 1 m x .7 m x 2 cm slabs from the SMF continuous caster) to deposit 740 tons of interconnects, enough for one SPS.

As shown in Fig. 7.56, five deposition belts moving at 2 m/minute through 5-meter-long deposition sections are used to deposit the 50 micron thick interconnects. Depositing at 20 microns/minute requires 347 kW per belt, or 10 EB guns each receiving 34.7 kW. Geometrically, the equipment is similar to the sections for Al rear contact deposition (Sec. 7.8.3) and for DV of Si (Sec. 7.8.5). A total of 233 kg of liquid sodium per strip is pumped at 1.[illegible] kg/sec through the EB guns and thermal cooling plates beneath the belt (400°K input, 600°K output). A 135 m^2 aluminum sheet radiator dissipates the heat from the liquid sodium at an average temperature of 475°K.

After the 1.05m wide layer of deposited aluminum is peeled form the belt, it is rolled up, with a 50 micron thick teflon film between successive layers to prevent vacuum

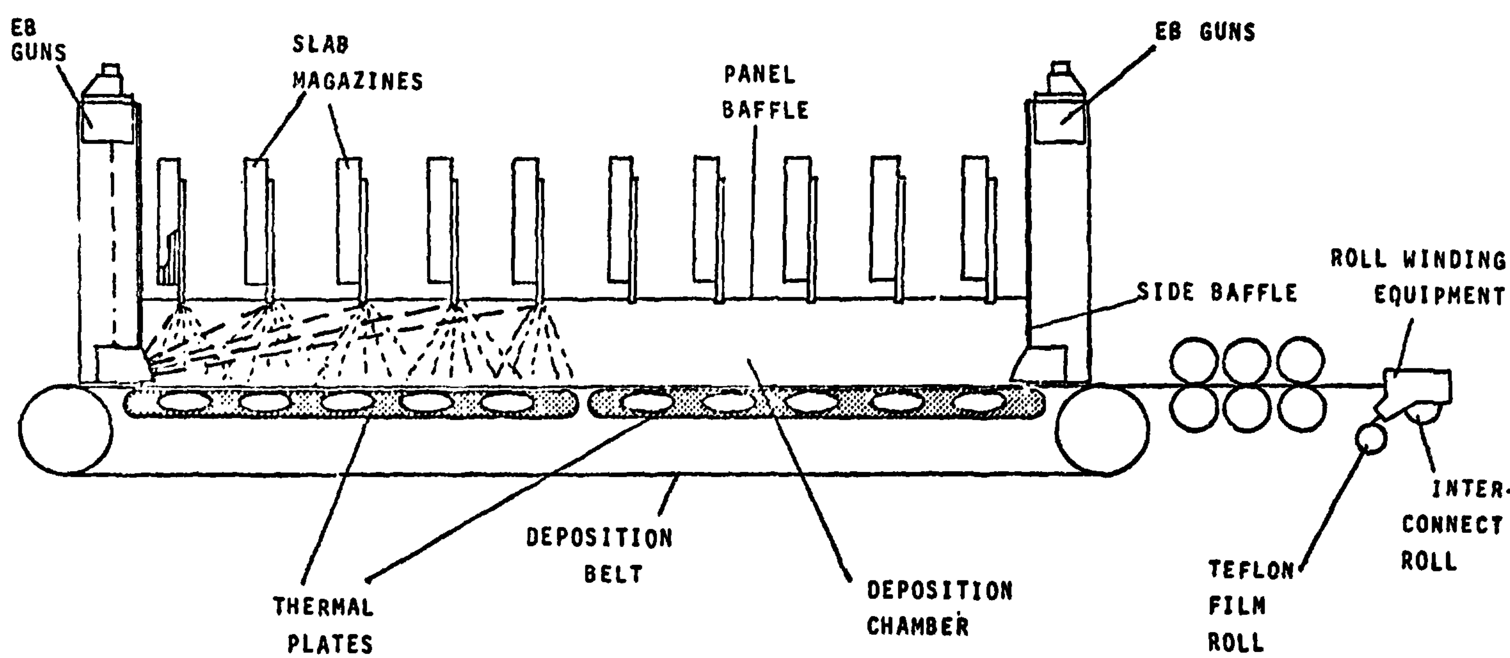


FIGURE 7.56: DV OF INTERCONNECTS

welding of the aluminum. Each 276-meter-long roll is 20 cm in diameter, and lasts through 10 array segments for cell interconnectors and 170 array segments for panel interconnectors.

SPECIFICATION SHEET

Machine Name: DV of Interconnects

Function of Machine: To produce aluminum interconnect strips for panel and cell interconnection

Mass of Machine: 2650 kg

Physical Dimensions: 6 m x 1.05 m x 7 m

Throughput/Machine (tons/year): 740

Power Requirements (KW/machine): 358

Number of Machines: 5

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	10	25	34.7
Filament Magazine	10	.04	0
Slab Feeder	10	50	.01
Panel Baffle	2	.5	0
Side Baffle	2	.7	0
Side Baffle Guide	2	25	.01
Belt	1	1400	10
Cooling System	1	500	1
Roll Winging Equipment	1	50	.1

7.8.15 Cell Interconnection: Immediately after crosscutting, the cell-to-cell interconnect is attached (see Fig. 7.57). An interconnect feeder (see side view) slides a 1.05 m wide interconnect into the 1 mm-wide slot between sections. The 50 micron thick interconnect is then electrostatically welded to the rear of the aluminum substrate of the leading section and to the collector bars of the following section. The electrostatic welder is in two units, which clamp the sections and interconnects from above and below during welding. An alignment mechanism on the lower unit ensures a 1 mm gap between sections. These two units, together with the interconnect feeder, travel with the sections at .85 m/min during this operation. They then return to wait for the next gap between sections. The final configuration is shown in Fig. 7.58. The 1-mm 'tail' on the interconnect is the end held by the feeder during clamping and welding. Mechanical cutters sever the interconnect from the interconnect strip immediately after welding.

The timing on the interconnection is such that no section is ever cut entirely loose -- it is either still a part of the continuous strip or already connected to the one ahead of it. The exception is the section leading a panel, which is not connected to the trailing section of the preceding panel; therefore the panels are separate after this production step. Each panel consists of 18 6.4 cm x 110 cm sections. Therefore

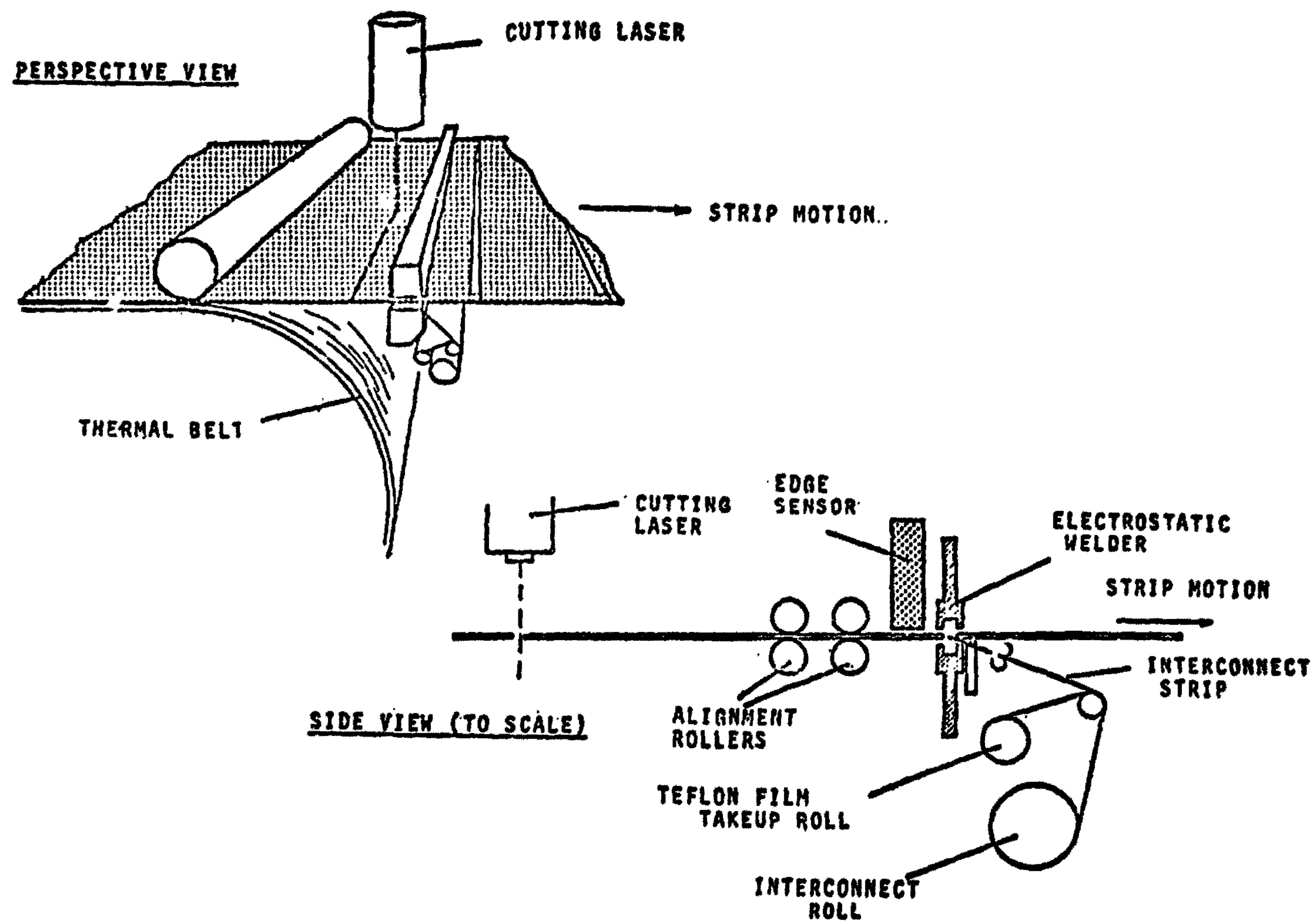


FIGURE 7.57: CELL INTERCONNECTION

every eighteenth gap between sections is left open by the interconnecter. All the sections are held between rollers (omitted in the figure) during all phases of the operation.

The interconnects are fed from spools of interconnect strips produced by a separate machine (see Sec. 7.8.14). The teflon film inserted between layers of aluminum (to avoid vacuum welding) is wound onto another spool as the interconnect strip is unwound, and the teflon strips are returned to the interconnect production equipment.

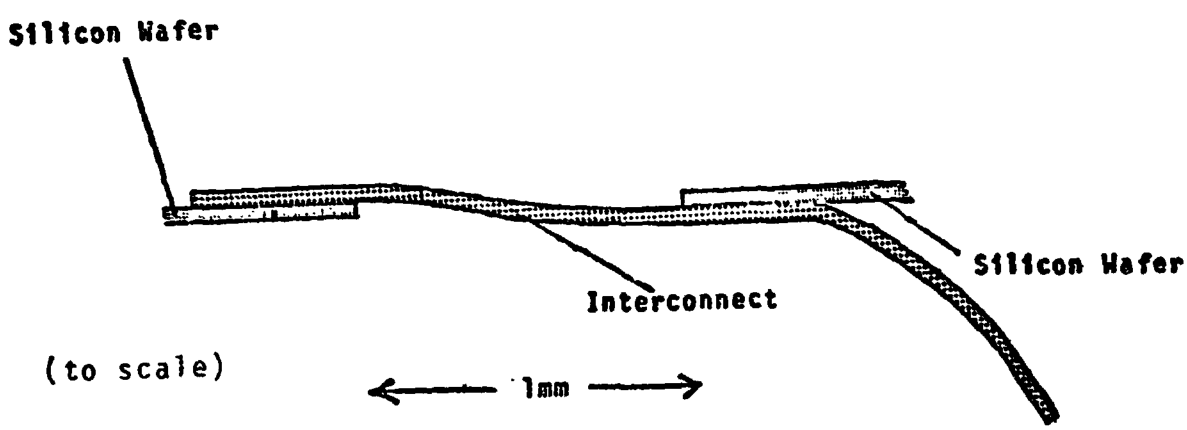


FIGURE 7.58: SIDE VIEW OF INTERCONNECT

SPECIFICATION SHEET

Machine Name: Cell Interconnection

Function of Machine: Application of interconnects between cell sections

Mass of Machine: 70 kg

Physical Dimensions: .5 m x 1.1 m x 1.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 4.1

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Electrostatic Welder	1	10	.5
Interconnec[illegible] eeder	1	20	1
Interconnect Roll	1	15	0
Sensors	2	.1	.1
Variamble Speed Rollers	4	.8	.1
Motor and Tracking	2	[illegible]	1
Guide Rolers	4	.5	0

7.8.16 DV of SiO_2 Optical Cover: After the 6.4 cm x 110 cm sections are interconnected into 18-section pannels, the 75 micron silica glass optical cover is deposited onto the silicon wafers, front contacts, and interconnects. The deposition is done by direct vaporization, using equipment similar to that used for the DV of the Al rear contact (Sec. 7.8.3) and for the DV of Si (Sec. 7.8.5).

As shown in Fig. 7.59, the deposition length of 15.9 meters is divided into three 5.32 m sections. The solar cell material travels at .85 m/min on a soft-surface belt through the deposition sections, where the SiO_2 is direct-vaporized at 4 microns/minute. The belt has a soft surface to avoid putting bending stresses on the cell material, which now has interconnects protruding from its surfaces.

Each deposition section contains 10 electron beam guns and 10 slab feeders. The EB guns (clustered in groups of five) each receive 7 kW of input power. Each slab (1.0 m x 1.0 m x .04 m) lasts 7.9 days; the slab magazines each hold 6 slabs. The slabs are delivered ready-to-use to the SMF.

Since the panels have not yet been connected together, the collector bars of the leading sections and the rear contacts of the trailing sections in the panels must be left un-covered for later interconnection. Therefore, before the panels enter the first SiO_2 deposition section, a masking device places a magnetic masking strip (4 mm x 1 m) over the

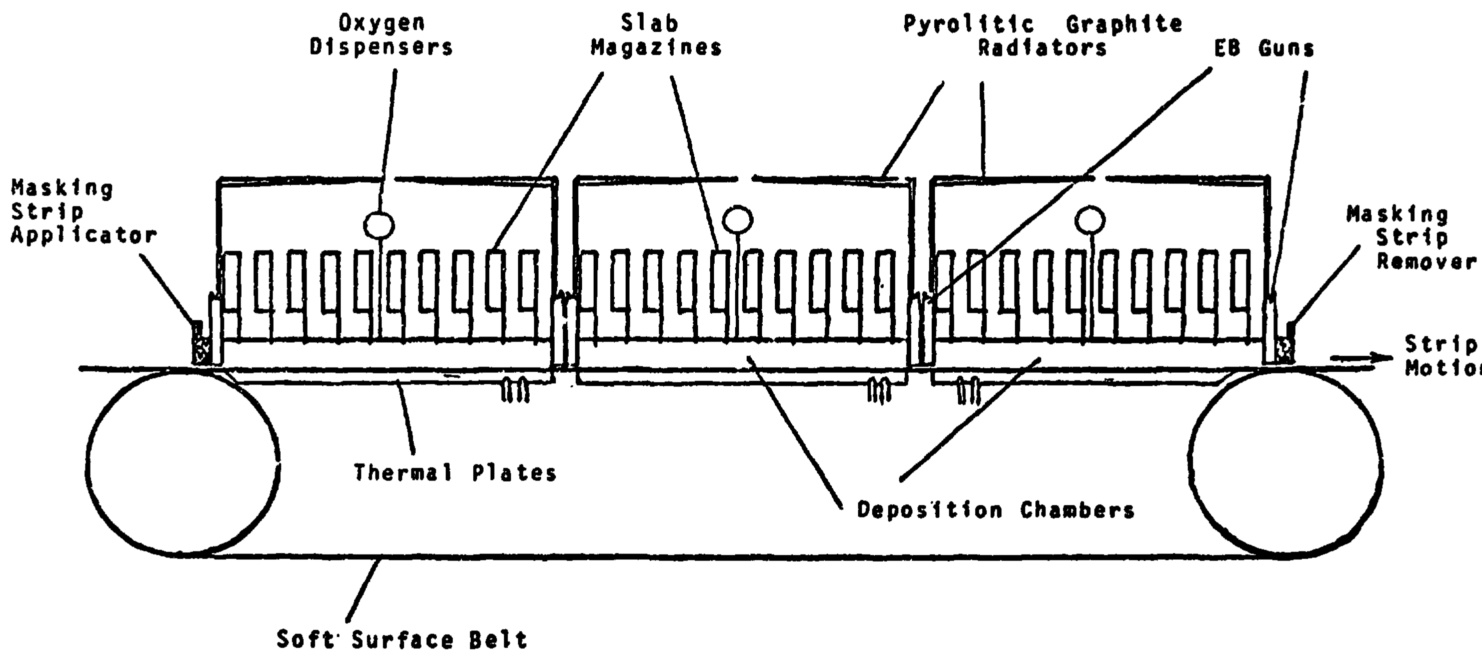


FIGURE 7.59: DV OF SiO_2 OPTICAL COVER

inter-panel gap (see Fig. 7.60). The strip is magnetically attracted to the belt and rests across the two panels, holding them to the belt. The back edges of the strip are shaped to overhang the contact surface, thus shielding it without becoming attached to the panel by the SiO_2. The masking strips are removed by a handling device as the panels leave the last deposition section. Each masking strip picks up 75 microns of SiO_2 as it passes through the sections. When that coating exceeds .5 mm (7 passes through the sections) the masking strip is taken to a cleaning facility. Cleaned strips are returned to the deposition equipment.

In solid form, SiO_2 is not sufficiently conductive to return electrons from an electron beam to the gun. During normal operation, however, the molten layer of SiO_2 at the lower edge of the slab can conduct the electrons to pickup brushes at the side edges. To start the deposition process (such as after maintenance and repair shutdowns), the slab feeder heats the slab resistively along its lower edge. The problem could also be avoided by using lasers rather than EB guns, but they are not as energy-efficient (15% vs 50%), and lasers with wavelengths appropriate for glass (e.g. CO_2 lasers) tend to be heavy and to require more maintenance. Further experimental research on DV of SiO_2 is needed to develop this process in detail.

When SiO_2 is vaporized onto a surface, some chemical dissociation tends to take place, leading to a layer of SiO

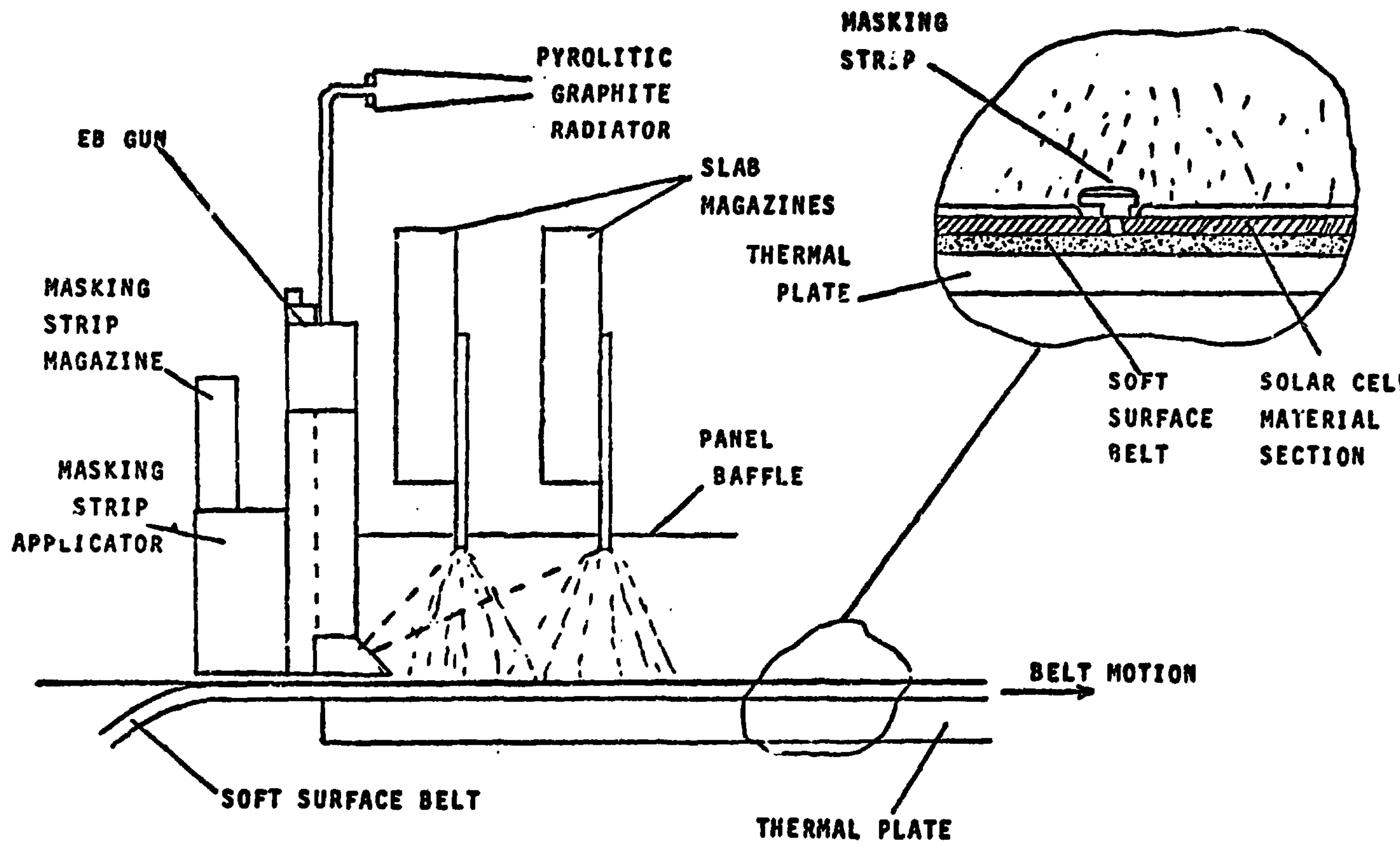


FIGURE 7.60: DV OF SiO_2 OPTICAL COVER DETAIL VIEW

rather than SiO_2. This can be avoided by operating the process with excess oxygen. Therefore oxygen (available from the moon) is kept in pressurized cannisters above the slabs and released toward the solar cell strip as needed. This oxygen is eventually lost to space.

The soft surface belt serves both for structural support and thermal control of the solar cell material during deposition. Each belt is 53 meters long, with geometry similar to the thermal belt used in earlier processes (Sec. 7.8.2). The belt is cooled by thermal plates. For each strip, 40% of the input power to the EB guns [(.4)(210 kW) = 84 kW] is removed through the thermal plates by .3 kg/sec of liquid sodium (400°K input, 600°K output). Estimating a total pipe length of 100 meters to a radiator and back, and a flow velocity of .5 m/sec, each strip requires 62.7 kg of liquid sodium. The radiator is a 37.2 m^2 aluminum sheet at 475°K located roughly 30 meters below the returning portion of the soft surface belt. This radiator area is 2.2 times the deposition area, and therefore extends beyond this deposition section. In addition each 7 kW EB gun wastes 50% of that power through a 13.8 kg pyrolitic graphite radiator at 630°K.

Following the deposition and the removal of the masking strips, the solar cell material is separated from the soft surface belt and travels on to the next process. The soft surface belt curves around a roller and returns to the start of the section.

SPECIFICATION SHEET

Machine Name: DV of Silica Optical Cover

Function of Machine: To deposit 75 microns of SiO_2 onto the silicon wafer, front contact, and cell interconnects.

Mass of Machine: 6660 kg

Physical Dimensions: 19 m x 1.1 m x 3 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 231

Number of Machines: 266

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
EB Gun		25	7
Filament Magazine	30	.04	0
Slab Feeder	30	60	.01
Masking Strip Handling Device	2	50	1
Masking Strip Magazine	2	5	0
Oxygen Dispenser	3	10	.001
Panel Baffles	6	.25	0
Side Baffles	6	.05	0
Side Baffle Guide	6	2	.01
Soft Surface Belt	1	3000	0
Motor/Drive	1	700	15
[illegible] Roller	2	50	0
Cooling System	3	50	.037

7.8.17: DV of SiO_2 Substrate: Following the deposition of the optical cover, the solar cell material moves on to the direct vaporization of the silica substrate. As shown in Fig. 7.61, this section consists of two SiO_2 deposition sections operating on the underside of the solar cell material. The equipment in the section is exactly similar to the equipment for the deposition of the optical cover (Sec. 7.8.18), except that it is upside-down relative to that section, and that this section is only two-thirds as long (the substrate is 50 microns thick).

The 10.6 m deposition length (deposition rate 4 microns/min) is divided int sections, each with 10 EB guns and 10 slab feeders. The guns each receive 7 kw of power and waste 50% of that power through 13.8 kg pyrolitic graphite radiators at 630°K. The soft surface belt is 41 meters long, and is cooled by .2 kg/sec of liquid sodium through thermal plates (400°K input, 600°K output). Each strip requires 41.6 kg of sodium circulated to a 24.1 m^2 aluminum sheet radiator at 475°K, roughly 30 meters "above" the soft surface belt's returning portion. This radiator area is 2.2 times the deposition area and therefore extends beyond this deposition section.

Similarly to the DV of optical cover, masking strips are applied to the inter-panel gaps to shield the trailing edges of panel from the silica deposition. This leaves part of the rear contacts of the trailing solar cell sections exposed for later panel interconnection. Since these strips pick up

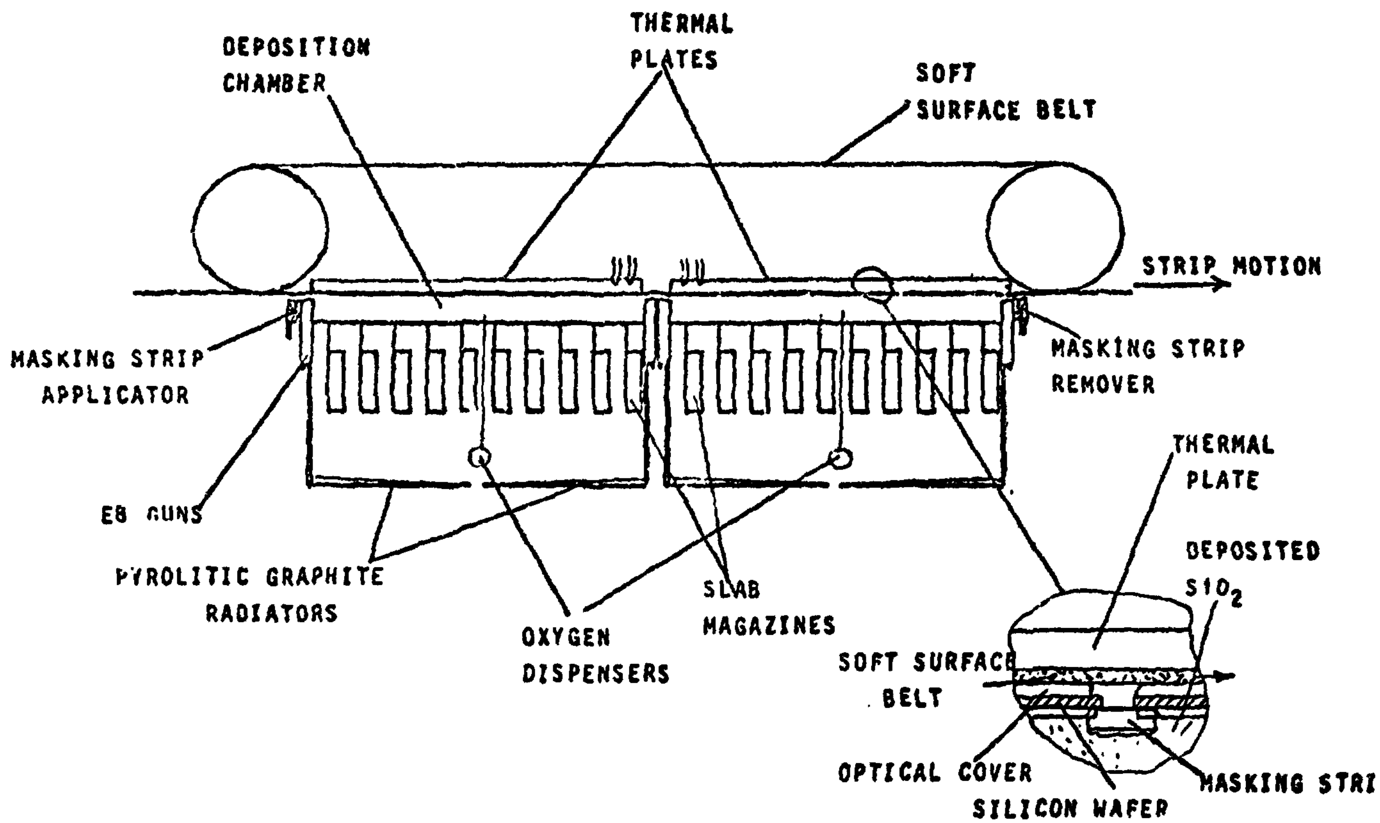


FIGURE 7.61: DV OF SiO_2 SUBSTRATE

50 microns of SiO_2 with each pass through the deposition sections, they are used ten times before the 0.5 mm of SiO_2 are cleaned off in a separate facility.

The successive applications of the SiO_2 optical cover (Sec. 7.8.16) and SiO_2 substrate coat the cell interconnects with silica, thus strengthening the connections between sections within a panel. The final cross-section of a cell interconnect is shown in Fig. 7.62.

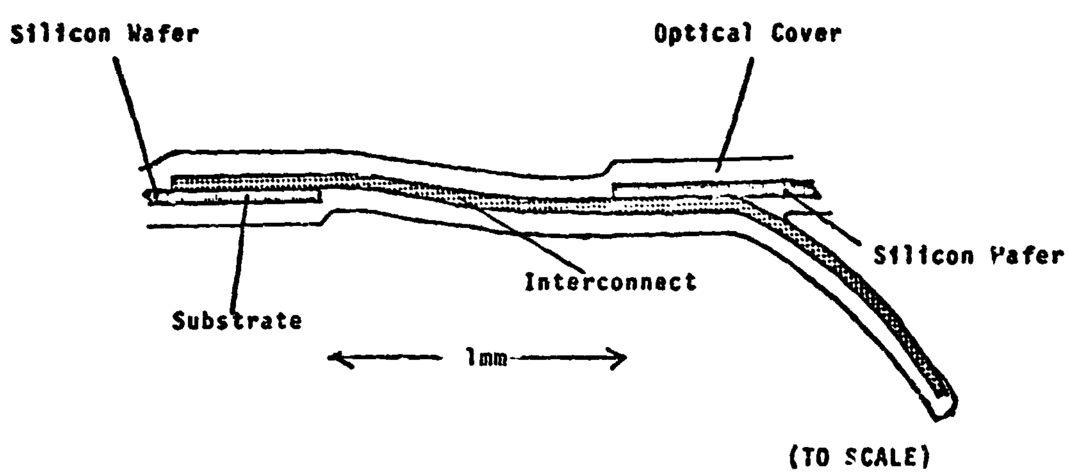


FIGURE 7.62: CROSS-SECTION OF CELL INTERCONNECT

SPECIFICATION SHEET

Machine Name: DV of SiO_2 Substrate

Function of Machine: To deposit 50 microns of SiO_2 onto the Al rear contact and cell interconnect

Mass of Machine:

Physical Dimensions: 13 m x 1.1 m x 3 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 155

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
EB Gun	20	25	7.
Filament Magazine	20	.04	0
Slab Feeder	20	60	.01
Masking Strip Handling Device	2	50	1
Masking Strip Magazine	2	5	0
Oxygen Dispenser	2	10	.001
Panel Baffles	4	.25	0
Side Baffles	4	.05	0
Side Baffle Guide	4	2	.01
Soft Surface Belt	1	2000	0
Motor/Drive	1	500	10
End Roller	2	50	0
Cooling System	2	50	.037

7.8.18: Masking Strip Cleanup: The silica-coated masking strips used in the direct vaporization of optical covers (Sec. 7.8.16) and substrates (Sec. 7.8.17) are cleaned in an automatic facility. This facility, conceptually similar to the mask cleanup device (Sec. 7.8.11), is shown in Fig. 7.63.

A masking strip magazine filled with coated strips and an empty magazine are loaded into an evacuated outer chamber (the two-chamber design reduces pumping requirements). After the chamber is sealed and filled with argon, the strips are automatically fed through cleaning rollers and into the empty magazine.

The silica flakes removed from the strips by the brushes are suspended in the argon and filtered out by a gas recirculation system. Once the strips are cleaned, the interchamber slits are closed and the outer chamber is evacuated. The magazine with the clean strips is removed, and another magazine of coated strips is inserted. Estimating that each magazine holds 200 strips, each strip takes 15 seconds to clean, and the pumpdown and reload steps take 10 minutes; each magazine-full requires 1 hour for cleaning. Based on an allowable thickness of .5 mm of silica before cleaning (7 passes through DV of optical cover, or 10 passes through DV of substrate), and a yearly production of 9.5×10^7 panels per year (including wastage allocations), roughly 2.3×10^7 masking strips must be cleaned per year, and therefore 15 masking strip cleaners are required (90% duty cycle).

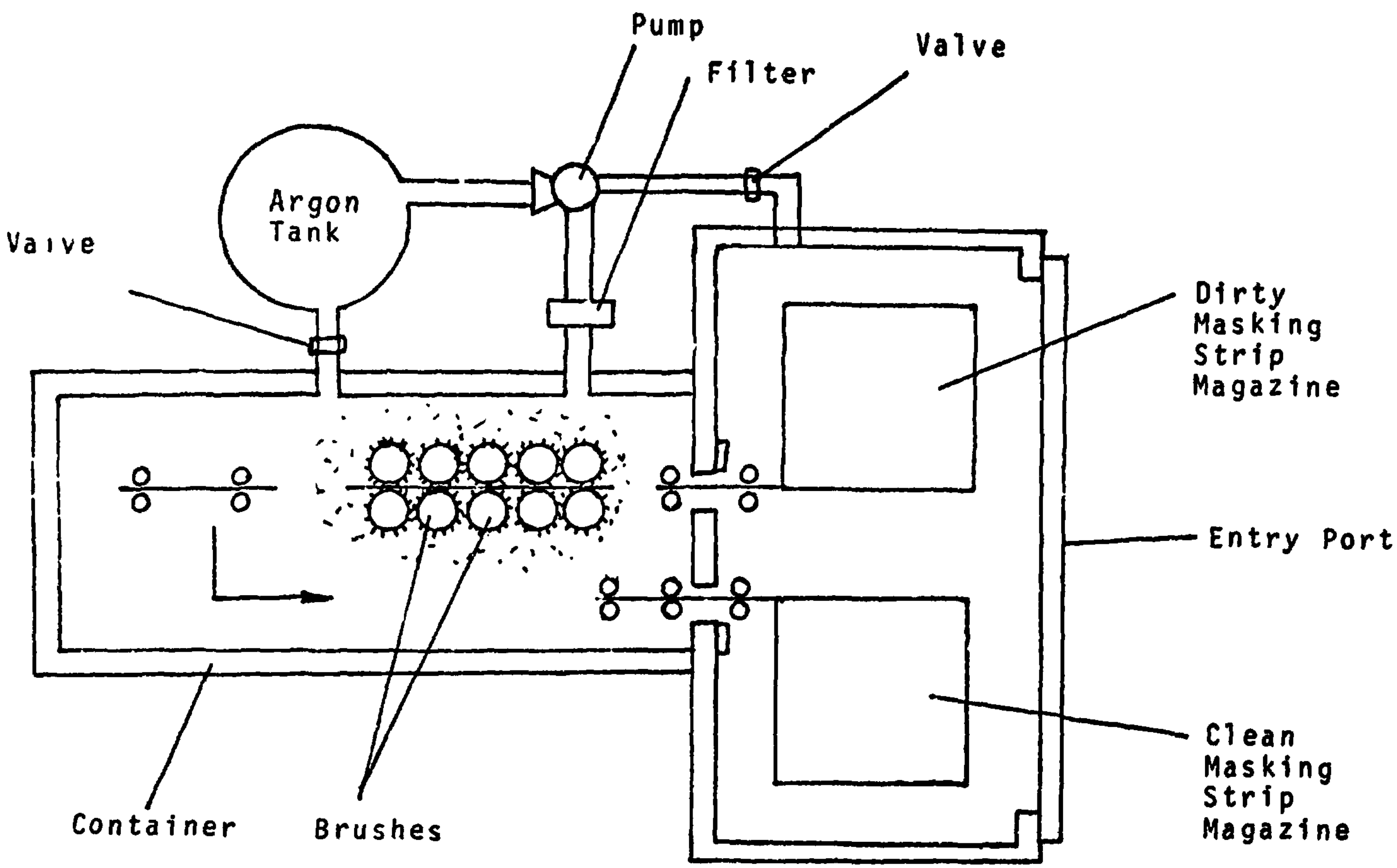


FIGURE 7.63: MASKING STRIP CLEANUP

SPECIFICATION SHEET

Machine Name: Masking Strip Cleaner

Function of Machine: To remove deposited silica from masking strips

Mass of Machine: 180 kg

Physical Dimensions: 5 m x 4 m x 2 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 7

Number of Machines: 15

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Handling and Feed Systems	1	20	1
Brushers and Drive	10	5	1
Gas Circulation Pump	1	10	5
Filter System	1	1	0
Container	1	100	0

7.8.19. Panel Alignment and Spare Panel Insertion: After the optical covers and substrates have been deposited on the 110.3 cm x 117 cm panel, each panel is accelerated to 1m/minute by soft-surface belts (soft-surface to avoid bending stresses, since the interconnects protrude), then guided by rollers through the panel removal and insertion zone. The panels then enter the panel deceleration zone, where they are decelerated and aligned with their predecessors, adding to the backlog of panels waiting panel interconnection. The operations are shown in Fig. 7.64; although the figure shows this machine in two sections, the solar cell panels actually move in a continuous straight line. When the panels are accelerated to 100 cm/min, the gap between them widens to 20 cm (12 second time lag), facilitating removal/insertion operations. The purpose of this arrangement is to guarantee a continuous supply of panels to the panel interconnection, each panel aligned with its neighbors.

The first device in the panel removal and insertion zone is the defective panel shunt. If quality control devices indicate that the now-completed panels are substandard, the defective panels are diverted into the defective panel hopper. The contents of this hopper are discarded as waste during maintenance operations.

Next, satisfactory panels travel through the extra panel shunt. If the strip is producing panels faster than its neighbors, or if there is a stoppage in the downstream array assembly operations, some or all of the produced panels can be diverted into the extra panel hopper. These panels then become spare panels, to be used in factory production strips with insufficient output.

The next device in the sequence is the spare panel inserter. Should one strip be slower than the others, its backlog of panels dwindles relative to the other strips. Optical sensors report this, and a computer sends commands to speed up that strip. Should the strip not speed up, or should a strip fail entirely, such that its backlog threatens to drop to zero, the computer requests spare panels. These are inserted just before the deceleration zone. The spare panel hoppers are restocked from the panels accumulated in the extra panel hoppers. The hoppers are emptied or refilled by a "crawler' (similar to the one shown in Fig. 7.40; crawlers are described in Chap. 8). In case of breakdown of a panel insert machine, the crawler is also capable of feeding spare panels into the production strip until repair of the machine is completed.

After the removal and insertion zone, panels travel through the deceleration zone before reaching the backlog area, where the panels are moving at .85 m/min. The objective is to stop the panel within 1-2 mm of the moving trailing edge of the backlog. Optical sensors track the leading edge of the coasting panel and the trailing edge of the backlog and

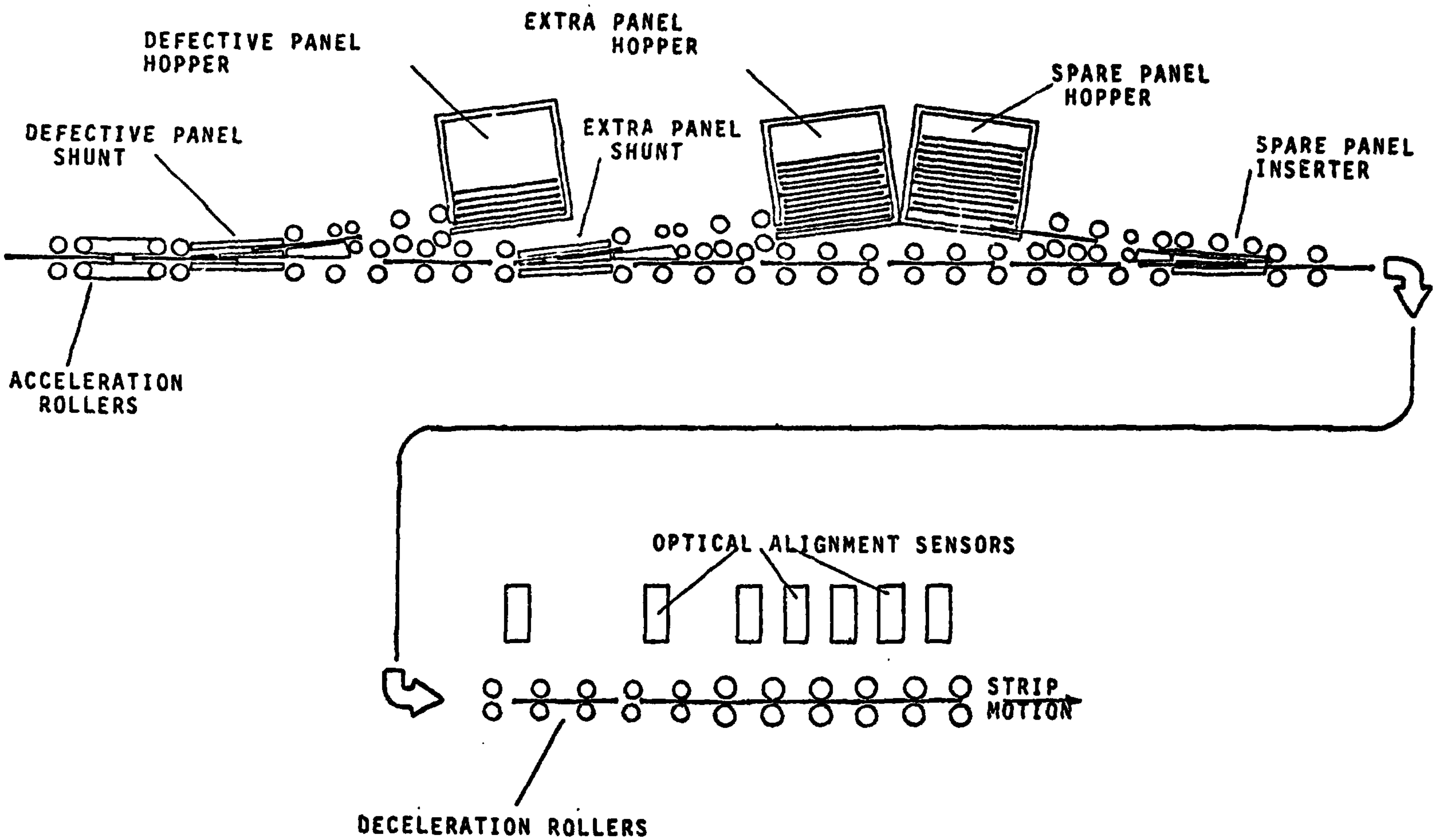


FIGURE 7.64: PANEL ALIGNMENT AND SPARE PANEL INSERTION

a microprocessor calculates the intersection time and place. Computer-controlled variable-speed rollers then slow down the panels and bring them into close alignment, ready to enter the panel interconnect machine.

SPECIFICATION SHEET

Machine Name: Panel Alignment and Spare Panel Insertion

Function of Machine: Removal and insc spare panels and panel alignment

Mass of Machine: 284 kg

Physical Dimensions: 18 m x 1.1 m x 2 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 10

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Accelerator Belts	1	70	.5
Variable Speed Rollers	32	.8	.2
Panel Remover	2	22.5	.7
Panel Inserter	1	22.5	.7
Panel Hopper	3	30	0
Sensors	10	.1	.1
Guide Rollers	60	.5	0

7.8.20. Panel Interconnection: As shown in Fig. 7.65, the aligned panels (110 cm x 117 cm) are now interconnected in a manner similar to the cells (Sec. 7.8.15). An interconnect feeder places an aluminum panel-to-panel interconnect (14 cells wide) between two successive panels in a strip.

The side view in the figure shows that the interconnect is applied between the aluminum rear contacts at the trailing end of the leading panel and the collector bars on the leading end of the following panel. These surfaces were protected from the SiO_2 deposition by masking strips (Sec. 7.8.16 and 7.8.17), and are therefore accessible to the interconnect. The panel-to-panel interconnect is electrostatically bonded in place.

The combination of panel alignment (Sec. 7.8.19) and panel interconnection produces 14 parallel strips of interconnected panels (on 14 parallel production strips) in each solar cell factory subsection. The parallel panels are lined up with each other, in preparation for structural interconnection, which will form the 14-panel wide array segments. At this stage, however, each panel consists of 16 solar-cell-material sections, each 6.4 cm x 110 cm; each of these will be cut into 14 solar cells.

Connections between strips of panels can be made in similar fashion, by electrostatic welding of cross-connectors. This operation depends on the actual circuits required in the solar cell arrays, which are not entirely clear to the study group from the literature studied.

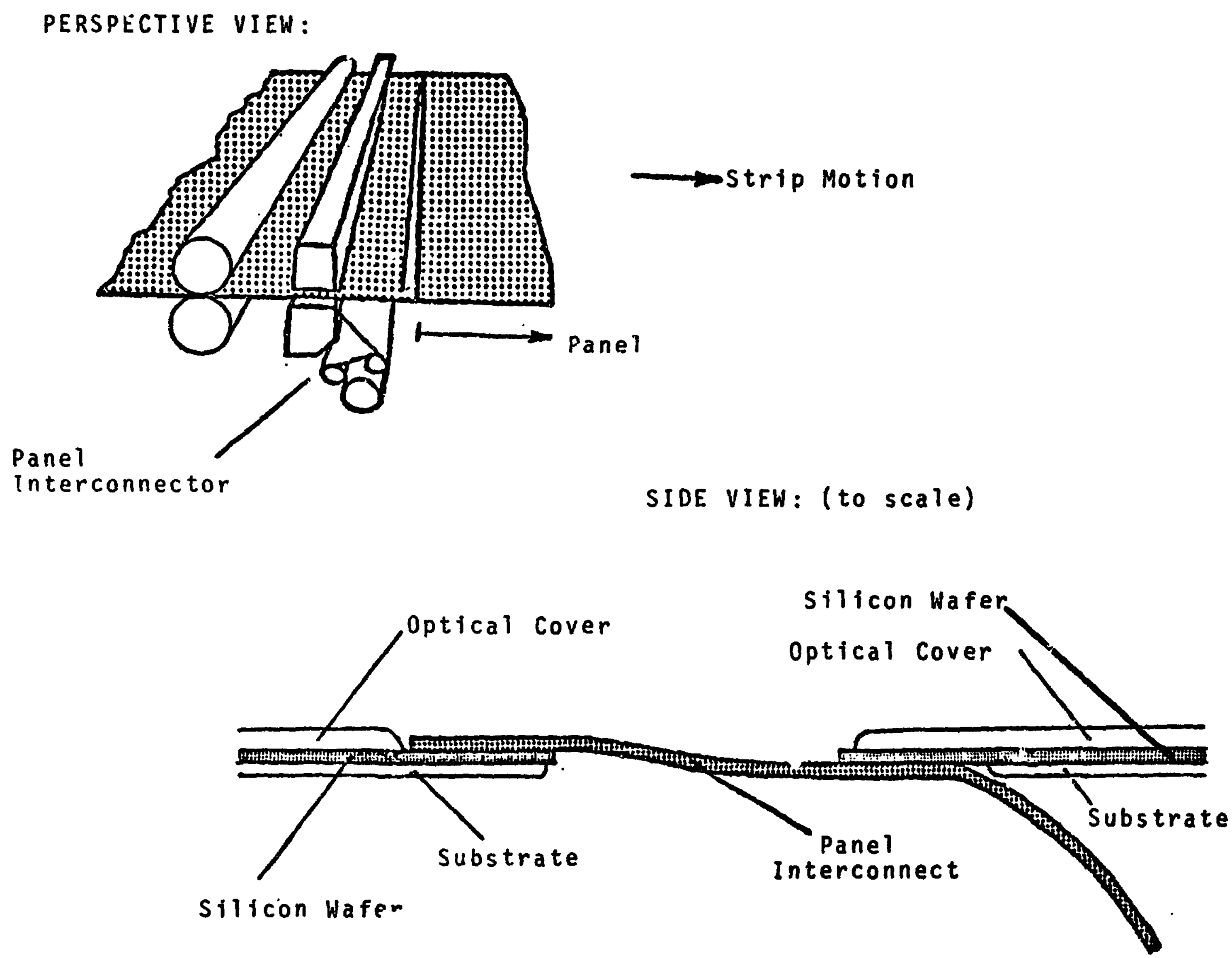


FIGURE 7.65: PANEL INTERCONNECTION

SPECIFICATION SHEET

Machine Name: Panel Interconnection

Function of Machine: Application of interconnect between panels

Mass of Machine: 65 kg

Physical Dimensions: .5 m x 1.1 m x 1.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 7.1

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Electrostatic Welder	1	10	.5
Interconnect Feeder	1	20	1
Interconnect Roll	1	15	0
Sensors	2	.1	.1
Variable Speed Rollers	4	.8	.1
Motor	1	15	5
Guide Rollers	4	.5	0

7.8.21. Longitudinal Cut: After the panel interconnection, the strips of panels are cut lengthwise (along the strip) by a laser. This laser, similar to the one used in cell crosscut (Sec. 7.8.13), produces 13 parallel lengthwise cuts in the panels, at 7.8 cm intervals. With 1 mm kerf loss, the resulting solar cells are 7.7 cm x 6.4 cm, and the panels each hold 252 cells (14 x 18 cells), as per JSC-Boeing design.

Figure 7.66 shows the cutting process. The laser cuts through the cell interconnects (but not the panel interconnects). This separates the cells from their side neighbors, leaving them connected in series along the strip, but cross-connected by the panel interconnects. As shown in the top view, the longitudinal cuts do not extend all the way through the leading panel, leaving intact the leading edge of the interconnect. Although the trailing row of cells therefore remains connected across their rear contacts, this is acceptable since the rear contacts of the panel's last 14 cells are connected by the panel interconnect; they are therefore electrically equivalent, and need not be physically separated. The top contacts of those cells are separate, whether or not the cells are cut apart.

The leading edge of the following panel is different, however. There the top contacts of the first 14 cells are connected by the panel interconnect, and therefore electrically equivalent. However, each rear contact has a cell between it and the equivalent top contacts, and should therefore be

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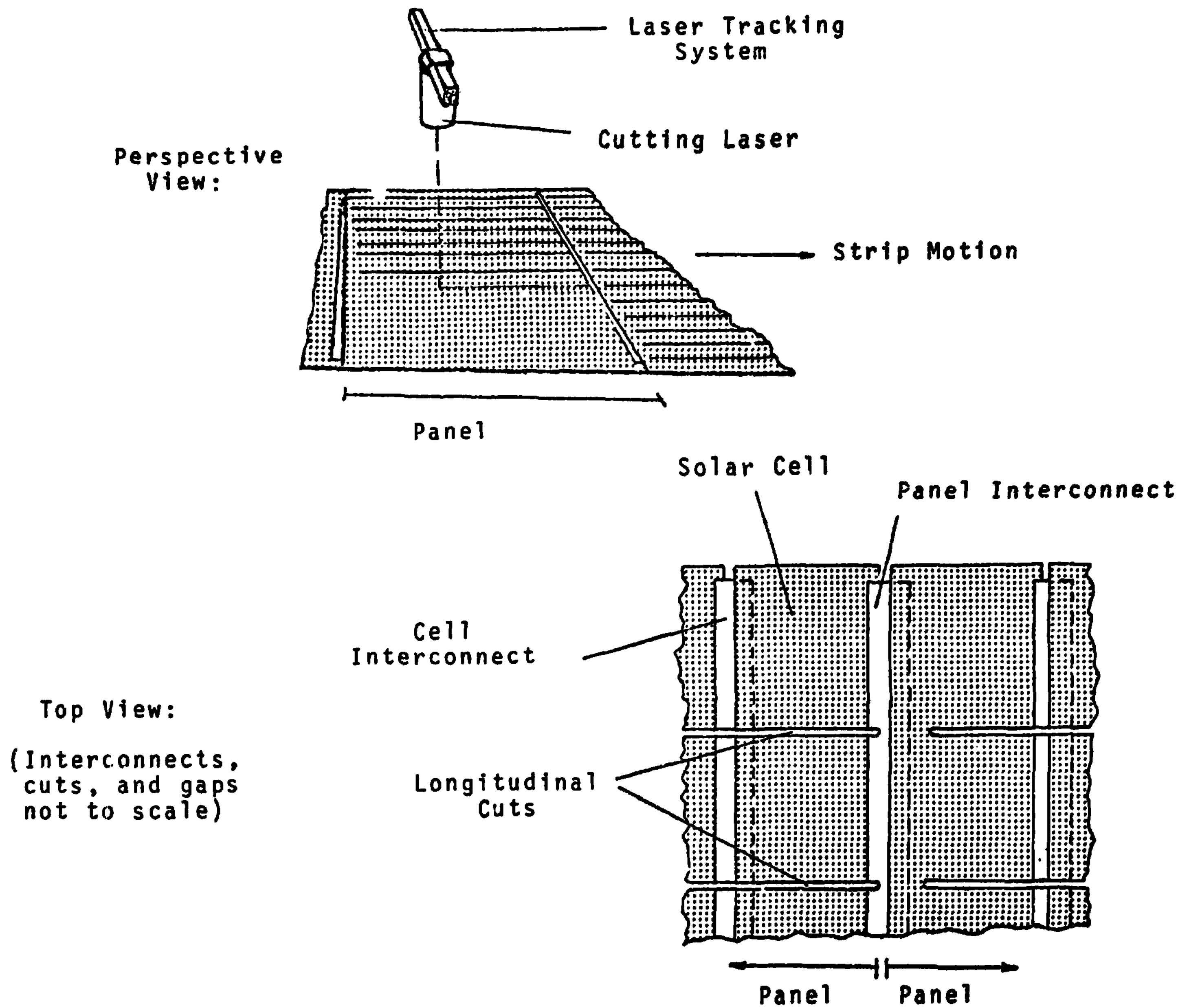


FIGURE 7.66: LONGITUDINAL CUT

separate. The cuts therefore start ahead of the cells, notching the panel interconnect.

Should it be advantageous to separate the leading panel cells as well, the longitudinal cuts can extend into the leading edge of the panel interconnect also. In that case the study group recommends that the spacing between panels be increased to 4 mm, and the panel interconnects widened accordingly. Therefore the notches cut into the panel interconnects would not structurally weaken them too much.

The laser makes all the longitudinal cuts in a 110.3 x 6.4 cm section before going on to the next. It must cut a total of 83.2 cm in 4.5 sec or about 20 cm/sec in performing 13 longitudinal cuts. The laser is moved across the section by a tracking system, in 7.8 cm intervals. Including beam turn-on and shut-off power, the laser requires about the same power as the laser crosscutter, and therefore has the same parameters.

<u>SPECIFICATION SHEET</u>

Machine Name: Longitudinal Cut

Function of Machine: To make 13 lenghtwise cuts in each panel, separating the panel sections in solar cells

Mass of Machine: 48 kg

Physical Dimensions: .5 m x 1.1 m x 2.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 2.6

Number of Machines: 266

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Laser	1	20	2.5
Krypton Lamp Magazine	1	1	0
Guide Rollers	2	.5	0
Shield	1	1	0
Laser Tracking System	1	25	.1

7.8.22. Kapton Tape Application: As shown in Fig. 7.67 (a view from "below" the solar panel strips), kapton tape is applied both crosswise and lengthwise to fasten adjacent panels together. Stationary rollers unroll 13 strips of tape lengthwise, onto the underside of the solar cell array, while soft rollers provide support on the topside. Each stationary roller originally holds 633 m of kapton tape, the length of each solar cell array 'package.'

After the sheet passes through the stationary rollers, cross rollers unroll tape across the strips, onto the intersection between successive panels; each roller is also accompanied by a soft roller for support on the topside. These rollers move along with the panel in the lengthwise direction, at .85 m/sec, and move back after each tape application. There are 8 crossrollers, each of which can tape 2 panel widths at a time. The crossrollers tape in a staggered manner (as shown in the figure) from row to row so that the array is entirely connected together. Each individual roller tapes only two panel widths (2.2 m) at a time, so that the failure of one crossroller will not cause a production shutdown. Spare tape rolls are stored in magazines which are periodically refilled by crawlers. The crawlers can also temporarily take over the function of a roller during repairs.

The kapton tape connects the panels into connected arrays 14 panels (15.5 m) wide by 541 panels (633 m) long, as per

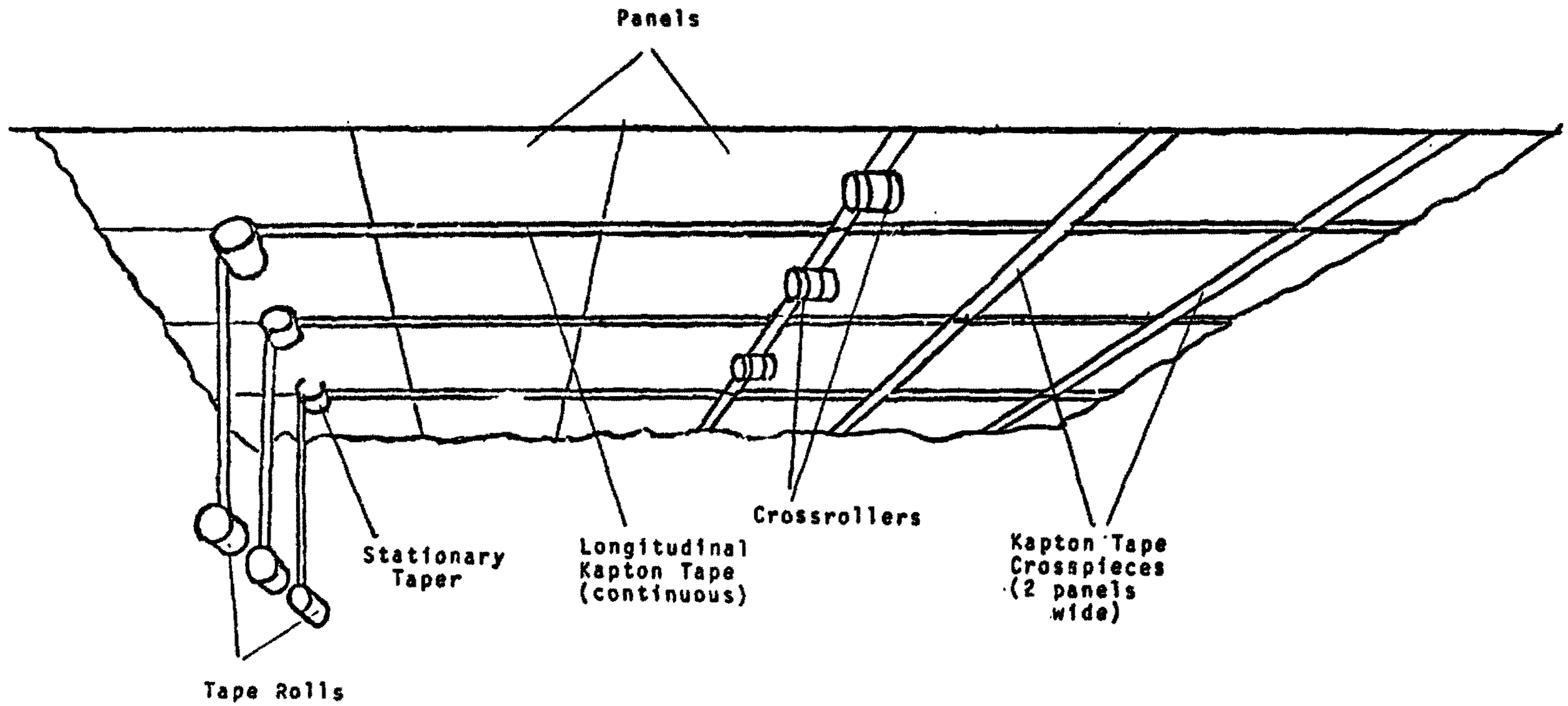


FIGURE 7.67: KAPTON TAPE APPLICATION

the Boeing design. At full production, the entire solar cell factory could produce 19 of these 'packages' at one time, from 266 strips grouped into 19 sets of 14. In actuality, some of these strips are down for maintenance or repair, and some are producing spare panels (see Sec. 7.8.19).

SPECIFICATION SHEET

Machine Name: Kapton Tape Application

Function of Machine: Application of Kapton tape to glass substrate in crosswise and lengtiwise directions, bridging separate panels

Mass of Machine: 215 kg

Physical Dimensions: 5 m x 16 m 3.5 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 12

Number of Machines: 19

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
Stationary Taper	13	5	.5
Stationary Tape Refill	13	.6	0
Cross Taper	1	25	.5
Cross Tape Refill	1	.6	0
Soft Roller	22	.5	0
Guide Roller	112	.5	0
Cross Tape Motor	1	50	5

7.8.23. Array Segment Folding and Packaging: The solar cell packager accordion-folds the final solar cell product, a 15.5 m x 663 m array, directly into a cushioned storage box. Vertical deflectors buckle the incoming solar array so that it folds properly (see Fig. 7.68), and a mechanical arm guides the trailing edge into the box. The filled box is pushed down below the folding section by mechanical rollers and its top is attached. At this time the box is labeled with the production strip and time and any other relevant information (e.g. defects, expected efficiency).

A crawler (dedicated to the packaging section) picks up the finished box of solar cell array. The crawler also loads an empty box into the packaging machine above the following section. Box tops are loaded below the folding section.

The crawler can carry 4 boxes at one time. Finished boxes are loaded by the crawler directly into the internal transport system for transfer to the input/output station.

Since a number of boxes and box tops for the 'finished' arrays are in transit and at the SPS assembly site at any time, each machine has 10 boxes and box tops allocated to it, to ensure their availability. Empty boxes and tops are returned to the SMF from the SPS assembly site. The boxes are the longest item (16 m long) to be handled by the SMF's internal transport system (described in Chap. 8).

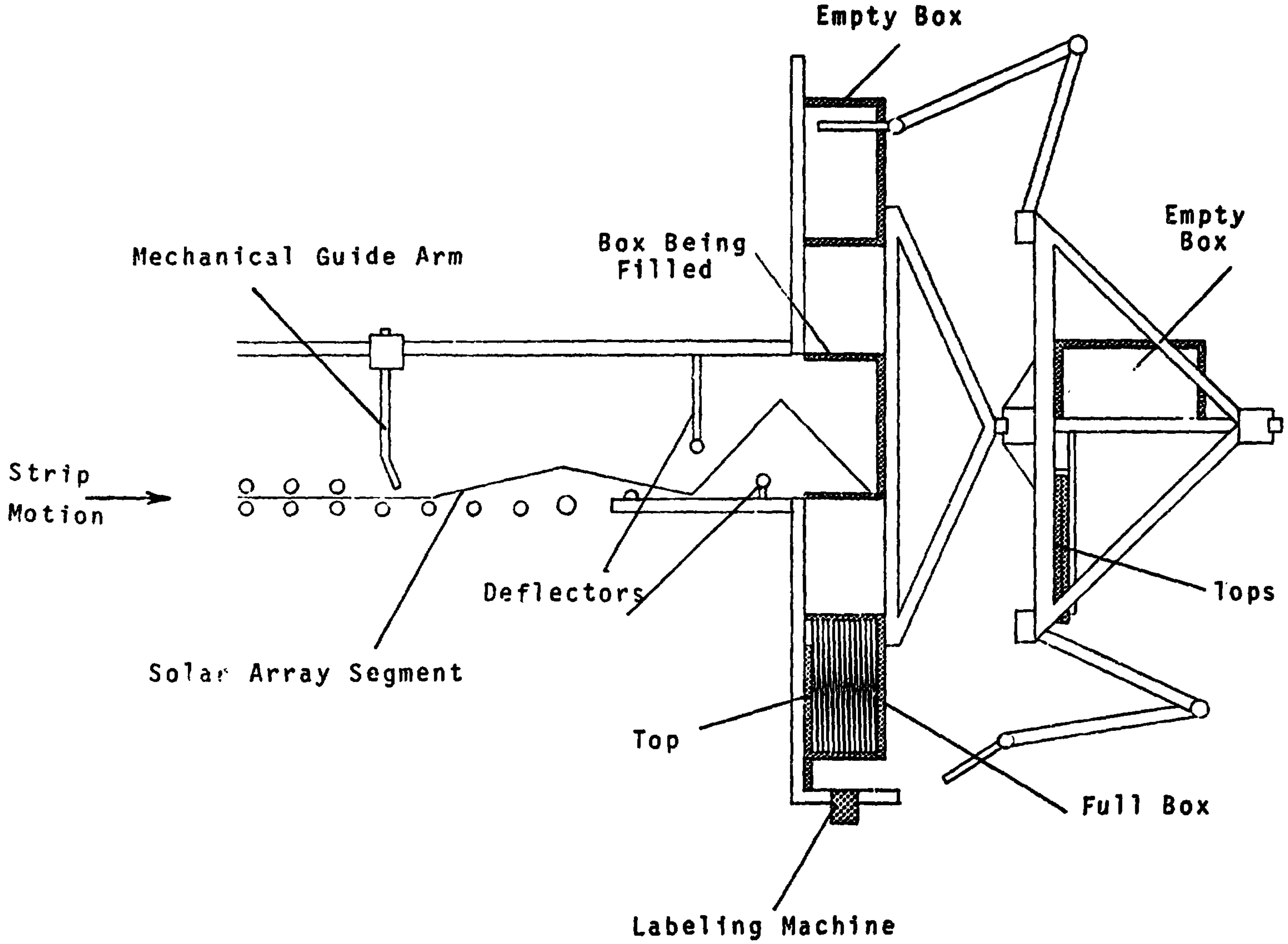


FIGURE 7.68: ARRAY SEGMENT FOLDING AND PACKAGING

SPECIFICATION SHEET

Machine Name: Array Segment Folding and Packaging

Function of Machine: Accordion-fold and package solar cell arrays

Mass of Machine: 1460 kg

Physical Dimensions: 8 m x 16 m

Throughput/Machine (tons/year): 2200

Power Requirements (KW/machine): 1.1

Number of Machines: 19

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Guide Rollers	154	.5	0
Vertical Deflectors	3	10	.1
Box Alignment	1	300	1
Trailing Edge Guide	1	50	.01
Box Labeling	1	5	.01
Boxes and Tops	10	100	0

7.8.24. Note on Radiators: As described in the preceding sections, the deposition, recrystallization, annealing, and sintering processes dissipate roughly 40% of their input power by circulating a fluid through thermal plates below their deposition belts and out to 1-mm-thick aluminum sheet radiators. Estimating that this cooling is done with liquid sodium with inlet temperature 600°K and outlet temperature 400°K, the 'thermal average' temperature is 475°K, from the formula

$$T_{rad} = T_{inlet} \frac{\left(\frac{T_{inlet}}{T_{outlet}}\right)^2 - 1}{\frac{2}{3}\left[\left(\frac{T_{inlet}}{T_{outlet}}\right)^3 - 1\right]} \qquad \text{(Ref. 7.7)}$$

At this effective temperature, the radiator sizes required for the various production steps along a strip are shown in Fig. 7.69, a modification of Fig. 7.41. Each radiator has the same width as the strip (1.1 m). As the figure shows, although some radiators extend beyond their associated deposition section, the total radiator area does not extend beyond the factory area.

The radiators are roughly 30 meters away from the production strips, in a plane parallel to the factory. They therefore collectively shield the equipment from micrometeorites. The 30-meter distance was chosen to allow free movement of the free-flying teleoperators (described in Chap. 9) between the radiators and production equipment. The total travel distance ofthe coolant was estimated at 100 meters, including travel within thermal plates and pumping systems, travel along the radiators, and the round trip between factory and radiator.

Those sections requiring coolant-fed radiators (and several other processes as well) require thermal waste system to dissipate the remaining energy input. Estimating that 10% is lost by direct radiation from the equipment and in deposition vapors lost to space, roughly 50% of the input power to a number of processes must be dissipated. In all of these processes, this waste heat must be removed from electron beam guns or lasers, and these EB guns and lasers are on the opposite side of the production strip from the thermal belt radiators. Therefore these EB guns and lasers can be cooled by radiators on their side of the production strips.

The EB guns and lasers are cooled passively, by heat pipes feeding pyrolitic graphite radiators (except for the DV of interconnects, which are cooled by circulated coolant). Since most of the EB guns used in deposition are clustered in groups of five, each gun occupies roughly 20 cm of the 110-cm width of the production strip. The pyrolitic graphite radiators are therefore rectangular, with width 20 cm and length equal to half the length of the deposition chamber (thus sharing the area with the EB gun cluster at the other end of the chamber) such as in the DV of SiO_2 (Secs. 7.8.16 and 7.8.17). In those cases where only two EB guns are used, their radiators are 50 cm wide.

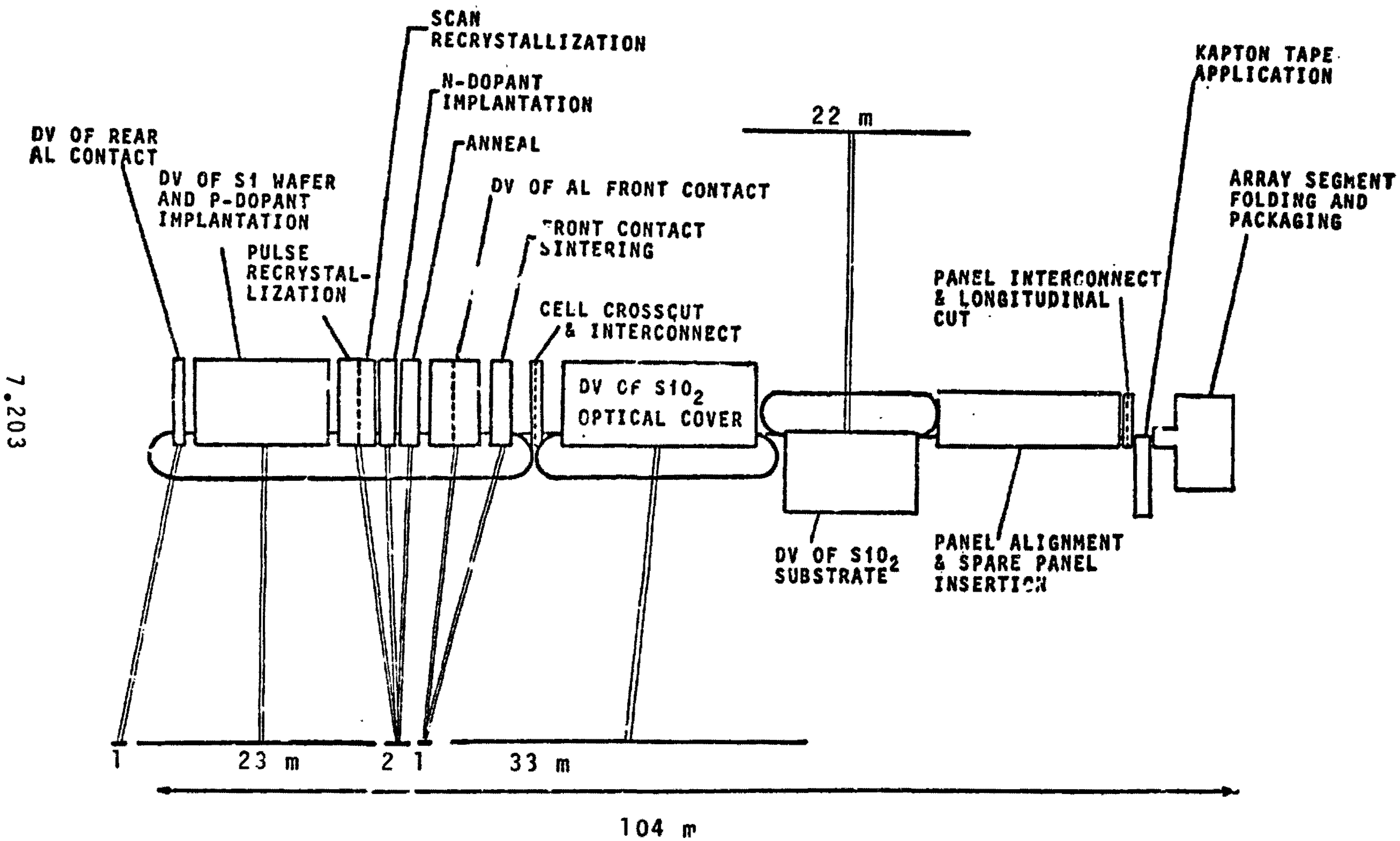


FIGURE 7.69: ALUMINUM SHEET RADIATOR SIZES FOR SOLAR CELL FACTORY

Given this sizing, the radiators for the EB guns range in operating temperature from 260°K to 720°K. The laser radiators operate at 410°K. Collectively, these pyrolitic graphite radiators cover the deposition sections on the side unprotected by the aluminum radiators, thus completing the micrometeorite protection of the equipment. These radiators need not be removed to access the EB guns, but at least one radiator from a cluster of five must be removed to access the slab feeders in a deposition section. The radiators are therefore designed with disconnect fittings at the end of their heat pipes. Removal of one radiator from a cluster of five allows a crawler to slide a slab into the section, mail-slot-style. The crawler then rotates the slab 90 degrees and loads it into a slab magazine. Since the radiator's EB gun can be shut down during the process (the other four take over), this does not require a production stoppage. Radiators are sized to handle the extra load when four guns assume the functions of five.

CHAPTER 8

SMF SUPPORT EQUIPMENT

8.1 GENERAL REMARKS

Fig. 8.1 is a plan view of the reference SMF. To the right side of the figure is the solar array which provides, along with emergency fuel cells, power for the SMF operations. The solar array is the only part of the facility requiring close pointing to the sun ($\pm 1^{o}$). The rest of the factory does not require close attitude control, but should stay in the shadow of the solar array to alleviate heat waste problems and thermal deformations.

To the left of the array is the habitat, providing housing for the SMF crew. In the figure, this area is partially visible through the cut-away section of the waste heat radiators, mounted top and bottom of the habitat. A pressurized tunnel connects the living area to the rest of the factory.

The repair shop is the area in which maintenance and repair of components from the factory is carried out. This section consists of a cluster of shuttle tanks and life support equipment. Maintenance and repair are discussed in Chapter 9.

The docking facility is close to the components factory (to minimize the movement of inputs and outputs), yet distant from the fragile solar array, solar cell factory, and habitat (in case of docking accidents). Input containers are cylinders sized to hold three months of lunar inputs each (assuming production of one 10GW SPS/year). The containers are unloaded

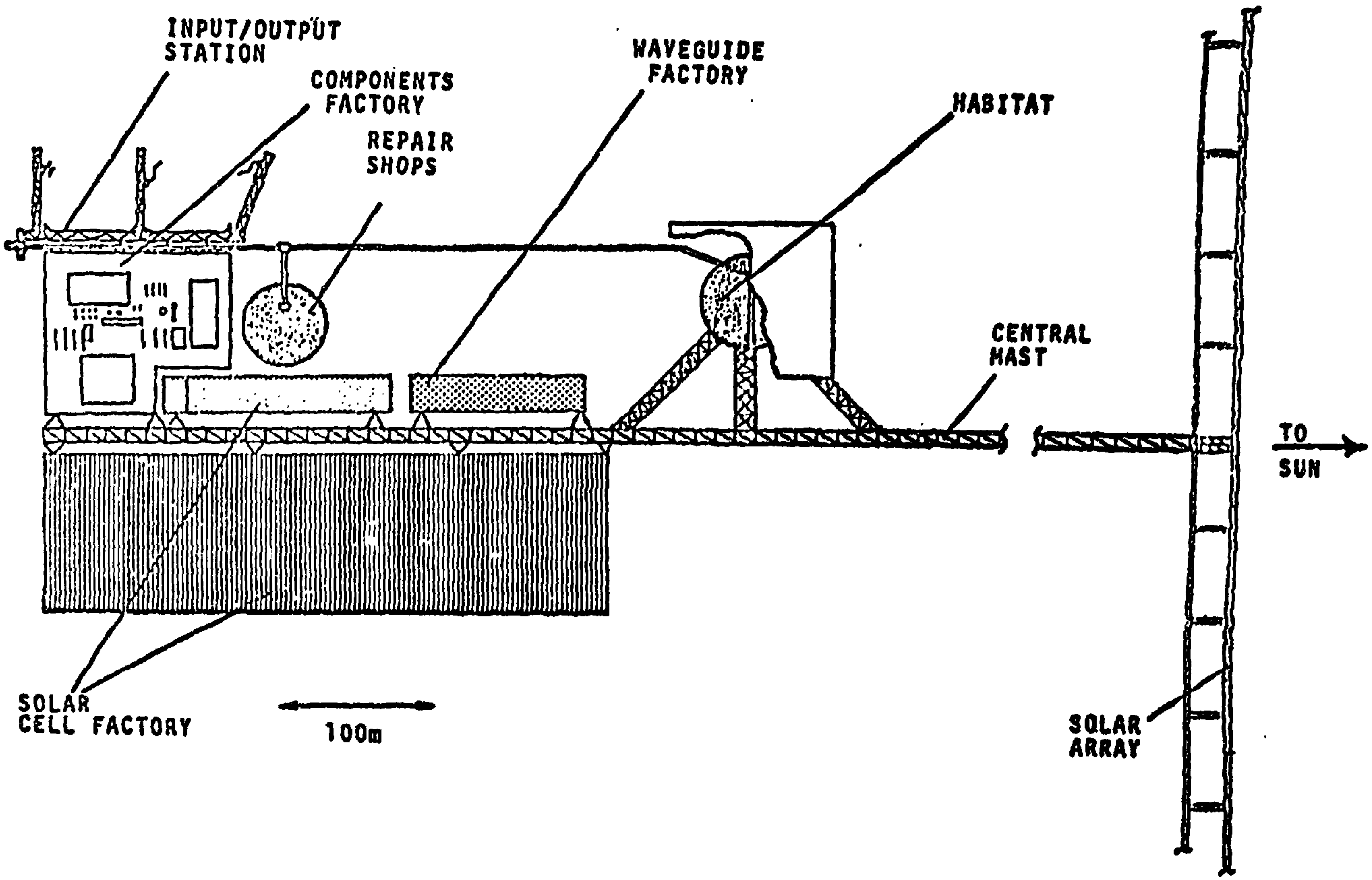


FIGURE 8.1: "TOP" VIEW OF REFERENCE SMF

by manipulators. Output containers may also be docked to this facility and loaded by the same manipulators. The need for such containers may not arise if the SMF were at the same location as the SPS assembly site. A pressurized docking mechanism is provided for the loading and unloading of the SMF crew.

The docking facility and other sections of the SMF are connected by a network of tracks along which magnetic transporters travel. These transporters travel through the facility to supply machines, transport personnel, and place containerized materials in dedicated storage devices.

In the solar cell factory, an overhead crawler system is used to perform all routine maintenance and support operations. The crawler system is described in section 8.4. More complex repair operations in the solar cell factory are performed by remote free-flying hybrid teleoperators which are described in Chapter 9.

Not shown in Figure 8.1 is the factory production control network. This three-command-level factory control system uses sensors to check output quality and machine operation and is described in section 8.4. The use of automation in factory control is discussed in Addendum II.

This chapter contains descriptions of the SMF support equipment.

8.2 INPUT/OUTPUT STATION

The functions of the input/output station are described in section 6.6.1. The docking area consists of two sections; an unpressurized area in which cargo modules are loaded and unloaded, and a pressurized personnel docking area. Figure 8.2 is a rough sketch of the input/output facility.

The personnel docking area consists of a standard androgyne docking mechanism to which personnel modules are docked. Personnel then transfer through the docking ring to a pressurized tunnel leading to the habitation and repair sections of the SMF. A pressurized docking facility is used because it removes the need for transiting crew members to wear space suits. The habitat is at some distance from the docking area so that, in the event of a docking accident, a minimum of damage to pressurized areas will result.

The unpressurized docking areas are the input/output stations for SMF materials. Cargo modules--sized to hold three months worth of lunar input (for a production rate of 1 SPS/year)--dock between trusswork piers. Two manipulator arms, each with a 40m reach and the ability to move along the trusswork piers, are used to load and unload each container. A human operator controls each of the manipulators; however, determination of the order in which unloading of goods occurs is a function of the production management system (described in section 8.5). In addition to the loading and unloading of the containers, the manipulators are used to transport

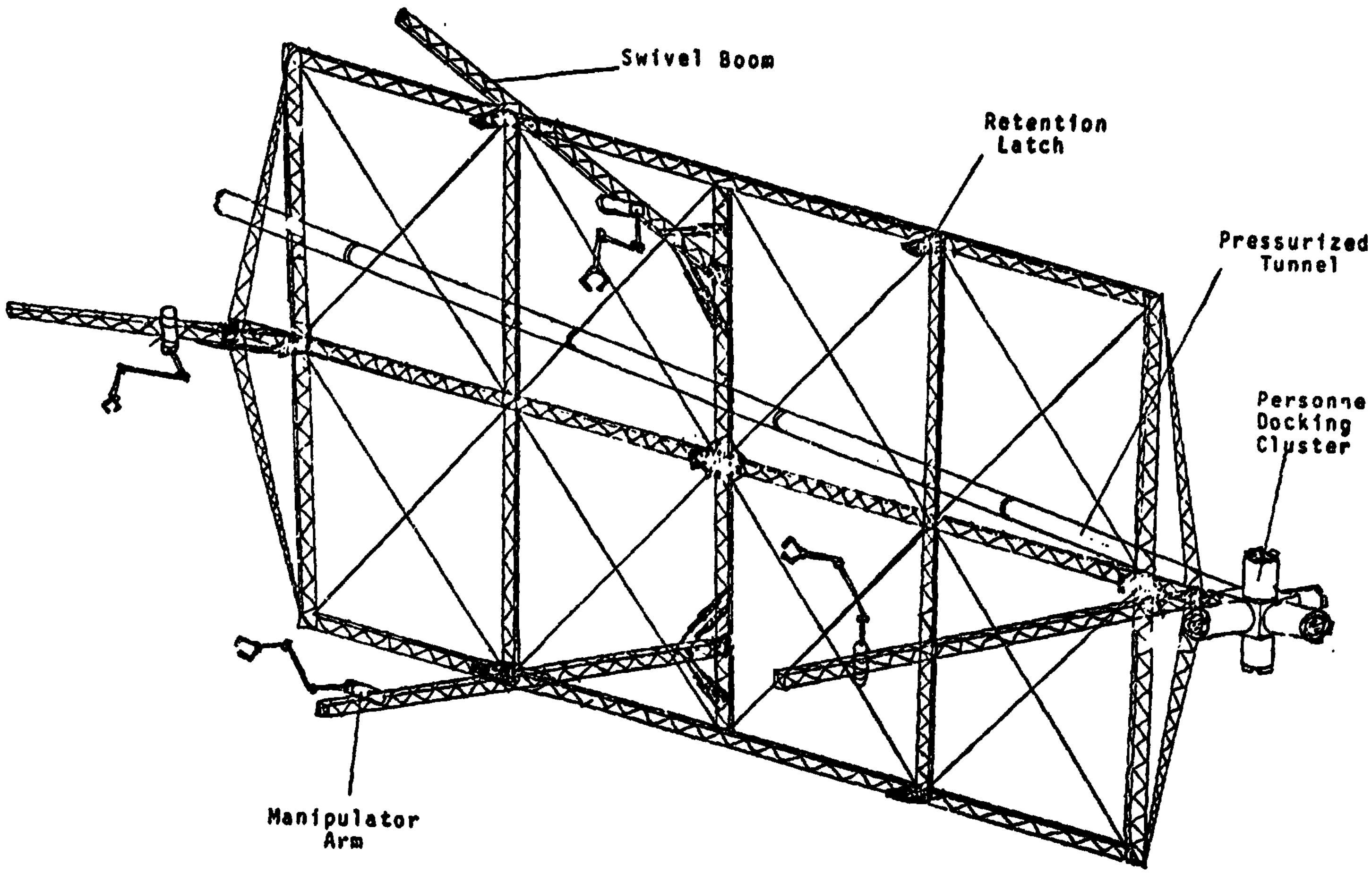


FIGURE 8.2: INPUT/OUTPUT STATION

assembled DC-DC converter radiators from their production area to the output station.

The input-output station is a major terminal for the internal transportation system. Goods unloaded from the containers are placed aboard magnetic transporters for dispatch throughout the facility (see section 8.3).

8.3 INTERNAL TRANSPORT SYSTEM

8.3.1 Overview: The SMF internal transportation system is designed to carry raw materials, personnel, and finished products within the facility. In the reference design a containerized, magnetic transporter system is used. It should be noted that this system uses passive containers; however, personnel containers can carry life-support batteries.

Table 8.1 presents a list of the items to be moved to, from, or within the SMF. All of these items mass less than 3 tons, and nearly all of them could each fit in a space 1.5 x 2.5 x 16 meters (some are far smaller). Thus, almost all of these items may be packaged in specialized containers and moved by the magnetic transport system (described in section 8.3.2). Storage areas for the specialized containers are provided in the system to prevent backups and guarantee supply of transporters along the tracks (see Fig. 8.3).

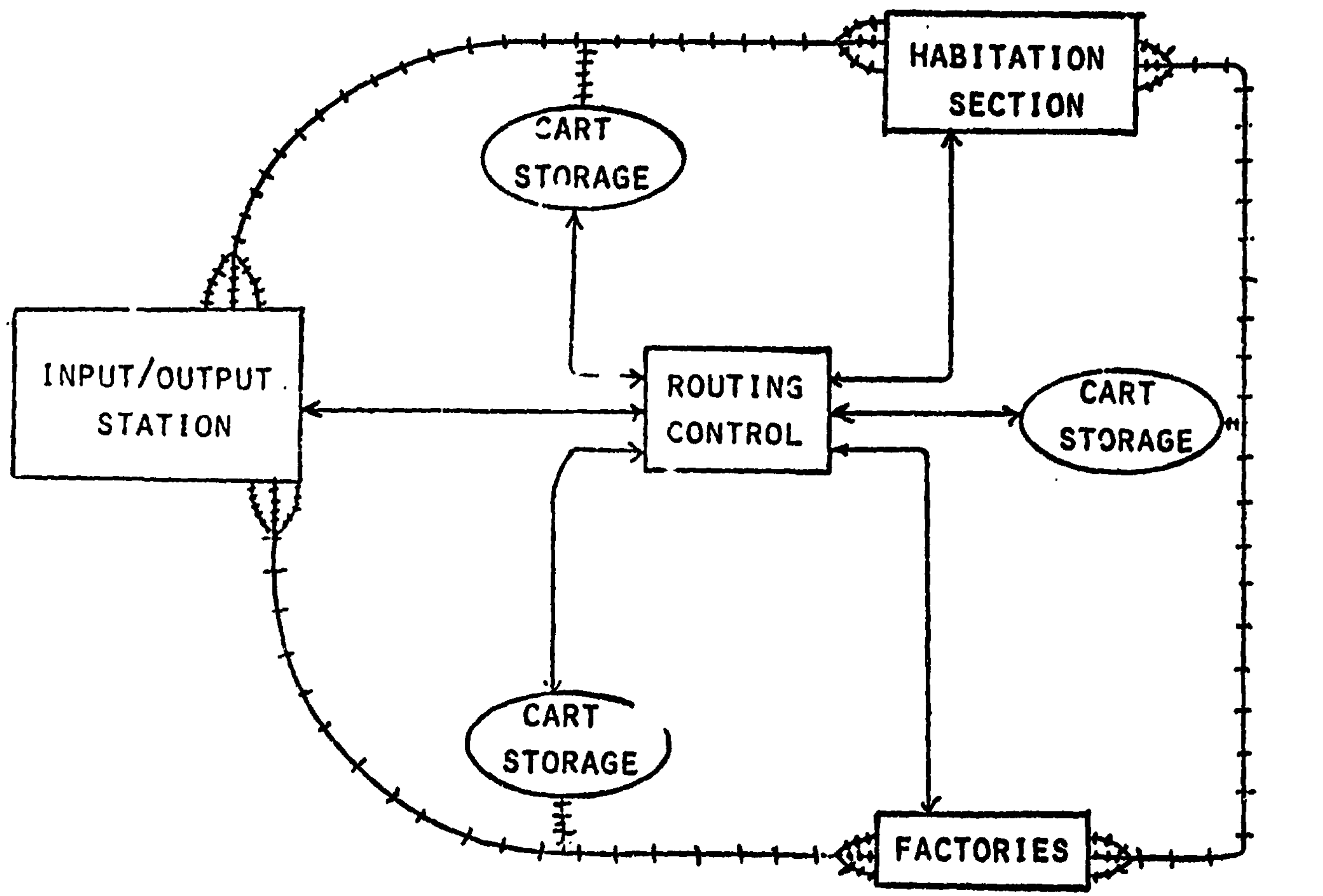
Molten metal or alloy cannot easily be packaged for transport in this system. Pipelines (described in section 7.2) provide the necessary movement for molten metal or alloy.

TABLE 8.1: ITEMS TO BE MOVED WITHIN THE SMF

INPUTS	INTRA-FACTORY		OUTPUTS
Aluminum Rods	Manifolds	Solenoid Cores	Busbar Strips
Glass Rods & Slabs	Metal Slabs*	Aluminum Rods & Slabs	DC-DC Converters
Magnesium Rods	Wire	Silicon Rods & Slabs	DC-DC Converter Radiators**
Silicon Rods & Slabs	Dopants	Transformer Cores	Electrical Wires & Cables
DC-DC Converter Parts	Cavities	Interconnects	End Joints
Kapton Tape Rolls	Housings	Glass Rods & Slabs	Joint Clusters
Klystron Parts	Kapton Rolls	Klystron Electronics	Klystron Assemblies
Oxygen Tanks	Spare Parts	Insulation -- Glass Cloth	Structural Members
Spare Parts	Pole Pieces	Klyston Radiators	Solar Cells
Iron Rods	Repair Crew		Waveguides
Natural Lunar Glass Powder			
Dopants			
Glass Foaming Agents			

All these items can be transported by a magnetic transport system, except:

*These items are too hot
**These items are too large



Double-headed arrows represent information going to Routing Control and commands going to SMF Sections and Cart Storage locations

TRANSPORT TRACKS

FIGURE 8.3: INTERNAL TRANSPORT SCHEMATIC

Metal slabs are also too hot to be easily packaged and therefore proceed directly from the caster to the rolling mill. Finally, DC-DC converter radiators, which will not fit in the transportation system, are produced near the input/output station and handled with manipulator arms.

One of the functions of the transportation system is to transfer materials to and from storage areas. There are three types of storage within the reference SMF. The first is bulk storage at the input/output station (materials stored in the input/output containers). The second type is within the factories. When a machine requires small pieces as inputs, an internal transport cart can hold many such pieces and serve as internal storage. The cart is parked on a sidetrack next to the input of the machine, which empties the cart as needed. When emptied, the cart moves away and a full cart replaces it. Similarly, machines which produce small outputs can fill a cart, which moves away when full.

The third type of internal storage is a dedicated storage device; this system is described in section 8.3.3.

8.3.2 Magnetic Transporter System: The magnetically driven transport system shown in Fig. 8.4 carries most SMF inputs and outputs as well as repair and maintenance personnel. Containers designed to carry particular items (i.e. klystrons, solar panel rolls, or repair crews) are supported by a 1.5 meter cubic framework. Two frameworks may be needed to support

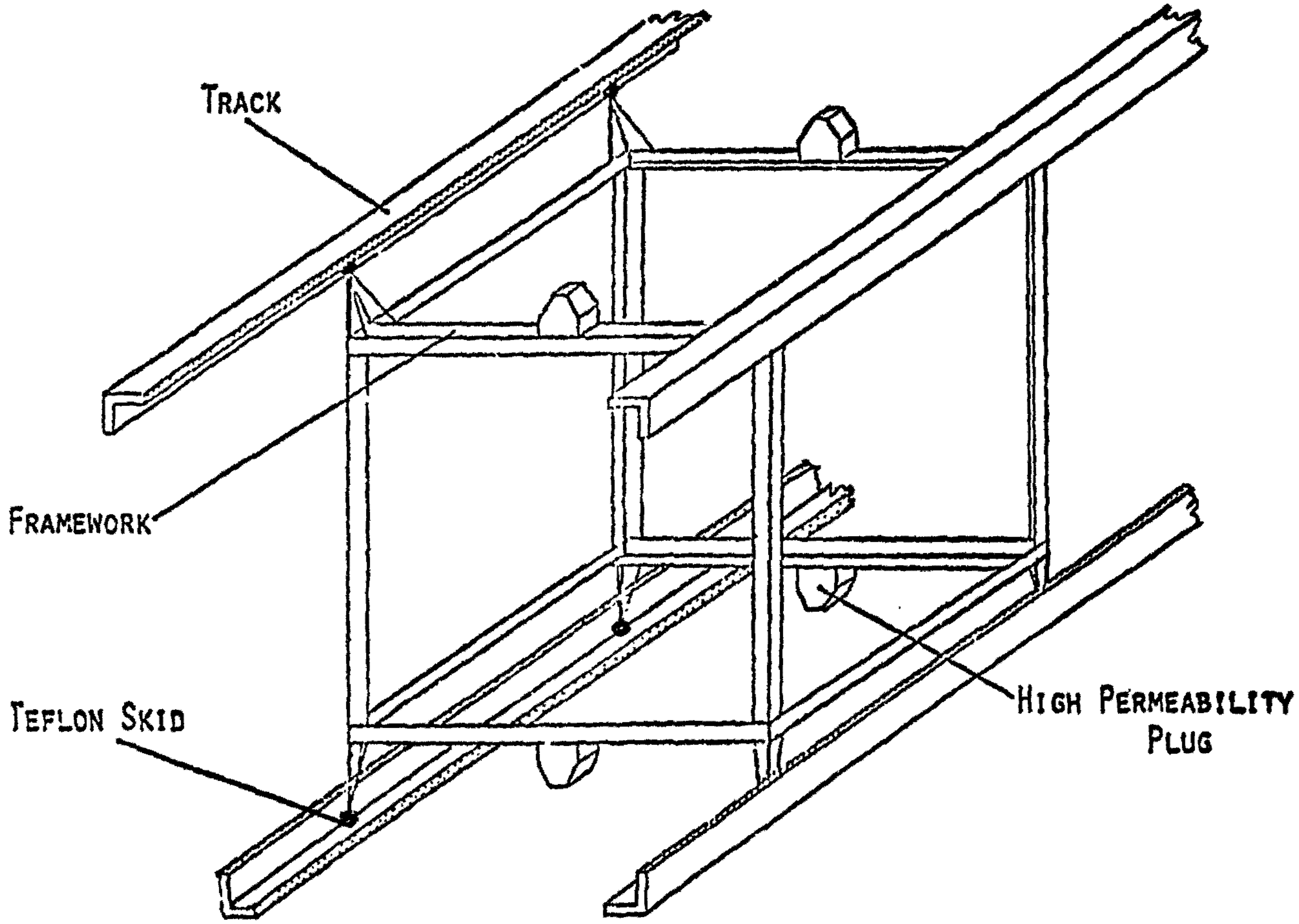


FIGURE 8.4: MAGNETIC TRANSPORTER CART

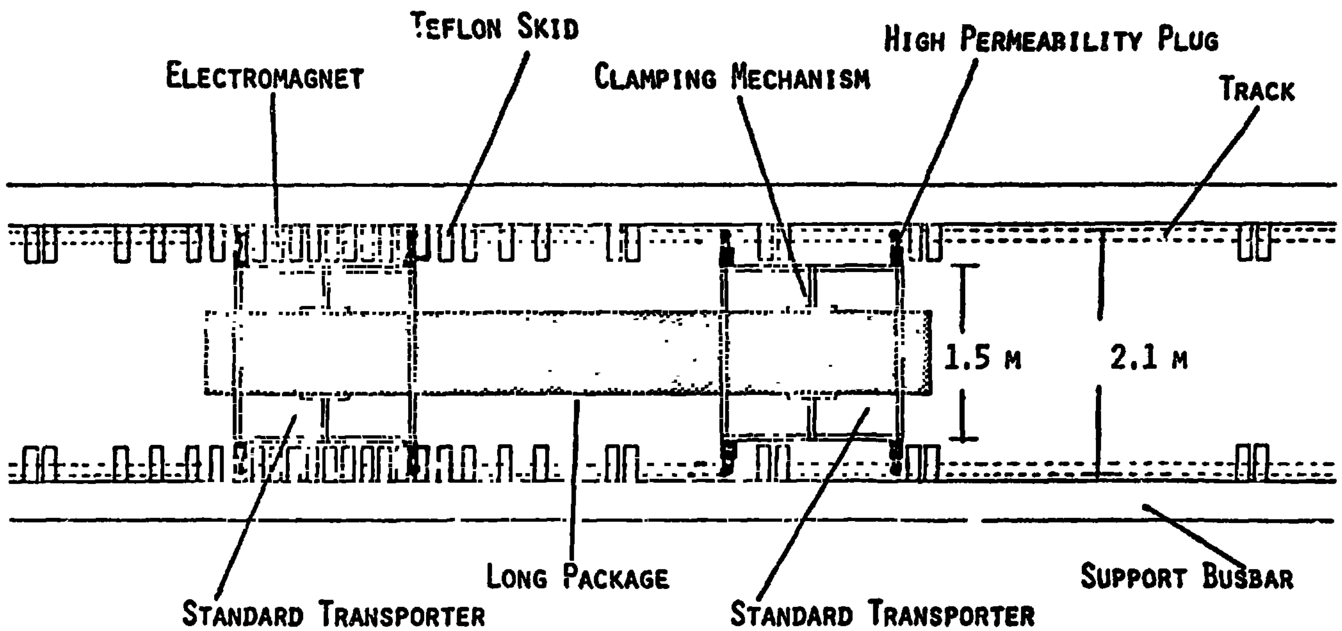


FIGURE 8.5: TRACK FOR MAGNETICALLY DRIVEN TRANSPORTER: SIDE VIEW

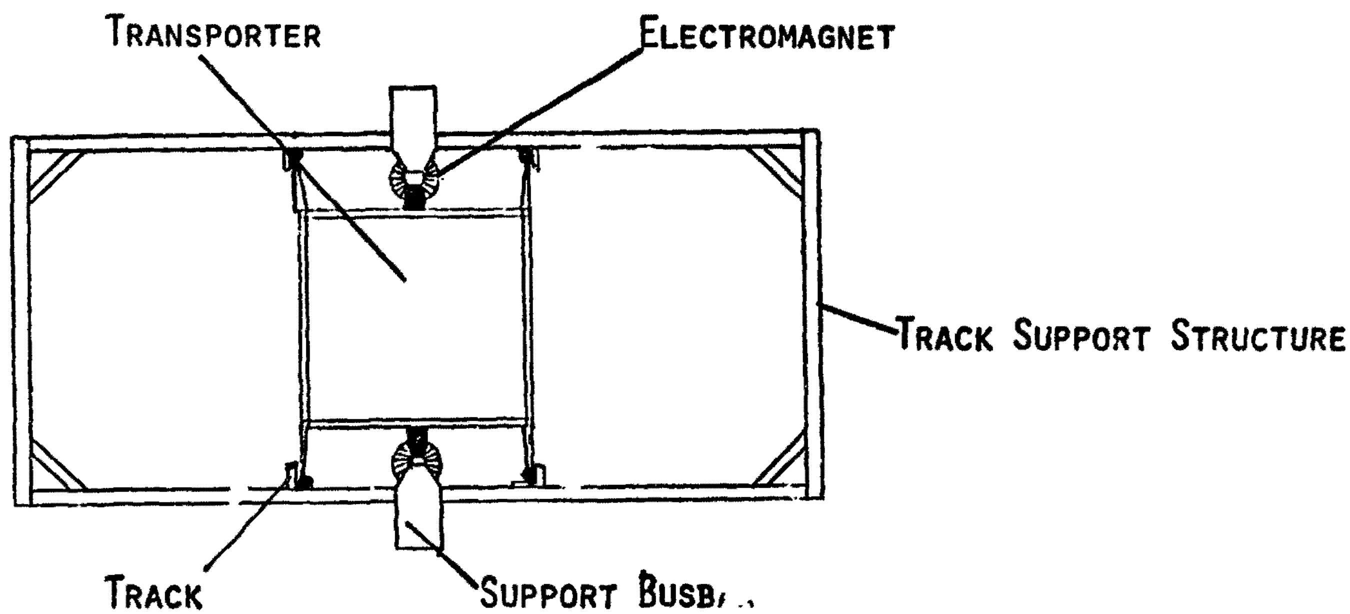


FIGURE 8.6: MAGNETICALLY DRIVEN TRANSPORTER: FRONT VIEW

containers longer than 1.5 meters, with pivot clamps between payload and transporters. Such a payload would then behave like a two-bogie railroad car (see Fig. 8.5). Eight teflon-coated skids keep the framework aligned along a fixed set of tracks.

As shown in Figs. 8.5 and 8.6, the transporter is propelled along the track by magnetic induction. Four high-permeability plugs are attached to each framework as shown. The plugs are made of supermalloy, a nickel-based material with permeability 800,000 at 8000 gauss. Such a material produces a higher magnetic field concentration than a permanent magnet. The transporter is driven by toroidal electromagnets made of supermalloy cores wound with copper or aluminum. The plugs fit loosely into the gap between the ends of the electromagnet, which creates a field of 8000 gauss (if the plug is fully inserted), providing energy of 25 joules per pulse. Thus 20 electromagnets are needed to accelerate a two-ton block from rest to a speed of 1m/sec.

The track contains 2-meter-long acceleration/deceleration sections near input/output and storage locations Acceleration is produced by a series of closely spaced electromagnets, each of which applies force to the plug within it at the command of a computer. The computer controls the acceleration by varying the current flowing through each electromagnet. After acceleration, transporters are allowed to coast while widely spaced electromagnets maintain speed.

SPECIFICATION SHEET

Machine Name: Magnetic Transporter Cart

Function of Machine: Transport of materials within the SMF

Mass of Machine: 87 kg

Physical Dimensions: 1.5 m x 1.5 m x 2.1 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): ---

Number of Machines: (depends on detailed design)

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
Frame	1	50	0
High Permeability Plug	4	6	0
Teflon Skid	8	1	0
Container	6	30	0

SPECIFICATION SHEET

Machine Name: Transporter Track

Function of Machine: Guide, control and accelerate transporters

Mass of Machine: 166400 kg

Physical Dimensions: 1800 m x 3 m x 2.2 m

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 22.8

Number of Machines: 1

Number of Operators: 0

Components:

	Number/ Machine	Mass (Kg)	Power Required (KW)
Track (800 m)	4	4000	0
Magnetic Drivers	1280	30	.01
Busbars	2	45000	0
Routing Control	1	2000	10

8.3.3 Internal Storage Device: The internal storage device is used to maintain a backlog of materials and parts at key points in the facility.

A magnetic transporter cart stops in front of the machine and a push arm unloads a container into the storage tube. The container is held in place by a spring and by release clips at one end of the tube. The eight tubes hold four containers each for a total storage capacity per device of 32 transporter loads. The internal storage device rotates to provide multiple loading and unloading points.

The number of machines was determined by planning for a backlog of one day at critical production points. The cost of the machine was determined from materials costs and from costs of similar industrial equipment.

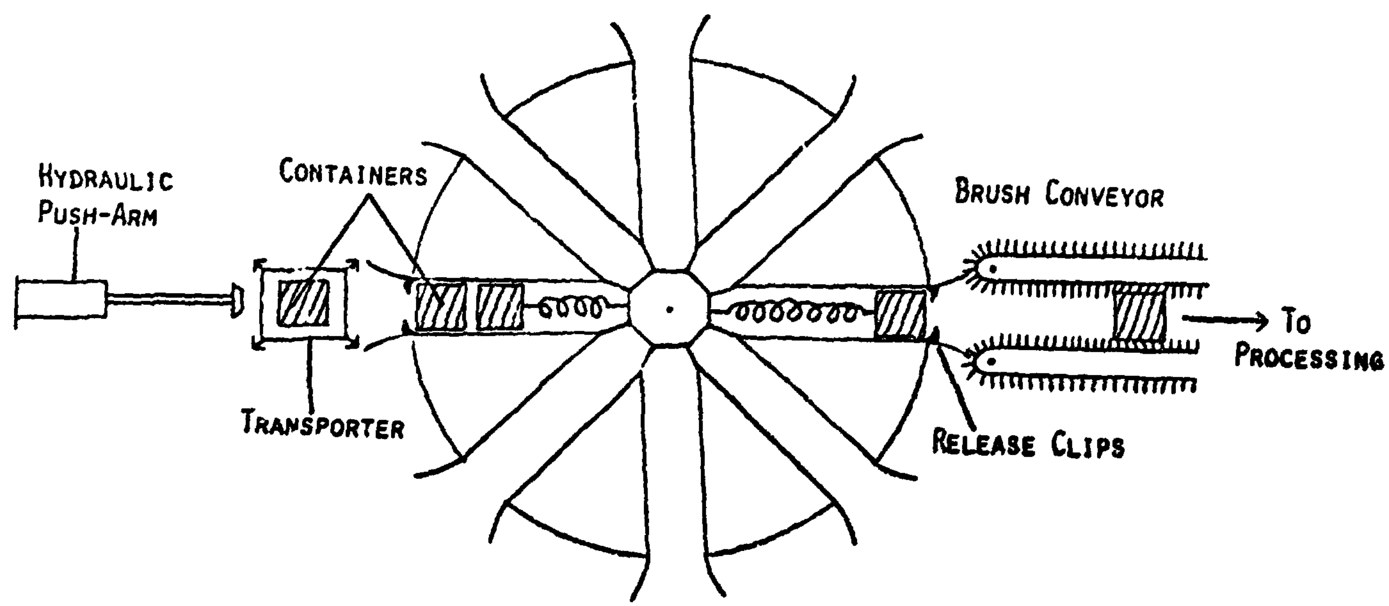


FIGURE 8.7: INTERNAL STORAGE DEVICE

SPECIFICATION SHEET

Machine Name: Internal Storage Device

Function of Machine: To maintain a backlog of materials and parts at key points in the SMF

Mass of Machine: 380 kg

Physical Dimensions: 15 m diameter; 1.6 m thickness

Throughput/Machine (tons/year): ---

Power Requirements (KW/machine): 2

Number of Machines: 8

Number of Operators: 0

Components:

	Number/Machine	Mass (Kg)	Power Required (KW)
Circuitry	1	200	1
Tubes	8	30	0
Push-Arm	1	150	1

8.4 CRAWLER SYSTEM

The crawler system performs all routine maintenance and support operations for the Solar Cell Factory (SCF). It delivers slabs, filament magazines, and baffle rolls to the deposition machines; interconnect rolls and kapton tape rolls to the assembly machines; spare panels to the panel insert machines; and it collects the solar array packages at the end of the assembly line. The crawler can, in addition, replace broken machines such as EB guns.

Crawlers move back and forth along tracks running perpendicular to the production strips, and dispense material and parts in a predetermined sequence. The crawlers

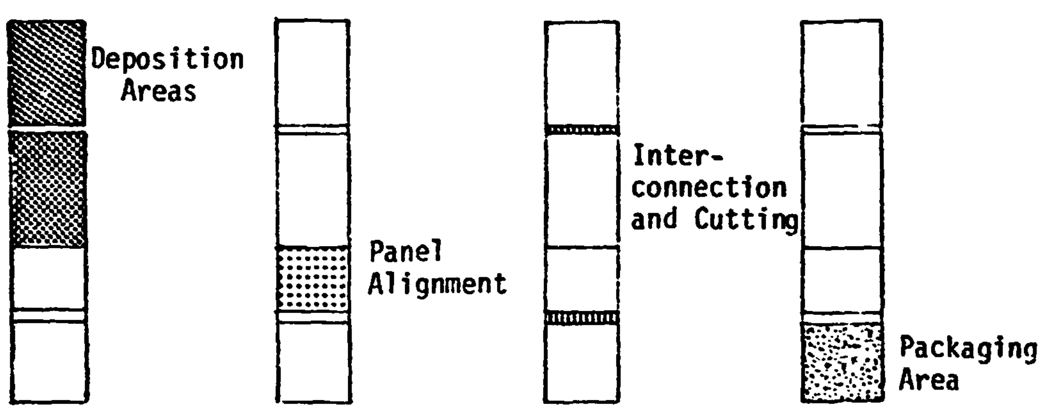


FIGURE 8.8: SOLAR CELL FACTORY SECTIONS
REQUIRING DIFFERENT CRAWLER TYPES

periodically replenish their supplies, and unload broken EB guns and filaments, at warehouses located between production strips of the SCF. Control of the crawlers is completely automatic, requiring no human supervisors. Individual crawlers are programmed in different ways, depending upon which section of the SCF they serve.

The SCF may be divided into four subsections that have essentially independent support requirements and may be served by a dedicated crawler system (Fig. 8.8). The areas are deposition area, panel alignment area, interconnection and cutting area, and packaging area. The main diffences between different types of crawlers are the loads they carry, their manipulators, their end effectors, and their operating programs.

Each crawler has the same basic frame and drive mechanisms (Figs. 8.9 and 8.10). The frame is triangular in cross-section 5m x 3m x 7m long except for the crawler serving the packaging section, which is 17m long. Manipulator arms are mounted on tracks to increase their effective reach. Their 5m length allows them to cover the widest deposition sections. The manipulator end effectors are tailored to the sections where they will be used. Deposition section manipulators, for example, must have end effectors that are capable of handling filament magazines, baffle rolls, slabs, and replacing broken EB guns. The manipulators must, correspondingly, have replaceable end effectors.

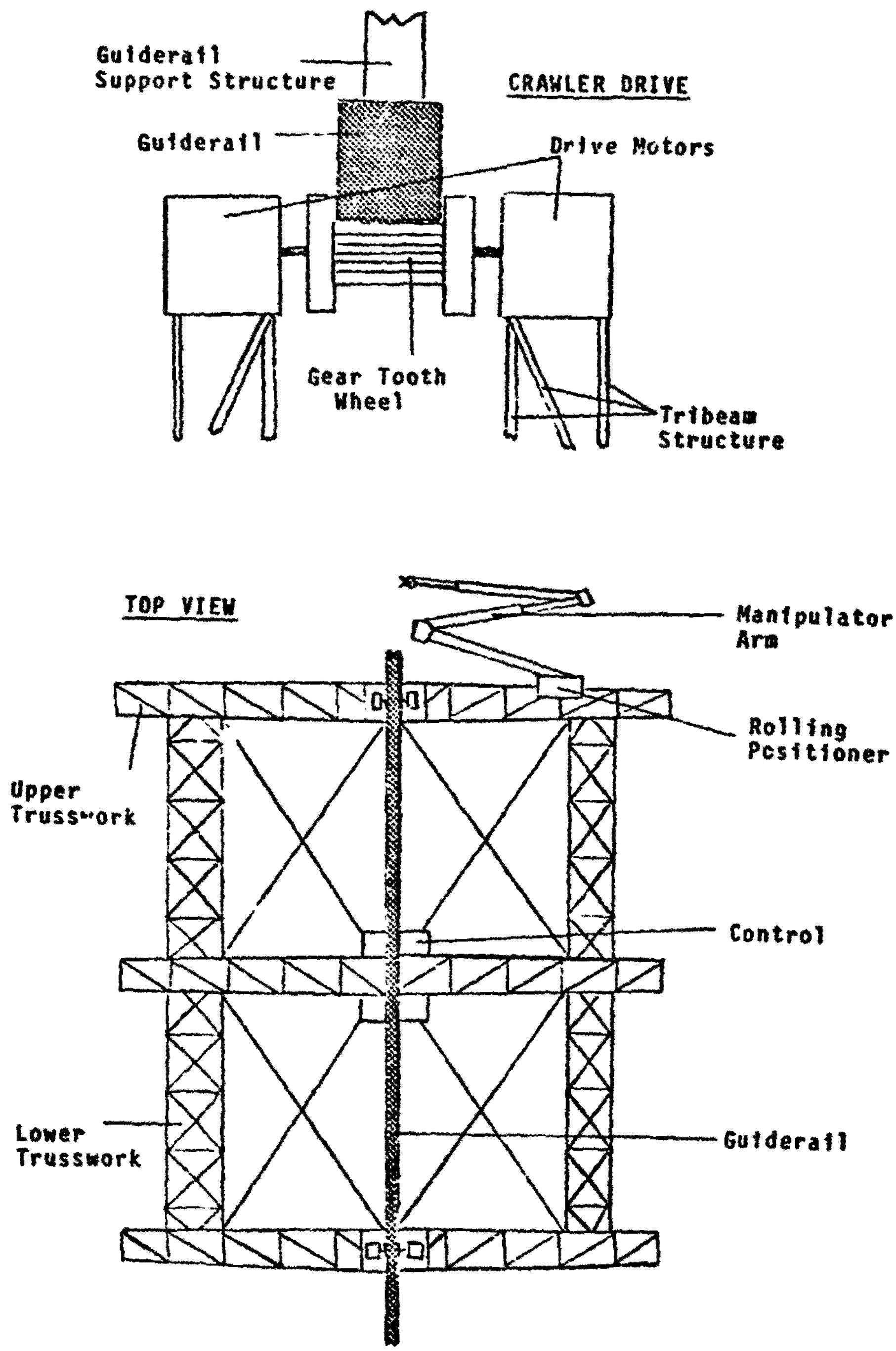


FIGURE 8.9: CRAWLER DRIVE
AND TOP VIEW OF CRAWLER

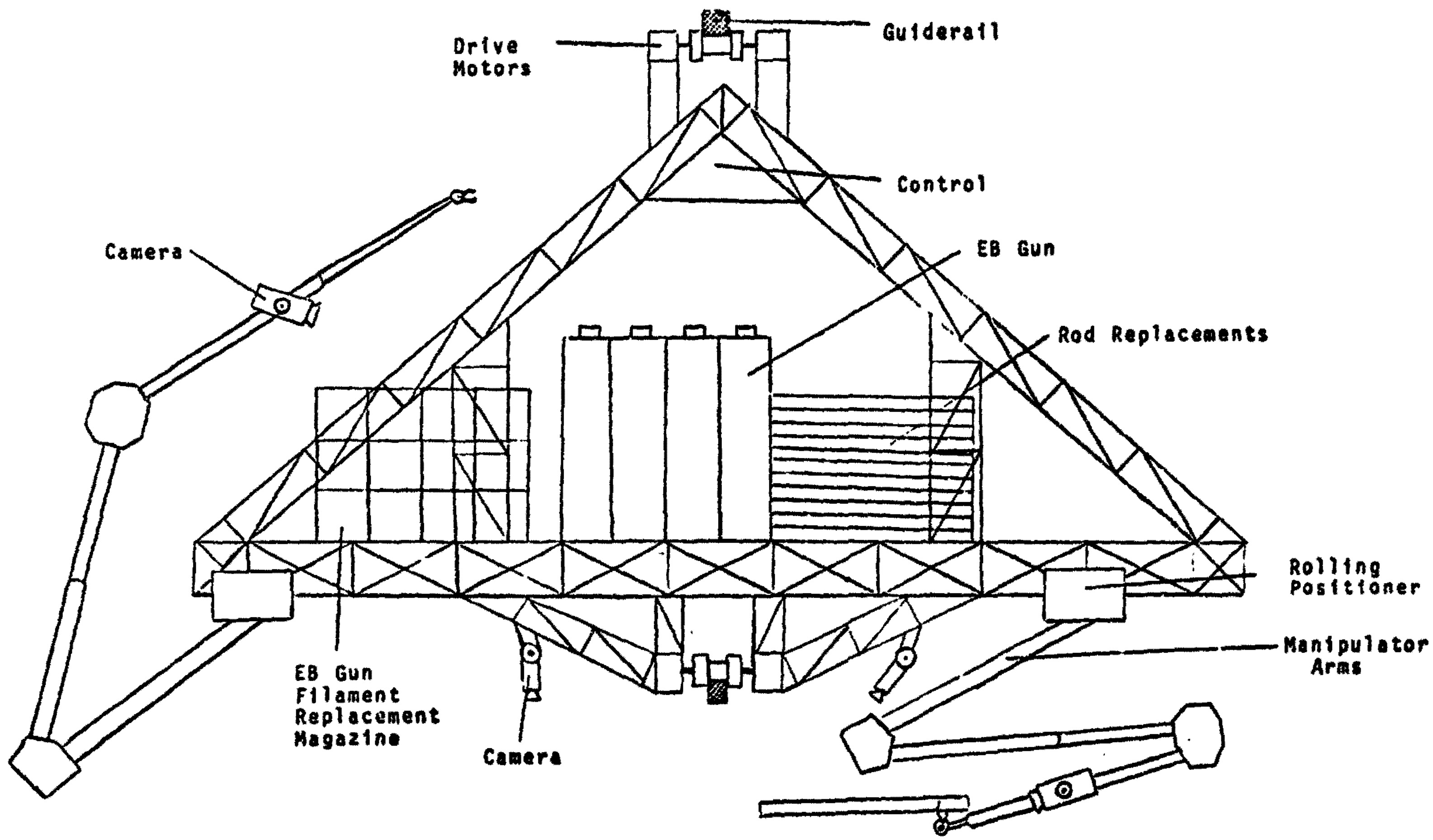


FIGURE 8.10: CRAWLER: END VIEW

Crawlers travel between two tracks, one above and one below the crawler, and are moved by an electrically driven gear (Fig. 8.9).

8.5 POWER PLANT EQUIPMENT

Power for the SMF is produced by a solar array situated outside the production facilities and connected by a flexible joint. The array is the only part of the facility requiring accurate pointing toward the sun ($\pm 1^{\circ}$). The remainder of the factory is shaded by the solar-cell array, thus easing waste heat and thermal cycling problems.

Estimates of power consumption, defined from the specification sheets for various SMF processes, are given in Table 8.2. The total power requirement for the SMF is approximately 240 MW, which, assuming an array efficiency of 12.5%, equates to a solar cell area of 1.37 km^2 (a square 1200m on a side).

All the power provided to the SMF is in DC form, except that which operates the induction furnaces. The furnaces require high AC power at 300 Hz. The DC voltage from the array must be fed to each process at a specific voltage level. This power conditioning may be achieved by either using DC-DC converters or by "tapping" current at appropriate points from the solar array by suitably positioned multiple busbars. The reference SMF design was DC-DC converters positioned along the central structural mast to provide power to the various

TABLE 8.2

POWER USE IN REFERENCE SMF

COMPONENTS FACTORY	POWER (KW)
Metals, furnaces, and casters	300
Ribbon and sheet operations	1600
Insulated wire production	550
DC-DC converter production	3
Klystron production	40,000
WAVEGUIDE FACTORY	
Waveguide production	8,900
SOLAR CELL FACTORY	
Solar cell production	186,000
FACTORY SUPPORT	300
LIFE SUPPORT (@9 kw/person)	4,000

SMF sections. The AC power for the production furnaces is provided by DC-AC converters.

In case of solar eclipse, or malfunction of the solar array pointing system, power can be produced by emergency fuel cells which feed DC power to the power conditioning system. During primary power failure, these fuel cells produce enough power to avoid damage to equipment and danger to personnel while the production equipment shuts down; to keep essential support services (docking, internal transport, lift support, repair, and attitude control) working until primary power returns, and to keep the life support systems of the habitation section operating. The fuel cells are designed to supply emergency power for up to 30 days. From Table 8.2 it can be seen that factory support equipment requires 300 KW and life support requires 9 KW/person. In the case of a power loss the latter figure may be cut down to 3 KW/person with suitable power conservation measures. The total mass of the emergency power source (assuming 440 workers at the SMF) is 21T--using a typical fuel cell mass of 16 kg/kw.

The fuel cells are actually operated at low output at all times, to keep them in operating condition, and to produce power to handle peak loads (the solar array produces mainly baseload power). The cells are fueled with lunar oxygen and Earth hydrogen; their water output makes up the water losses in the food and water cycles.

8.6 PRODUCTION CONTROL

8.6.1 Control Structure: As described in section 6.6.4, production control within the reference SMF is exercised at three levels: factory monitoring, factory resources management, and production management.

The lowest level is factory monitoring, which continuously receives information on machine operation and output quality. If product quality is substandard, the factory monitoring section sends commands to the factory to adjust the appropriate equipment settings.

If the substandard output persists, or if a machine breakdown occurs, the factory monitoring section sends commands to the factory to shut down the affected equipment, and sends commands to the maintenance and repair section to fix the problem. Similarly, the factory monitoring section monitors the need for maintenance of the factory equipment, and sends commands to the maintenance and repair section to do that maintenance.

In order to perform these tasks, equipment monitors both the quality of output, and the operation of circuitry to initiate corrective commands. For example, in the solar cell factory, measurements of deposited film thicknesses, grain size of deposited silicon, dopant concentrations, etc. are made during production to ensure quality of machine outputs. Measurement devices employ a variety of techniques. Additionally, the performance of equipment such as electron beam guns, peg welders, and contact masks is monitored so that a comparison between output quality and machinery status will allow faults to be isolated. For maximum effectiveness (minimum wastage) quality control is then exercised at each stage of production within the reference SMF.

Equipment requirements for the factory cannot be easily evaluated since the machinery required for quality control is, to some extent, dependent upon the final production machinery designs. It is clear, however, that sensors, communications lines, computational facilities, audio and/or video monitoring, and, possibly, teleoperator capabilities will be required . Quality control concepts, applied to the Solar Cell Factory, are discussed in section 7.6.2.

The next level in SMF production control and management is the factory resources management section. This section receives information from several sources. From the factory monitoring section, it receives continuous information on the status of the factory, i.e. which machines are working, which are shut down, which are approaching scheduled maintenance. From the factory itself, the factory resources management section receives information on the contents of internal storage systems. From the input/output station, it receives information on the input and output inventories in the cargo modules.

From all this information, the factory resources management section builds and continuously updates a picture of the resources available for production: status of machinery, size and location of material inventories. Based on this picture, this section models and predicts factory throughput. It then optimizes factory operations in the predictive model.

The work of the factory resources management is largely computational, receiving data from sensing equipment located around the factory.

Inventory control equipment is responsible for the identification of and accounting for parts within the facility. Additional equipment is required to monitor the contents of each of the internal storage devices throughout the factory. Inventory control (as applied to the Solar Cell Factory) is discussed in section 8.6.3.

The system employed is comparable to that currently used in factories with automated inventory control. In fact, the SMF system is a good deal simpler than that used in, say, the automobile industry which keeps account of up to 15,000 different parts at a given time. The particular case of resource management of the Solar Cell Factory is the subject of current work by the study group.

The factory resources management section of the SMF includes several personnel to oversee the operations of the complex SMF factories. The large volumes of information required are processed by computers.

The upper level of production control and management is production management. The SMF production manager receives information from within the SMF and from other sectors of the space industrialization scenario. From the factory resources management section, production management receives updates on the resources available to the SMF. From the Moon and the SPS assembly site, the SMF production manager receives information on shipment schedules for both expected input shipments and required output shipments. These facts are then evaluated, together with long-range planning goals, to determine the near-term objectives of SMF production. Production management then gives these objectives to the factory resources management section for implementation.

The production manager must receive information about the status of all parts of the factory on request, and, therefore, equipment is for communications, data links, computation, etc. The actual equipment required is largely dependent on final factory designs.

8.6.2 Quality Control Concepts: Quality control equipment will be needed in the SCF to monitor thicknesses, temperatures, dopant concentrations and machinery health. This section of the Addendum will address options available for some of the quality control equipment.

During the initial part of the solar cell deposition the cell layers will be deposited on a thermal belt designed to provide temperature control for several machine processes. Ref. 20 surveys temperature instrumentation, of which only thermocouples, resistance versus temperature devices (RTD's) and radiation pyrometers operate in the range of temperatures encountered by the thermal b . Infrared thermometers operate in the temperature range of concern and are described in Ref. 21, which provides an excellent comparison of thermocouples and infrared thermometers.

The advantages of an IR thermometer over a thermocouple include its quicker response time, virtually infinite life and the fact that it is a non-contact sensor. Compared to IR thermometers the thermocouples require no cooling services and can measure temperatures in inaccessible places. Because it is non-contacting, the IR thermometer seems ideal for a manufacturing process; however, the vapors in the various machines could interfere with the optics of this instrument.

An attractive technique for the analysis of film thickness and in the case of the doped silicon, the composition as well, is the use of X-ray emissions (Ref. 3). X-ray emission involves exciting a thin film with a high-energy source such as X-rays or an electron beam. The film produces a characteristic radiation, the intensity of which is linearly proportional to the thickness for thin films and increases exponentially for thicker films up to a maximum value. The procedure has been demonstrated for multicomponent films. This nondestructive technique, which is highly accurate and requires a short analysis time, is readily applicable to inline process (manufacturing) control. The literature indicates that this technique could be very useful for the aluminum contacts and for the boron doped silicon which is five micrometers in thickness. Ref. 3 is not clear as to whether this method could be used for the entire silicon film which is 50 micrometers thick, or for the silicon dioxide covers which are 50 micrometers and 75 micrometers in thickness.

8.6.3 Inventory: The Solar Cell Factory requires seven different outside inputs for the manufacture of solar cells, in addition to interconnect rolls and zone-refined silicon slabs which are internally manufactured. The seven inputs are aluminum, silicon, dopants (boron and phosphorus), silica, oxygen, and kapton tape. All of these are delivered by crawlers on a routine basis and, with the exceptions of oxygen and kapton tape, are in slab form.

For the input materials, the accounting system is required to keep track of the inventories in the SCF machines, crawlers, warehouses, and also the SMF central warehouse. Specifically, the system keeps information on the quantity of each input type and where and when it was produced. Thus, if a defect in material inputs to the production process is found to cause inferior quality cells, the defective slabs can be traced back to the machine that produced them and the problem investigated. The slabs are always handled in special racks after being formed and before being unloaded from the crawlers to prevent vacuum welding and contamination. When the crawlers unload slabs into the deposition machines, the pertinent information about the slabs is relayed to a central accounting computer along with the time and the machine location. This central computer also keeps track of materials delivered to and sent from the SCF and SMF warehouses. Thus the central computer is aware at any given time of exactly how much of a given input material is in stock or in transit, to or from, the SMF warehouse, the local SCF warehouses, the crawlers, or the SCF machines.

The central accounting computer has data concerning expected support requirements for such articles as EB gun filaments and kapton tape rolls, and unscheduled breakdowns of components and is thus able to allocate its resources in the most efficient manner possible, ensuring that no warehouse is ever understocked. If for some reason a shortage of supplies exists, the accounting computer determines which sections of the SCF are most capable of absorbing a shortage while maintaining adequate levels of production and distributes supplies accordingly.

The computer's method of gathering information on the SCF output (solar array packages) is necessarily different from that of the input materials because the outputs may not be of completely uniform quality like the input materials are. A solar array slightly below average cannot be recycled, so either an entire array must be thrown away or a package of slightly lower efficiency will be accepted and the SPS resized accordingly. Information concerning the quality of a solar array package can be relayed to the SPS assembly site prior to its arrival so that appropriate measures, if any, can be taken to accommodate the lower quality packages.

The central computer keeps on file all information pertaining to the quality of a solar array package. It receives data from the panel insert zone concerning how many spare panels were inserted and whether any panels are missing from a package. Most importantly, the computer records the results of the panel test done prior to the panel insert zone. The computer will also be aware of deposition thickness and uniformity, dopant concentrations, grain size, interconnect weld quality, taping quality, etc. The above information will be useful for speeding up repairs to failed panels, and for planning array maintenance and renewal strategies.

The SCF deposition and assembly components that can be replaced by the crawler also require an accounting system. When these components fail, they are replaced by spares stored on the crawler. New and refurbished spares are also stored in the SCF warehouses. Components are either in operation, in the repair shop, or in a warehouse, or crawler. This repair/replacement system is discussed in more detail in Chapter 9.

8.7 HABITATION

The configuration chosen for the SMF habitat is illustrated in Fig. 8.11. As in the JSC-GD study, the habitat consists of a number of modules constructed from shuttle external tanks. For every seven modules, six are designated "habitation

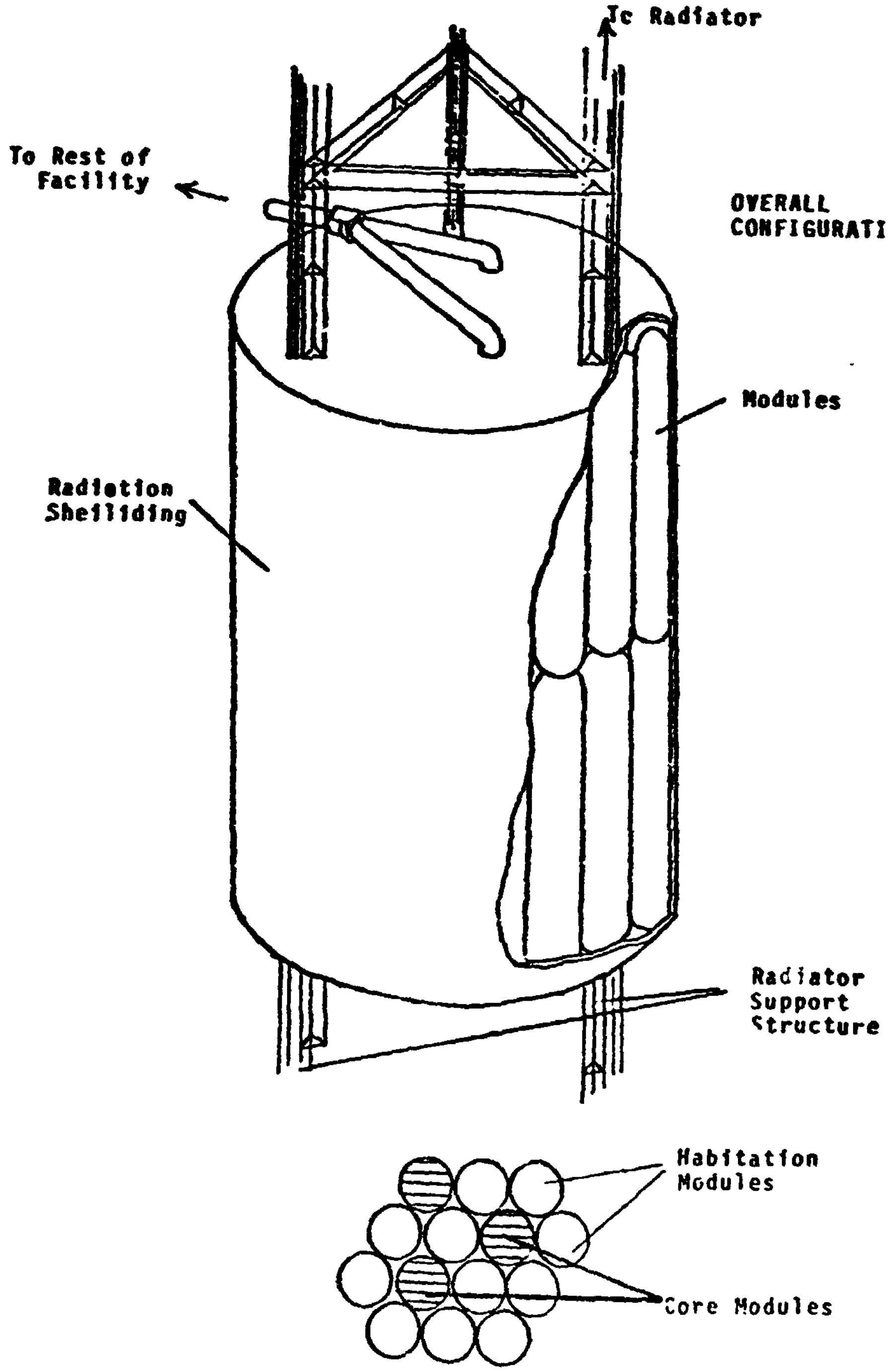


FIGURE 8.11: REFERENCE SMF HABITAT

modules" and one a "core module." The habitation modules are the basic residential modules, each having eleven levels and supporting twenty-one people. The core modules contain dining and some recreational areas, and provide support for as many as 125 people in case of a severe solar flare. More detailed descriptions of these modules are contained in the JSC/GD study.

The ECLSS (Environmental Control and Life Support System) modules are nested between the External Tanks. Additionally, doorways are cut between habitation modules in several places. A small amount of material is used to seal these connections, material which may be salvaged from external tank wastage (such as parts of the LO_2 tanks). The two airlock modules are affixed to core modules at both end modules.

The major departure from the General Dynamics' design has been switching from a one-g environment, provided by rotation, to a zero-g environment.

A zero-g habitat was chosen for the SMF for three reasons. First, the Soviet Salyut 6 missions have demonstrated no limit to zero-g flights up to nearly five months, assuming that a rigorous exercise program is adhered to. Thus a six month tour of duty (set by radiation limits) should be possible in a zero-g habitat. Second, attempting to cycle between a one-g habitat and a zero-g SMF twice daily may cause vestibular problems to some of the crew. Third, this design reduces the shielding requirement by a factor of 2.2. This shielding is provided by a stored backlog of input materials for the SMF. The earliest input from the Moon becomes this radiation shielding, and a reduced shielding mass means that only 0.33 months of solid input are required (based on one 10-Gw SPS/year production).

One problem that is intensified by the above design change is heat rejection. However, this may only require an increase in fluid piping, and not a significant change in radiator mass.

Table 8.3 shows the habitation specifications for the reference SMF with a crew of 600 people. As in the JSC/GD study, a crew stay time at the SMF of 6 months total per year was assumed--three months in space followed by three months on the ground up to a personal maximum of one year in space. This was based upon galactic radiation shielding of 210 g/cm^2 of lunar-derived material. The total shielding mass is 3.5 kT. (The mass and power estimated for the SMF habitat are adapted from the JSC/GD P.R. #4.) The paraphernalia associated with rotation of the tanks (hub modules, radial connection assemblies, etc.) have been eliminated. Also eliminated are the "Central Shaft and Conveyor" assemblies of each residential and core module. Finally, flooring mass/area has been set equal to that for partitions and walls at 2.5 kg/m^2.

The habitat total mass (not including shielding) comes to 1800 T.

TABLE 8.3

HABITAT SPECS

Total Earth Launched Mass (Inert)	1.3×10^3 tons
Habitat Shielding Mass (Lunar Material)	3.5×10^3 tons
Population	440
Power Requirement	4.0 MW (9 KW/Person)
Waste Heat	3.6 MW
Total Radiator Area	9.0×10^3 M^2
Consumable Requirement	178 tons/year
Emergency Supply	67 tons

8.8 STATION KEEPING EQUIPMENT

Station-keeping equipment requirements for the SMF are dependent upon the orbit in which the facility is placed. In the study guidelines, no specific orbit was allocated for the facility, and selection of an orbit is outside the scope of this study. Correspondingly, no specific descriptions of the equipment requirements can be given.

Two alternative attitude control systems for the reference SMF are control moment gyros and thrusters. Because of the high moments of inertia of the largely planar SMF, a massive control moment gyro would be required. Additionally, in the reference design, large moment arms for the action of thrusters are available. It would appear then that a thruster system would be the more likely candidate for reference SMF use. The analysis of the system requirements (number of thrusters, fuel requirements, etc.) is, for the reasons given above, beyond the scope of this study.

8.9 SMF STRUCTURE

The structure of the SMF (not shown in the figures) is assumed to account for approximately 10% (2,000,000 kg) of the overall mass of the facility. The structure is assumed to consist of trusswork, flexible joint for the solar array mounting, radiator support structure, and actively damped connectors between each of the factory sections. The main structural element is the central mast (see Fig. 8.1) to which all sections of the facility are attached. In addition, the mast carries the main factory power distribution equipment, and and provides a clear section through which intra-factory transporters can operate. Again, detailed design of the structure requires a better definition of the design loads which, in turn, depend on the orbit of the facility.

CHAPTER 9

MAINTENANCE AND REPAIR

9.1: GENERAL REMARKS

The maintenance and repair operations for the SMF can be approached by a variety of different strategies, depending on the complexity, location, size, and number of machines being repaired. The SMF has at its disposal human technicians, crawlers, and free-flying hybrid teleoperators (FHT's) for on-site machine maintenance, repair, and/or removal to the repair shop. In the repair shop itself, the SMF may use either repair automatons or human repair crews.

In general, humans service the components factory, and crawlers and FHT's service the solar cell factory. The components factory includes many different machines with little or no duplication. The variety and complexity of the factory, coupled with the lack of duplication of components prohibits servicing by any sort of computer-controlled, automated system. Human repair crews, however, are highly versatile and could easily perform a wide range of sporadic but complex repair tasks.

The solar cell factory poses a different design problem. It consists of hundreds of identical deposition and assembly strips, each operating independently from the others. The SCF EB guns also produce a high radiation environment which makes it desirable to minimise human contact with it. A completely automated or teleoperated maintenance/repair system is ideally suited to these circumstances. A crawler system (described in Sec. 8.4) performs all routine maintenance and support operations. It is completely automated and is capable of performing only routine tasks. The free-flying hybrid teleoperator (FHT) does all unscheduled repair work. It has more sophisticated manipulator and sensor systems than the crawlers, and is designed to completely substitute for human repair crews. It can operate in a completely automated mode, or under limited or total human control when excessive complexity or uncertainty is encountered.

9.2: REPAIR OPTIONS TRADEOFFS

Similar repair options are encountered in both the SCF and the components factory. Scheduled maintenance is done to avoid disruptive breakdown and subsequent unscheduled repair. The breakdown of a vital component, such as the deposition belt in the SCF, can cause a major disruption or shutdown of part of the solar cell production process. This can be partially avoided by preventive maintenance, which can involve complete replacement of a machine component, use of rotable spares, or on-site inspection and refurbishment.

In some cases, such as the metals furnaces, it is desirable to periodically replace a component (the furnace casing, in this example) before it breaks or wears out. The furnace casings are therefore periodically removed and replaced with new ones. The old casings which are worn out can not be recycled, so they are discarded.

Preventive maintenance may also be implemented by using a system of rotable spares. In a rotable spares system, a number of extra components (such as EB gun filament magazines) are kept on hand and are periodically used to replace the components in the machine on a fixed usage schedule. The old compon is then refurbished and returned as a spare.

Some machines (such as the SCF deposition belts) cannot be removed or replaced. Periodic on-site inspection reveals worn parts or other potential problems, which are fixed or replaced, as required.

Scheduled maintenance cannot prevent all breakdowns. A number of combinations of different repair options are possible: redundant design, rotable spares with refurbishment at the repairshop, repair on site, and throwaway components.

Redundant machines (such as EB guns in the deposition sections) allows continued production even after one machine breaks down; the remaining ones take over until the broken EB gun is replaced.

Repair of EB guns is done using a rotable spares system. When an EB gun fails, the crawler replaces it with a working spare. The failed gun is then taken to the repairshop. After repair it is returned to one of the crawlers, to be used as a spare.

When a failed machine cannot be removed, it is repaired on-site by either human repair crews or FHT's, depending on the location. However, when machines are repaired on-site, production halts until the repair is completed, unless redundant machines are available (as with the EB guns).

Some machines have components that cannot be repaired after they fail (EB gun filaments, for example). When the filaments burn out, they are replaced with new ones, which are brought up from Earth and the old ones are discarded.

9.3: REPAIR SHOP

The repair shop is formed from a cluster of 24 Shuttle External Tanks in a similar configuration to the habitat. Unlike the habitat, however, the life-support modules have the increased capability to deal with the gaseous products of operations in the workshop. The workshop is separate from the repair shop because of the different life support requirements, and in order to prevent workshop accidents from jeopardizing living quarters. Also included in the repair shops are active damping systems for the machinery, racks for spare parts, input/output systems, and emergency systems.

As discussed in Sec. 9.1, the repair of machines in the waveguide and component factories is achieved by on-site human labor. In the solar cell factory a certain class of components (such as EB guns) is capable of being removed for repair and replaced by a serviceable unit. There are three clasees of these plug-in/plug-out modules:

1) Expendible parts which are thrown away on failure, such as baffles;

2) Those simple enough to be repaired by automatons, such as EB guns; and
3) Those requiring complex repair or those small in number, requiring human repair, such as sensors.

Within the repair shop there are two types of machinery:

1) Repair Automatons -- these are automatic repair stations each dedicated to the repair of one type of component. Each Automatons has limited diagnostic capability; any problems outside its capabilities are referred to a human repair crewperson. There are 42 different types of automatons in the reference SMF design.
2) Workshop machinery to allow the fabrication of parts without having to order them from Earth.

9.4: FREE-FLYING HYBRID TELEOPERATOR

Much of the onsite repair work on the solar cell factory can be handled by the crawler system, which replaces defective components with operational spares. However, some of the repair jobs are expected to be either out of the reach or beyond the capabilities of the crawler system. Examples of such repairs are fixing thermal belts, radiator systems, array packagers, or the crawlers themselves. It is not cost-effective to equip the crawlers with the extended ability to do these repairs, since they are seldom needed, and that crawler equipment would not be used very often. On the other hand, the use of human labor for repairs on the solar cell factory poses a health hazard due to the x-rays emitted by the EB guns. The study group therefore proposes a Free-flying Hybrid Teleoperator

(FHT), with the mobility and sophistication to handle almost any repair job at the SMF. The FHT should be able to: propel itself with thrusters to the repair site; insert itself into the structure where it is needed (such as between the upper and lower sections of the thermal belts ; attach itself to a structure, carry tools and spare parts; carry a variety of sensors; navigate; diagnose and repair faults; and communicate with its human supervisors.

A preliminary sketch of such a device is shown in Fig. 9.1. The FHT consists of a central container holding the onboard computer, propellant tanks, batteries, thrusters, control circuitry, and communications equipment. Attached to this container are communications antennas, tool and end effector racks, spares racks, anchor arms, sensor systems and light sources, and repair manipulators. The FHT's are dispatched from support racks which refuel and recharge the units.

The FHT can move around the factory in three fashions. First, it can use its thrusters to move across open space to a general location; once there, the FHT grabs onto the structure. Second, it can "walk" through the structure, using its guide arms and manipulators. Third, it can attach itself to a crawler; the crawler then takes the FHT to (or near) its destination. The choice of locomotion depends on the cost of fuel, the urgency of the repair, and the availability of the crawlers.

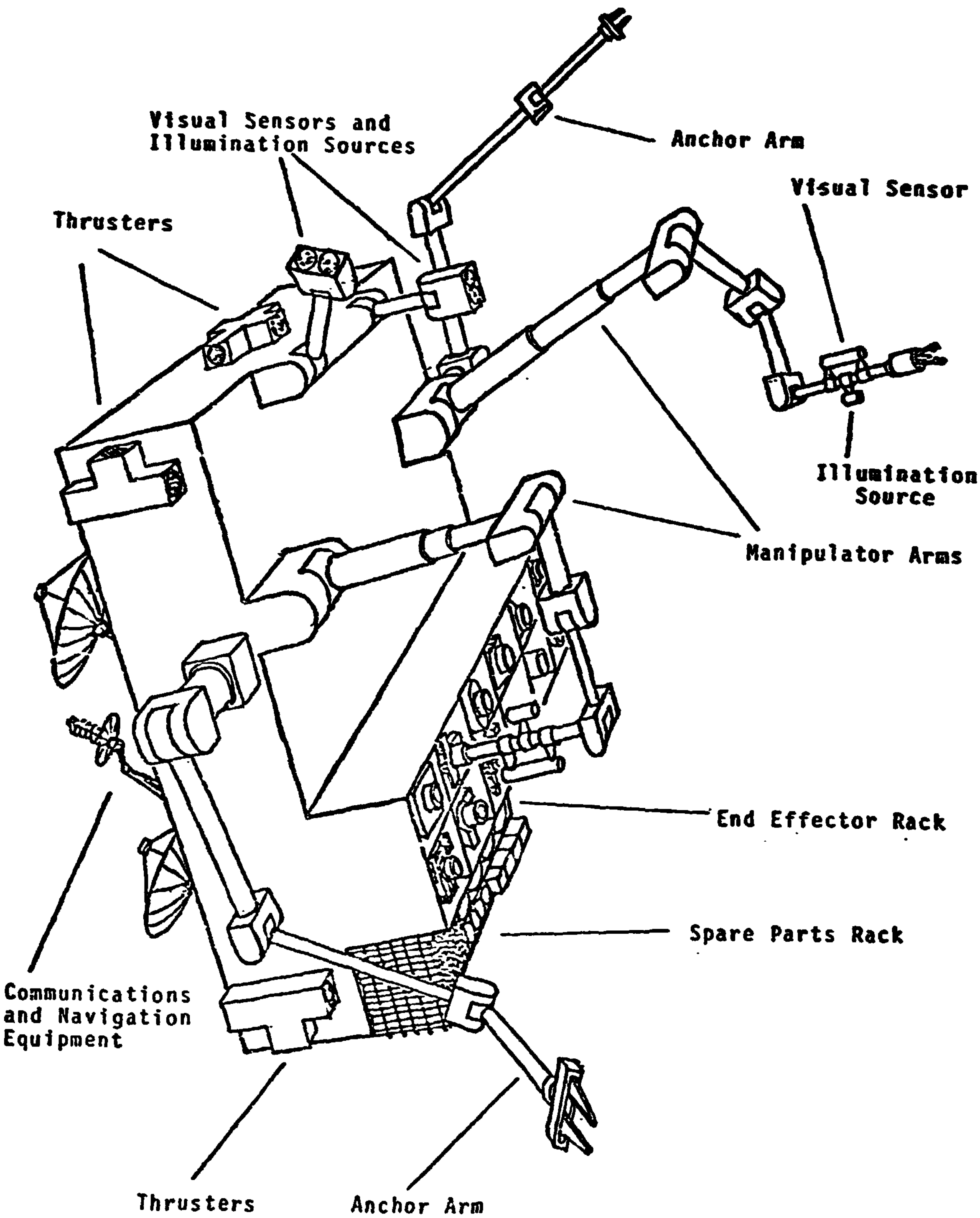


FIGURE 9.1: FREE-FLYING HYBRID TELEOPERATOR

For navigation, the FHT relies on a set of transponder beacons in specified locations around the factory, and a "map" of the factory in its onboard computer. It locates itself on its map by directional fixes on the beacons. For close-quarters navigation (for example, within the factory structure) the FHT uses some form of electromagnetic vision (e.g. light and camera, radar). At this time, state-of-the-art vision systems can determine the orientation of a two-dimensional structure (such as the integrated circuit pattern on a silicon chip). Increasing this capability to three-dimensional navigation inside a structure would require advancing that level of technology. Current experimental systems which perform three-dimensional pattern recognition require large computer capacity and long computation time to update the internal map of their immediate surroundings as they travel (Ref. 9.1). This would make such devices much slower in their movements than human beings. However, the computer capacity is expected to be available by 1990. Also, the computation time can be reduced by two factors. First, the use of transponder beacons can be made more accurate and damage tolera by using many beacons, so that the FHT is always near several, and by giving the FHT the ability to selectively ignore defective or displaced beacons. Second, the FHT's computer can hold in memory detailed blueprints of all the locations in the factory. The ability to use comparison techniques in pattern recognition, rather than a continuously updated map of the surroundings, can reduce the necessary computations. Even with these simplifications, however, the current ability of computers to deal with location in three-dimensional space is insufficient to the FHT's needs.

Thus the FHT could use several navigation systems, depending on its mode of travel. When it is travelling long distances, such as "above" and across the factory, it uses the beacon network. To latch onto and walk through the structure, the FHT uses vision and pattern recognition by comparison of its actual surroundings with its stored factory blueprints. When the FHT reaches the area to be repaired, where components can be distorted or broken (and therefore no longer match the blueprints), the FHT switches to the continuous updating of an internal map of the surroundings. Any of these modes of navigation could also be performed by human remote control, and in fact the continuous-update mode of navigation may be done faster and more accurately by a human operator.

Current computer vision systems can benefit greatly from control over the angle of illumination of their surroundings, because variations in lighting angles change the perceived view of the surroundings, and thus require more sophisticated pattern recognition software (Ref. 9.1). Since the SMF is shadowed by its solar array, the solar illumination will not be a problem. The SMF could be illuminated by fixed sources throughout the structure, but these sources would be seldom used. The preferred system is to mount the illumination sources on the FHT, so that the sensors perceive their surroundings illuminated "straight on". It should be noted that these illumination sources need not be human-visual-range lights, but could use any kind of electromagnetic radiation. Even when the FHT is under human remote control, the visual display provided to the operator would be computer-generated on a screen; such a system can operate from any sensor input (e.g. radar).

The FHT relies on a variety of sensory feedback mechanisms to acquire a complete picture of its environment. These include force, torque, moment, proximity, touch, and visual sensors.

Force and torque sensors were developed with early adaptive control systems (Ref. 9.3). These sensors were found to be inadequate for all but the most basic assembly operations that used adaptive control, because they relied on tolerances greater than most factory machining tolerances. These systems could not adapt to slightly off-design parts and small assembly misalignment problems.

Moment sensors and compliant wrists were developed during peg-in-hole investigations (Ref. 9.4), and have proved to be highly effective. Touch sensors provide pressure, contour, and force information associated with manipulator end effectors. They are usually smaller and more sensitive than the force sensors, but still require futher development.

Proximity sensors are non-contact, optical sensors that detect the presence or absence of an object within a specified range of the sensor surface. Proximity sensors have been found extremely useful in controlling large-scale movements of manipulator arms, and specifically is stopping the arm's movement before contacting and possibly damaging the manipulator. In this respect they are superior to mechanical limit switches, They can also be used for detecting object contours and so can be used as an aid in positioning the manipulator hand in a certain orientation with respect to an object, such as above the highest point.

Visual sensors are the most sophisticated and have the most versatility of all the FHT sensors. Visual input is used as a basis for all repair operations. The FHT requires visual analysis to:

1) provide the human operator with a view of the operating environment
2) determine its location and attitude within the factory
3) determine what movements and manipulator motions are required to reach a given location
4) compare its surroundings with blueprints on file in the SCF computer in order to determine what, if any, repairs should be undertaken
5) correct the motions of manipulator arms to avoid collision or contact with obstructions
6) update its internal map of the SCF, in case of damage or other discrepancies in its environment

Current visual analysis technology is either inexact or requires large amounts of computing power (Ref. 9.5). Many early vision systems could recognize and manipulate simple geometric objects by analyzing their edges and corners. The difficulty of finding mathematical solutions made the analysis of more complex objects prohibitive; however, research has shown that some prior knowledge of the object and its surroundings greatly aids analysis. For example, information about an object can be extracted from the shadows it casts on walls, floors and other objects. The shading on an object also gives information about surface properties. Interestingly, relative depths can be determined more easily by analyzing the shading on round or curved objects than by using a range finding device or stereoscopic vision. The repair procedure can benefit from having several views of the operation from different angles. Therefore some sensors and illumination sources should be mounted either on the manipulator arms or on separate arms of their own. The development of low-mass sensors (such as the current solid-state cameras) can alleviate moment-of-inertia problems in such arms. In addition, the system should have sensors and illumination sources mounted on the body of the FHT itself, to provide an overall, "fixed" view of the situation.

Machine systems are now able to assemble relatively complex items (for example, automotive distributors) both from drawings (Ref. 9.6) or from video images (Ref. 9.7). This type of assembly requires detailed programs, tailored to specific assembly operations. The use of generalized descriptions of assembly operations would be desirable to direct assembly/disassembly work; however, this is not presently possible. The operation must be highly defined because the machine has trouble with many small details, e.g. where to put a bolt after removing it.

The study group has identified five useful command modes for the FHT. It is the mixture of human and automated control in these modes which gives the teleoperator its "hybrid" quality. These modes are: remote manual, automated robot, single step, remote override, and task learning.

In remote manual (RM) mode, a human operator has direct control of the FHT. The operator must respond personally to all sensory feedback (e.g. proximity, force, torque, video, etc). However, the commands from the operator are relayed through the FHT computer, which verifies that these commands will not put unacceptable stresses on the FHT components. Because of the difficulty in handling the manipulator arm's numerous degrees of freedom, this mode is not as rapid as the automated robot or single step modes for programmed motions. However, because the sensory analysis and motion commands are handled by a human being, this mode is expected to be the fastest in dealing with unexpected situations.

In the automated robot (AR) mode, the FHT is entirely on internal computer control. The FHT computer analyses the sensory input and updates the situation status in its memory (including a three-dimensional map of its surroundings). The FHT navigates, inspects, diagnoses, and repairs by using either preprogrammed routines, or by assessing the situation and deciding on a course of action. The AR mode bases its operation on the FHT's ability to do a certain amount of independent and abstract thinking. In this completely automated mode of operation, the FHT can deal with unexpected or uncertain circumstances without the benefit of a human supervisor. When performing repair operations, it must also be able to make many minor judgements, such as what to do with its manipulator arms, when to move from one repair step to the next, or where to put a piece after it has been removed from the device being repaired.

The FHT will be required to perform a wide variety of repair operations on many different components, where the operations have many tasks in common, e.g. bolting, cutting, welding. The physical layouts and repair sequences for these components, though, are quite different. Most assembly programs involve motion-by-motion types of commands expressed in fractions of millimeters that are tailored to the individual machines. Writing these programs involves much engineering design time and expertise and is practical when an operation must be repeated thousands of times. This is not the case with the FHT, where a given repair operation might only be used two or three times. The FHT must therefore be able to take an abstract definition of a repair task, a definition that has no dimensions, forces, etc., interpret the situation, and then execute the task. When the FHT has interpreted a task, it stores the resulting program with the learned tasks, so that if the same "repair sequence" is encountered again, the FHT computer will not have to repeat the interpretation process, but can immediately execute the repairs.

"Repair sequences" are sequences of defined repair tasks, written in a manner similar to automotive repair manuals. The FHT computer reads the sequence of operations and then plans a strategy for implementing them. Blueprints of the SCF and all of its components are used by the computer in relating the commands in the "repair sequence" to the FHT's visual input. These blueprints are also part of the FHT's internal map of the SCF. As mentioned above, the repair sequence process involves many independent decisions. Systems of this complexity do not currently exist.

Because this mode requires that the FHT be able to respond to uncertain conditions, it qualifies as a 'robotic' operations mode. The AR mode requires considerable computer capability, which may be difficult to include entirely onboard the FHT. If this is the case, the FHT can relay its sensory inputs and preliminary evaluations to a larger, more sophisticated computer, via its telemetry links. The issue of how much onboard capability is desirable is difficult to answer at this time, because it requires estimates of computer and telemetry capabilities ten years from now, and because it depends on the relative costs of individual computers in the FHT's versus fewer large, time-shared computers. More generally, there is a level of uncertainty beyond which assessing the situation by computer becomes prohibitively expensive, and it becomes cheaper to request human assistance. Thus the AR mode is valuable up to a certain level of complexity; what that level will be in 1990 is difficult to predict.

In the single step ( ) mode, the FHT performs pre-programmed instructions (stored in its memory) one at a time. The commands to execute the individual instructions are given by a human operator. This allows the human operator to do the situation updates and command decisions, which is faster than computer updates and decisions. And the use of preprogrammed instructions maximizes the speed of the individual operations and frees the operator to do other tasks while the FHT performs a task. One operator could even control several FHT's, feeding commands to each in turn.

The remote overrride (RO) mode is analogous to the automated robot mode, but includes the option of an interrupt order from a human operator. Thus the FHT can perform a series of tasks automatically, under the passive supervision of a human operator; when the FHT encounters an unexpected problem, or when a change in the operations sequence is desired, the human can override the FHT 's onboard control and manually take over the teleoperator. Both this mode and the single step can be used to check the validity of the FHT's onboard programming, by watching the results of the automated sequences.

In the *task learning* (TL) mode, the functions of the FHT are controlled by the human operator, but the sequence of operations is stored into the memory of the FHT, for later repetition. Thus the human operator teaches the FHT one or more operations, by "walking" the teleoperator through the required task(s). The usefulness of this mode can be considerably increased if the sequence being taught can be optimized either by the FHT's on-board computer or by a larger computer, via a telemetry link. Such optimization could include eliminating wasted motions, maximizing the speed and accuracy of motions, and choosing fuel and electricity-efficient methods of operation. In any case, the TL mode includes provisions for editing and modification of the new sequence by the human operator.

In those modes involving a human operator, a number of direct command hardware options are possible First, the operator can type in coded instructions, much as a computer is controlled today. Second, certain often-used sequences could be hardwired, and commanded by pushing buttons. Third, the video display could be on an electronic board, and a light pen could be used to indicate locations. For example, the operator could push the "travel to" button and indicate a spot on the visual display from the FHT's sensors; or the operator could request a listing of function codes on the display, and point the light pen at the desired operation. Fourth, commands to the FHT could be given by voice; the FHT computer could answer by voice also. In this case, it is recommended that the computer repeat a given command back to the operator (either by video or audio) to verify that the command is properly understood. Talking computers and voice actuated devices exist today; such a system would require increase in the voice-actuation vocabulary, better discrimination of voices and words by the computer, and the development of conversational logic software so that the computer can request clarification of commands. Fifth, the human operator can use one or more joysticks to 'fly'the FHT. These joysticks could control travel under thrust, or (with sophisticated computer interpretation) could control the FHT's walk through the factory structure. Sixth, the manipulators can be controlled by master arms handled by the operator. These could include force and torque feedback, and even tactile sense. One drawback to conventional master-slave manipulator systems is that during operation the operator's hands are not available to operate other functions. An integrated control system, using hands, feet, eyes, and voice, could be developed to give the human operator a high degree of control over the FHT.

CHAPTER 10

LINE ITEM COSTING

While the preceeding chapters have dealt with the engineering aspects of the concept of extraterrestrial material utilization, it is important to also begin to quantify the economic impact of such a project. Using the baseline case of manufacturing one solar power satellite per year, this chapter deals with the cost estimation of the point design SMF.

The necessary products for the manufacture of an SPS are listed in detail in Chap. 3. The machines required for the production of these components are detailed in Chap.7. Each machine is broken down further into its major subsystems, or components. The SMF can therefore be analyzed on three levels: system-wide costs (such as cargo transport costs), machine costs (for example, operating expendables procurement), and component costs (such as initial transportation). By applying the costing procedure selectively on all three levels, cost estimations can be ma more accurately with minimum increase in complexity.

The system-wide, or global, parameters are listed in Table 10.1. It is assumed in ths study that all of these parameters are constant throughout the system, neglecting such factors as different wage scales between job classifications. The pay scale is assumed to be $100,000 per person year. Since it is desirable to keep the SMF operating on an around-the-clock

TABLE 10.1: SMF GLOBAL PARAMETERS

W	Labor wage	\$/person-hr
T_c	Cargo transport cost	\$/kg
T_p	Personnel transport cost	\$/kg
F	Emergency repair fraction	---
U	Crew training cost	\$/person
M_c	Crew mass	kg/person
R	Rotation rate	times/year
L	Terrestrial life support usage	kg/crew-day
M_s	SMF structure mass	kg
P_s	SMF structure power	kW
C_s	SMF structure cost	\$/kg
E_s	SMF structure expendables	kg/yr
G	Powerplant cost	\$/kW
α	Specific power density	kg/kW
K	Number of production machine types	---
H	SMF production period	hrs/yr
S	Support overhead factor	---
A	Assembly productivity	kg/crew-hr
r	Yearly discount rate	---
Y	Program lifetime	yrs
M_H	Habitat mass	kg/person
P_H	Habitat power	kW/person
C_H	Habitat procurement cost	\$/kg
D_H	Habitat R & D cost	\$M

basis, three shifts are necessary. This gives a working week of 55 hours/person (for example, 8 hours/day, 7 days a week). The wage, W, is therefore $34.34 per hour.

The transportation costs are split between cargo and personnel, since cargo will be carried in low-thrust, long trip time orbit-to-orbit vehicles, while crews must necessarily be transported in faster, high-thrust chemical-powered spacecraft. In addition, some high-demand materials (such as perishable foodstuffs or repair parts not in the SMF inventory) must also travel on the crew transports, at a cost penalty. The values of T_c and T_p are a function of SMF location and vehicle details, and the complete analysis of these values are therefore outside the scope of this study. These costs are estimated from Ref. 10.1. Initial estimates, based on 10% of the SPS being of earth origin, indicate a yearly mass launched from earth to the SMF on the order of 15,000 Mg. This yields earth launch costs of $100/kg for cargo, and $200/kg for personnel. Cargo is assumed to be transported in space by tugs employing electromagnetic propulsion and lunar-derived propellants, and therefore incurs no further significant transport costs. However, personnel must be transported in high-thrust, chemically propelled vehicles, in order to keep trip times down to a reasonable level. It is assumed that this transporter will use an oxygen/hydrogen engine (I_{sp} = 470 sec), with only hydrogen brought from earth. The SMF is assumed to be in an orbit with a velocity interval from low earth orbit equivalent to geostationary, which gives a Δv = 4400 m/sec. The personnel transport makes a round trip, with crew carried each way, so the total Δv = 8800 m/sec. The mass ratio (kg of inert mass per kg vehicle gross mass) for the interorbital personnel shuttle is therefore

$$r = \exp\left[-\frac{8800 \text{ m/s}}{(9.8 \text{ m/s}^2)(470 \text{ s})}\right] = .148 \tag{1}$$

Assuming a vehicle inert mass fraction of .1, the propellant per payload ratio for this vehicle is 17.75. However, with a typical O_2/H_2 mass mixture ratio of 6, only 1/7 of the propellants mass needs to be brought from earth. This means that 2.5 kg of hydrogen is necessary for each kg of personnel carried. The total personnel transport costs are therefore increased by the cargo costs of the hydrogen to $450/kg.

As mentioned earlier, some repair parts will be needed in order to maintain production, but will not be in stock in the SMF warehouse. Rather than shutting down a critical machine until a cargo transport arrives, which could be a matter of weeks due to the nature of low-thrust trajectories, it will be necessary to ship these critical repair parts on personnel transports, thus increasing their costs. This emergency repair fraction, F, is taken to be .1.

A typical crew training cost, U, is on the order of \$100,000/person, and that number was assumed in this study. Crew transport mass (including some personal effects) is estimated to be 100 kg/person, and the total crew assumed to be cycled back to earth every 90 days, or R = 4 rotations per year. This rotation rate is based on allowable physical degradation in the zero-g environment of the SMF (Ref. 10.2), as well as allowable radiation limits in free space in an unshielded habitat (Ref. 10.3). Life support consumables are taken as L = .83 kg/person/day, based on lunar oxygen and terrestrial nitrogen atmosphere, shipping only hydrogen to be mixed with lunar oxygen to make water, and freeze-dried food (Ref. 10.4).

The structure of the SMF is characterized by its mass (kg), power (kW), procurement cost (\$/kg), and use of expendables from earth (kg/yr). These estimates were de[illegible] from the SMF layouts in the preceeding chapters. These values were taken to be M_s = 2000 Mg, P_s = 1000 kW, C_s = \$25/kg, and E_s = 0 kg/yr, for this case, respectively.

Space power represents an interesting change from the normal earth design environment. Energy intensive activities on earth are generally characterized by high recurring costs, due mainly to the use of fuels in energy production. In space, however, photovoltaics give rise to large initial costs, with no appreciable recurring costs thereafter. Power therefore shows up as a nonrecurring, rather than recurring, cost. The elements of this cost are the procurement price of the generating capacity (G, \$/kW), and the specific power density (α, kg/kW), which relates to transport costs. From current estimates of future space-rated solar cells (but not in SPS-sized quantities), these values might be expected to be \$2000/kW and 10 kg/kW (Ref. 10.2). Since the (cargo) transport rate is \$100/kg, the total power cost for the SMF is \$2000 + \$100 x 10, or \$3000/kW.

K is the number of different types of machines in the SMF: in the point design, 60. H is the number of scheduled operating hours per year, or 8766. The support overhead factor is the total on-site ratio of worker/production workers, and estimated from typical manufacturing projects to be about 2 or 100% overhead. The SMF is initially assembled from prefabricated components; the productivity of the assembly workers, A, is estimated based on MIT Space Systems Lab experience in neutral buoyancy simulations of EVA assembly as 300 kg/crew-hr (Ref. 10.5). Discount rate, r, is taken as its standard value of .1 (10% yearly), and the program lifetime Y was set as per the statement of work to 20 years.

With the specification of these global parameters, the accounting system must proceed into the machine level of costing. Each machine type has five parameters of interest: operating labor, earth expendables usage and cost, number of machines of this type, and number of different types of components. Seven parameters are likewise required to specify the costs of a component: the number of units of that type, the mass and power of an individual unit, duty cycle, yearly repair parts, and codes relating the technology level and repair technique for the component. These variables are summarized in Table 10.2 for machine parameters, and Table 10.3 for component parameters.

TABLE 10.2: SMF MACHINE PARAMETERS

l_j	operating labor requirement	crew hr/op hr
e_j	earth expendables	kg/hr
x_j	procurement of earth expendables	$/kg
n_j	number of units	---
k_j	number of component types	---
b_j	process R & D cost	$

TABLE 10.3: SMF COMPONENT PARAMETERS

n_{ij}	number of units	---
m_{ij}	mass of individual unit	kg
p_{ij}	power requirement	kW
c_{ij}	procurement cost	$
d_{ij}	duty cycle	---
l_{ij}	repair labor	crew hr/nonop hr
r_{ij}	replacement parts	kg/yr
b_{ij}	R & D cost	$

Perhaps the greatest problem in cost estimation is the estimation of research and development and procurement costs.

The study group attempted to categorize all of these costs as closely as possible, by calling manufacturers of similar devices wherever possible, and extrapolating present technology to the 1990 technology cutoff date. The cost data thus arrived at was felt to be fairly accurate, but many of the components offered no adequate earth analogue for this technique to be applicable. The estimates for these component types was based, in typical aerospace fashion, on the technology level and component mass. However, it was felt that one single costing rationale should be applied equally throughout. Since the technology/mass approach proved more conservative, that approach was the one chosen.

Each component was specified as being either low, medium, high, or ultra-high technology level. For example, passive structure would be low technology, electric motors medium, electron beam guns high, and autonomous computer systems ultra-high. Table 10.4 shows the assumptions used for estimating research and development and procurement costs for each of these levels, in terms of \$/kg.

TABLE 10.4: COSTING BASELINE

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

The other factor which was difficult to quantify was component and machine reliability. Again, consultations with manufacturers and users of earth analogues provided much of the data used. Since this seemed to be a critical item, however, the costing program developed was designed to let the component duty cycles be the independent variable in a variation of parameters study.

Machine duty cycles were calculated on a probabilistic basis from the duty cycles of its components. The probability that component i in machine j will fail is

$$P\langle comp_{ij}\ fail\rangle = \prod_{k=1}^{n_{ij}} (1-d_{ij}) = (1-d_{ij})^{n_{ij}} \tag{2}$$

Using this expression, the probability that the machine will be operating is the product of the probabilities that its component parts will be operating, or

$$d_j = P\langle mach_j\ op\rangle = \prod_{i=1}^{k_j} \left[1-(1-d_{ij})^{n_{ij}}\right] \tag{3}$$

This expression assumes that a single failure of any component will disable the entire machine. It was assumed that in the instance of multiple units of a single component type, the system would be doubly redundant: that is, the failure of two units of a single component would not affect the machine, but three failures would disable it. As implemented in the computer algorithm, therefore, n_{ij} in equation (3) was either 3 or the number of units of the component type, whichever was least.

The above analysis assumes the machines are individual units, and that the failure of one does not affect the production of the upstream or downstream units. The design of the baseline SMF, particularly in the components factory, was based on this approach, and parts transport systems were designed to enable cross-feeding of products between upstream and downstream machines. However, this is not true in the solar cell factory, since the vapor deposition processes depend on successive depositions on a continuously moving strip. If one of the direct vaporization machines fails, for example, there is no way for the upstream products (correctly deposited) to bypass the nonoperating machine on its own strip. Rather than run through nonfunctional solar cells, the entire strip, and all machinery on it, would be shut down until the malfunctioning machine is repaired. There is a series of 14 machines which are critical to strip production, and the number of strips is sized by the product of the duty cycles of these machines.

The question of machine reliability brings up the associated problem of machine repair. This impacts on the costing in two ways: costs associated with repair devices, and labor costs for human intervention in the repair process. Table 10.5 lists the five levels of repair available in the SMF.

TABLE 10.5: REPAIR OPTIONS

1.	Teleoperator repair on-site
2.	Crawler replacement with automated repair
3.	Crawler replacement of expendable parts
4.	Crawler replacement with human repair
5.	Human repair on-site

The first four apply only to the solar cell factory, and the fifth (direct human repair) is use[illegible]hout the rest of the SMF. This dichotomy is due to t[illegible]osition process used throughout the solar cell factory. [illegible]arge number of electron beam guns are continually operating in this area, and the region is too hot (both thermally and in terms of radiation) for a human to approach. For this reason, either teleoperators (repair option 1) or crawlers are used to make repairs to the operating machinery. The decision breakdown between the options is a function of the individual component. Each component of each machine design was assumed to be a possible failure. If the component was small enough to be unplugged and replaced as a module, it was assumed that the crawler would be used for this task. The failed component module would then [illegible] either repaired by an automatic repair device (option 2), thrown out (option 3), or repaired by a human being (option 4). On the other hand, if the component was too large or entrenched to be replaced by the crawler, the free-flying hybrid teleoperator (option 1) would be used to repair it on-site. Different levels of human supervision would be required for each of these options; the values of these levels (in terms of crew hr/repair hr) was left as a program variable.

As mentioned previously, the entire factory (except for the solar cell production area) was assumed to be directly repaired by humans. This was due to the different levels of production in the different sections. The large solar cell production, several orders of magnitude beyond current total yearly production, requires a large number of strips and machines, and therefore lends itself to automated repair. The components factory, on the other hand, has an output flow several orders of magnitude below that of a comparable plant on earth; automatic repair is probably not cost effective when there are only a few samples of each machine type. Although some studies indicate that the teleoperator has excess capability which might prove useful in the components factory, it was assumed that it would remain within the solar cell factory as a dedicated unit.

The entire question of automated repair, teleoperator and crawler capabilities, and machine interdependence within the solar cell factory led to the creation of a specialized program, SCFCOST, detailed in the Appendix. This program allows a more detailed analysis of the interactions of reliability and repair in the solar cell factory, at the price of increased complexity in program operation. Many of the capabilities of this program go beyond the scope of this study; its use in this report was limited to analysis of necessary characteristics of the teleoperator, crawlers, and automated repair equipment.

Ten direct costs can be applied to each machine, calculated from the quantities already specified. The costs are listed in Table 10.6; the expressions for each are listed in Table 10.7. The derivation of each is obvious from the definitions of the variables in Tables 10.1 - 10.3, and will not be further explained here.

TABLE 10.6: MACHINE COST COMPONENTS

Non-recurring:	
C_1	Research and Development
C_2	Procurement
C_3	Transportation
C_4	Power
Recurring:	
C_5	Operating labor
C_6	Expendables procurement
C_7	Expendables transportation
C_8	Repair labor
C_9	Repair parts procurement
C_{10}	Repair parts transportation.

TABLE 10.7

MACHINE DIRECT COST EQUATIONS

$$C_{1_j} = \sum_{i=1}^{k_j} b_{ij}$$

$$C_{2_j} = n_j \sum_{i=1}^{k_j} C_{ij}\, n_{ij}$$

$$C_{3_j} = n_j T_c \sum_{i=1}^{k_j} m_{ij}\, n_{ij}$$

$$C_{4_j} = n_j d_j\, (G + \alpha T_c) \sum_{i=1}^{k_j} F_{ij}\, n_{ij}$$

$$C_{5_j} = \ell_j d_j n_j HW$$

$$C_{6_j} = x_j e_j d_j n_j H$$

$$C_{7_j} = e_j d_j n_j H T_c$$

$$C_{8_j} = n_j HW \sum_{i=1}^{k_j} (1-d_{ij})\ell_{ij} n_{ij}$$

$$C_{9_j} = n_j \sum_{i=1}^{k_j} r_{ij} \frac{C_{ij}}{m_{ij}} n_{ij}$$

$$C_{10_j} = n_j T \sum_{i=1}^{k_j} r_{ij} n_{ij}$$

It should be noted, however, that the power cost (C_4) is multiplied by the duty cycle of the machine. This is due to the fact that a nonoperating machine does not consume any power. Therefore, although the number of a machine type might have to increase if the duty cycle decreases, in order to maintain a current level of production, the power demand does not increase, as it is tied to output, and not total number of machines. The details of the line item costing program, SMFCOST, are in the Appendix.

After the direct costs for each machine are found, the program finds the subtotals and totals for mass, power, and labor. The indirect costs are then calculated. The indirect nonrecurring costs consist of structure procurement, transportation, and power costs; SMF assembly costs; and habitat R & D, procurement, transportation, and power costs. The indirect recurring costs include SMF structure expendables costs, wages of the support crew, and training, transport, and consumables costs for the entire crew. The actual equations used in calculating these quantities are quite straight-forward, and can be found in the program listing in the Appendix.

The line item costing computer program produces a detailed listing of inputs, and accounting of costs. The nonrecurring costs, broken down into cost element and listed on a machine by machine basis, are presented in Table 10.8. The recurring costs, on the same basis, are detailed in Table 10.9. The summary table for the baseline case is shown in Table 10.10.

TABLE 10.8: NONRECURRING COSTS

	$$$$$$$$ R & L	NONRECURRING COSTS PROCUREMENT	$$$$$$$$ TRANSPORT	POWER	TOTALS
THERMAL BELT	39250000.	403567616.	140979984.	29431488.	572285440.
DV OF AL REAR CONTACT	11853224.	40663088.	4325689.	4589564.	58048944.
DV OF SI AND P-DOPANT	29413312.	483501568.	68170816.	133704560.	673310976.
PULSE RECRYSTALLIZATION	100680192.	11522491.	1172526.	2660035.	115080704.
SCAN RECRYSTALLIZATION	100380192.	6311843.	640527.	886923.	107696720.
N-DOPANT IMPLANTATION	10500000.	12350027.	1329999.	2582997.	25734432.
ANNEAL	10380199.	6311843.	640527.	590546.	17400368.
DV OF AL FRONT CONTACT	22813216.	333457408.	36475872.	7703553.	372635648.
FRONT CONTACT SINTERING	10380199.	6311843.	640527.	295641.	17105456.
CELL CROSSCUT	10405000.	5577291.	507860.	1839468.	17946064.
CELL INTERCONNECTION	20745488.	10007[illegible]9.	1606638.	2278658.	34505216.
DV SIO2 OPTICAL COVER	132740816.	845030912.	185912672.	169908160.	1256077820.
DV OF SIO2 SUBSTRATE	33740816.	599330304.	127089696.	114727056.	820269824.
PANEL ALIGN & INSERT	21820496.	34692384.	7756555.	10532290.	71610080.
PANEL INTERCONNECTION	10770500.	11150460.	1739638.	5218864.	27910272.
LONGITUDINAL CUT	10405000.	5577291.	507860.	1839468.	17946064.
KAPTON TAPE APPLICATION	20041088.	131546.	40658.	627288.	20827616.
ARRAY SEG. FOLD & PACK	10187750.	375424.	84455.	280417.	10928045.
TELEOPERATOR	187000000.	17400000.	270000.	106920.	204776912.
CRAWLER SYSTEM	127750000.	130083104.	24516000.	5024764.	288373760.
ZONE REFINER	134967488.	83398736.	13220331.	53793072.	285379584.
MASK CLEANUP DEVICE	100294992.	996196.	177500.	1081916.	102550576.
DV OF INTERCONNECTS	22125504.	12876095.	1377199.	5357177.	41735936.
LIQUID AL PIPELINE	20067488.	229000.	45800.	840.	20343104.
IRON PIPELINE	20107488.	37250.	7450.	6.	20152176.
AL ALLOYING FURNACE	58400000.	2520000.	364500.	9235394.	70519888.
IRON ALLOYING FURNACE	58400000.	840000.	121500.	3078464.	62439952.
CONTINUOUS CASTER	23054992.	614000.	178000.	446925.	24293904.
AL SLAB CUTTER	11000000.	200000.	10000.	296911.	11506911.
AL DIE CASTER	105250000.	17524992.	3550000.	676268.	127001248.

TABLE 10.8 (Continued)

$$$$$$$$ NONRECURRING COSTS (CONT.) $$$$$$$$

	R & D	PROCUREMENT	TRANSPORT	POWER	TOTALS
PE DIE CASTER	35524992.	1552500.	315000.	66951.	37459424.
TRANSFORMER CORE CASTER	75250000.	5525000.	1150000.	323433.	82248416.
ROLLING MILL	158050000.	14805000.	18720000.	991824.	192566800.
END TRIM/WELD/ROLL WIND	13410000.	27454160.	168124800.	395422.	209384368.
SHEET TRIMMER	10460000.	78000.	8400.	122022.	10668422.
RIBBON SLICER	45400992.	3545896.	7028000.	645248.	56620128.
RIBBON TRIMMER	10300000.	30000.	3000.	11935.	10344934.
STRIATOR	20000000.	1000000.	2000000.	148500.	23148496.
FORM ROLLER	21830000.	183000.	33900.	100863.	22147728.
KLYSTRON RAD. ASSEMBLY	20480000.	2884840.	445200.	1942292.	25752320.
DC-DC CONV. PRODUCER	30000000.	2000000.	400000.	7351.	32407344.
INSULATION WINDER	12500000.	2000000.	400000.	45600.	14945600.
GLASS FIBER PRODUCER	13222750.	20958736.	1634000.	1580516.	37396784.
DC CONV. RAD. ASSEMBLY	21734992.	372500.	56500.	148485.	22312464.
KLYSTRON PLANT	1624999940.	152500000.	30500000.	95999968.	1903999490.
GLASS FOAMING FACILITY	534249472.	113974992.	22794992.	20485968.	691504896.
FOAMED GLASS CUTTER	38684992.	2863500.	589000.	64840.	42207312.
SHEET CUTTER & SLOTTER	100184992.	224036992.	11238000.	858566.	336318208.
FOAMED GLASS SMOOTHER	101250000.	48374992.	2475000.	231637.	152331616.
WAVEGUIDE DV CP AL	13940125.	2910149.	280800.	792963.	17924016.
WAVEGUIDE PACKAGER	13005000.	1362498.	2595000.	88209.	17050704.
WAVEGUIDE ASSEMBLER	100674992.	386579712.	19428000.	1853276.	508535552.
PERSONNEL DOCKING MECH.	15000000.	2000000.	400000.	11880.	17411872.
PRESSURIZED TUNNEL	60000000.	30000000.	6000000.	15444.	96015440.
CARGO DOCKING MECH.	31000000.	3400000.	440000.	2398.	34842384.
LOAD-UNLOAD MANIPULATOR	190000000.	56000000.	2800000.	124146.	248924144.
MAGNETIC TRANSPORTER	50210000.	6187676.	3406000.	0.	59803664.
TRANSPORTER TRACK	77150000.	18023248.	16640000.	67716.	111880960.
INTERNAL STORAGE DEVICE	11900000.	2360000.	472000.	47045.	14779044.
REPAIR AUTOMATONS	120000000.	84000000.	840000.	504000.	205343984.
TOTALS	5045313540.	4300349440.	944832512.	697467904.	10732580900.

TABLE 10.9: RECURRING COSTS

$$$$$$$$ RECURRING COSTS $$$$$$$$

	OPERATING LABOR	EXPENDABLES PROCUREMENT	EXPENDABLES TRANSPORT	LABOR	REPAIR PROCUREMENT	TRANSPORT	TOTALS
THERMAL BELT	0.	232476.	1162379.	100101.	20178368.	951[illegible]148.	28844400.
DV OF AL REAR CONTACT	0.	116354.	1163541.	55416.	2033155.	291984.	[illegible]
DV OF SI A C P-DOPANT	0.	116471.	1164709.	591557.	24175068.	4601531.	[illegible]
PULSE RECRYSTALLIZATION	0.	116471.	1164707.	[illegible]	576124.	79145.	[illegible]
SCAN RECRYSTALLIZATION	0.	116471.	1164707.	32032.	315592.	43236.	[illegible]
N-DOPANT IMPLANTATION	0.	466353.	233175.	16016.	617501.	89775.	1315839.
ANNEAL	0.	116471.	1164707.	32032.	315592.	43236.	1546319.
DV OF AL FRONT CONTACT	0.	1164707.	11647082.	151113.	16672924.	2462121.	29084560.
FRONT CONTACT SINTERING	0.	116471.	1164707.	32032.	315592.	43236.	1546319.
CELL CROSSCUT	0.	290595.	1162379.	48045.	278864.	39680.	1682757.
CELL INTERCONNECTION	0.	34837.	232244.	172174.	540394.	108448.	1006285.
DV SIO2 OPTICAL COVER	0.	231780.	2317796.	835164.	42251552.	12549110.	53810560.
DV OF SIO2 SUBSTRATE	0.	231780.	2317796.	503549.	25966560.	8570563.	38544560.
PANEL ALIGN & INSERT	0.	34906.	232709.	1205217.	1734618.	523568.	3450492.
PANEL INTERCONNECTION	0.	34837.	232244.	172174.	557523.	117425.	1030[illegible].
LONGITUDINAL CUT	0.	290595.	1162379.	48049.	278064.	39680.	1682757.
KAPTON TAPE APPLICATION	0.	34970.	233171.	89210.	6577.	2744.	339109.
ARRAY SEG. FOLD & PACK	0.	34976.	233176.	95036.	18771.	5701.	387720.
TELEOPERATOR	0.	0.	0.	66225.	1739999.	36450.	1842673.
CRAWLER SYSTEM	0.	1735.	8677.	1791093.	9099153.	2225474.	13126132.
ZONE REFINER	0.	104877.	524383.	651563.	553127.	100582.	1934530.
MASK CLEANUP DEVICE	0.	0.	0.	835351.	15352445.	1184624.	17372416.
DV OF INTERCONNECTS	0.	874.	4370.	37632.	6013995.	2959468.	9016338.
LIQUID AL PIPELINE	0.	0.	0.	373270.	103000.	27810.	504080.
IRON PIPELINE	0.	0.	0.	30102.	28250.	7627.	65980.
AL ALLOYING FURNACE	0.	0.	0.	108369.	915000.	64800.	1088168.
IRON ALLOYING FURNACE	0.	0.	0.	36123.	305000.	21600.	362723.
CONTINUOUS CASTER	0.	0.	0.	66225.	27900.	5670.	99795.
AL SLAB CUTTER	0.	0.	0.	18061.	15200.	1026.	34287.
AL DIE CASTER	73758.	0.	0.	61215.	875000.	236250.	124[illegible].

TABLE 10.9 (Continued)

$$$$$$$$ RECURRING COSTS (CONT.) $$$$$$$$

	OPERATING LABOR	EXPENDABLES PROCUREMENT	EXPENDABLES TRANSPORT	REPAIR LABOR	REPAIR PROCUREMENT	REPAIR TRANSPORT	TOTALS
RE DIE CASTER	73021.	0.	0.	9031.	0.	0.	82052.
TRANSFORMER CORE CAS.[illegible]	1180[illegible].	0.	0.	6020.	275000.	74250.	367072.
ROLLING MILL	0.	1414.	7069.	63215.	402750.	352350.	826797.
END TRIM/WELD/ROLL WIND	0.	0.	0.	36123.	519094.	4059821.	4615038.
SHEET TRIMMER	0.	0.	0.	24002.	7140.	786.	32008.
RIBBON SLICER	0.	0.	0.	322096.	54000.	136080.	512176.
RIBBON TRIMMER	0.	0.	0.	9031.	2880.	397.	12308.
STRIATOR	0.	0.	0.	3010.	50000.	135000.	188010.
FORM ROLLER	0.	0.	0.	12041.	77630.	20579.	110250.
KLYSTRON RAD. ASSEMBLY	0.	0.	0.	2739314.	276414.	48393.	3064121.
DC-DC CONV. PRODUCER	59007.	69419760.	69419760.	6020.	150000.	40500.	139095024.
INSULATION WINDER	0.	0.	0.	120410.	100000.	27000.	247410.
GLASS FIBER PRODUCER	0.	0.	0.	1597548.	936696.	110596.	2644840.
DC CONV. RAD. ASSEMBLY	0.	0.	0.	183625.	29475.	3179.	216279.
KLYSTRON PLANT	0.	87659952.	350639616.	60205.	7649997.	2065499.	448074752.
GLASS FOAMING FACILITY	270681.	133986.	13398550.	261891.	7309494.	1973564.	23348112.
FOAMED GLASS CUTTER	0.	0.	0.	12041.	0.	0.	12041.
SHEET CUTTER & SLOTTER	0.	0.	0.	96328.	4201498.	285120.	4582944.
FOAMED GLASS SMOOTHER	0.	0.	0.	27092.	910500.	63585.	1001177.
WAVEGUIDE DV CP AL	0.	0.	0.	54186.	1522199.	126441.	1702624.
WAVEGUIDE PACKAGER	0.	0.	0.	785755.	11592465.	86064512.	98442720.
WAVEGUIDE ASSEMBLER	0.	0.	0.	469598.	12024000.	816480.	13310076.
PERSONNEL DOCKING MECH.	0.	0.	0.	12041.	100000.	27000.	139041.
PRESSURIZED TUNNEL	0.	0.	0.	36123.	250000.	67500.	353623.
CARGO DOCKING MECH.	0.	0.	0.	24684.	80000.	5400.	110084.
LOAD-UNLOAD MANIPULATOR	1132453.	0.	0.	72246.	2800000.	184000.	4193[illegible]97.
MAGNETIC TRANSPORTER	0.	0.	0.	1526229.	305837.	229905.	20[illegible]70.
TRANSPORTER TRACK	0.	0.	0.	389566.	604163.	321300.	1315029.
INTERNAL STORAGE DEVICE	0.	0.	0.	240819.	118000.	31860.	390679.
REPAIR AUTOMATONS	0.	5891.	29454.	2528604.	0.	0.	2563948.
TOTALS	1620690.	161109984.	462185216.	20097152.	228210608.	143282448.	1000278020.

TABLE 10.10: SUMMARY OF BASELINE CASE

```
TOTAL DIRECT NON-RECURRING COST =$10732580900.
TOTAL DIRECT RECURRING COST =$ 1000278020.

TOTAL DIRECT PRODUCTION MASS (KG) =  9448325.
TOTAL DIRECT PRODUCTION POWER (KW) =    232489.
TOTAL DIRECT PRODUCTION CREW =   216. PEOPLE

TOTAL SMF CREW =    433.
CREW TRANSPORT MASS =  173151. KG, CONSUMABLE MASS =  131140. KG
CREW TRANSPORT COST=$  77918080. CONSUMABLES COST=  13114043.

CREW TRAINING COSTS =$  21643920.
SUPPORT CREW WAGES =$  65153504.
SUPPORT EXPENDABLES TRANSPORT COST =$        0.

HABITAT MASS (KG) =   1315950.
HABITAT POWER (KW) =      3896.
R&D AND PROCUREMENT COST OF HABITAT ($) =   508594688.
TRANSPORT COST OF HABITAT ($) =   131594992.
POWER COST OF HABITAT ($) =    11687717.
NONRECURRING COST OF NONPRODUCTION SMF =$ 50000000.

TOTAL SMF MASS (KG) = 15138126.
TOTAL SMF POWER (KW) =  237385.

SMF SUPPORT TRANSPORT COST =$201000000.
SMF SUPPORT POWER COST =$  2000000.

SETUP COSTS =$ 3086410. FOR    8. PEOPLE


         $$$$$$$$   DIRECT COSTS: NONRECURRING =$10732580900., RECURRING =$ 1000278020.

         $$$$$$$$  INDIRECT COSTS: NONRECURRING =$  907963392., RECURRING =$  177829536.


         $$$$$$$$  SMF LIFE CYCLE COSTS=$  21670486000.

         $$$$$$$$  DISCOUNTED AVERAGE SPS COST=$ 1083524100.
```

The "bottom line" of the baseline case is a nonrecurring cost of $11.6 billion, with a recurring cost of $1.2 billion per year at a production rate of 1 SPS/year. It should be emphasized that this cost per SPS is only for operations at the SMF, and does not take into account the mining, refining, and final assembly stages of production, nor does it include the initial costs of the lunar base and transport system. With the exception of solar cell manufacture, the cost of products from the SMF are of the same order as those estimated previously for terrestrially manufactured components. In the case of the solar cells, an order of magnitude reduction in costs appears possible due to the favorable effects of the space environment. These include the ready availability of low cost power, the vacuum environment which allows use of the low cost vapor deposition techniques, and the integrated facility with all processes colocated (thus avoiding reheating the intermediate products between production steps, and intermediate packaging and transportation costs). Possible sources of cost variations could be the cost of ground support (not included here), possible increases in R & D and procurement costs above those listed in Table 10.4, and lack of experimental verification of the efficiencies of vapor deposited solar cells. The baseline cost estimate does, however, demonstrate that a space manufacturing facility could operate competitively with earth manufacturing. The required crew to operate the baseline SMF is 433 people.

With the results from the basel‸‸e, it is interesting to do a variation of parameters analysis to find solution sensitivity. Figure 10.1 shows the effect of normalized failure rate on the crew size of the SMF. The normalized failure or duty cycle for each machine or pr‸ s printed out in the program output given in the App ‸r example the base 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.

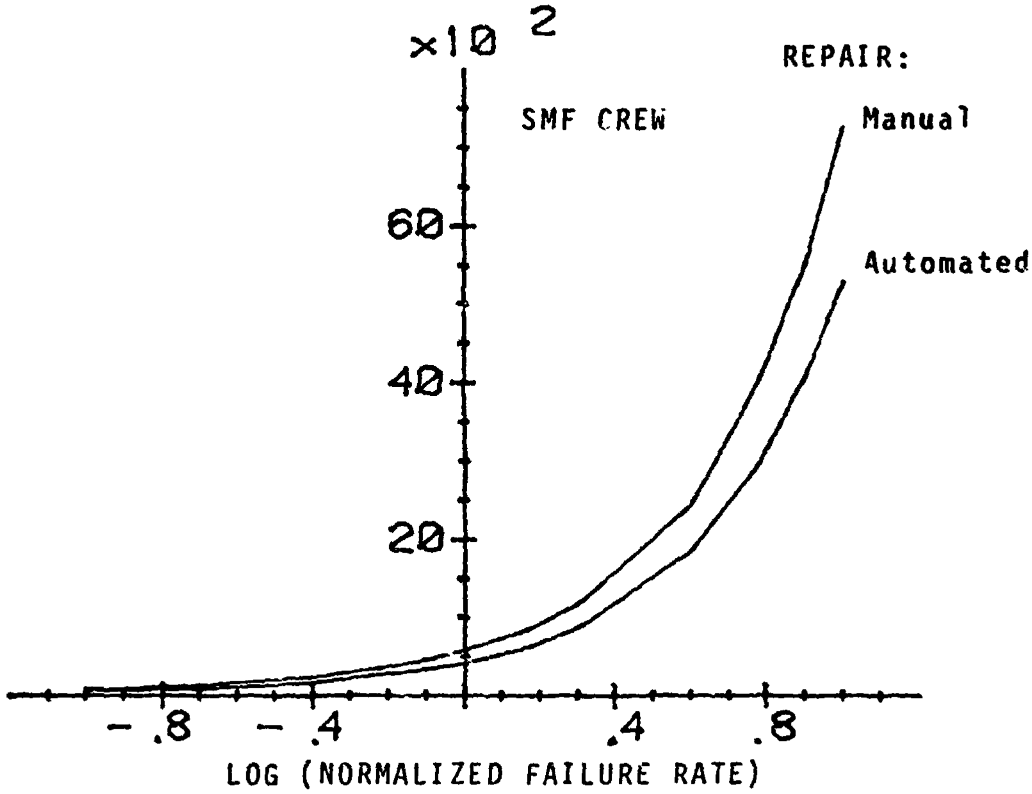


FIGURE 10.1

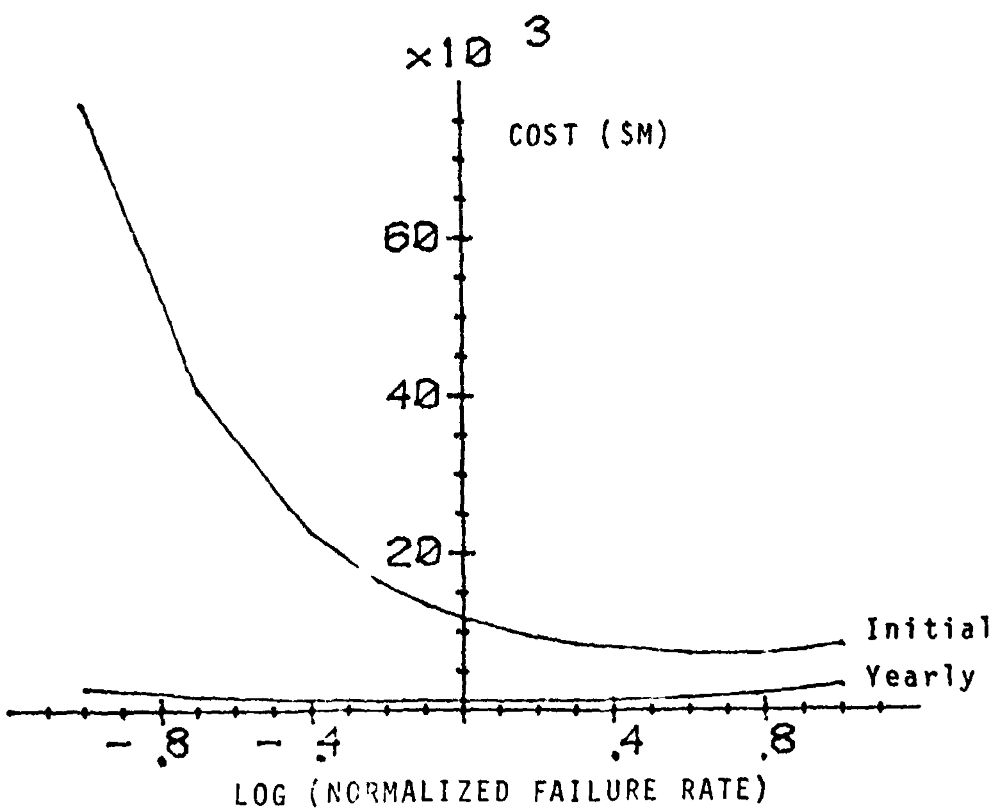


FIGURE 10.2

Figure 10.2 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 costs was \$20000/kg, and procurement cost was \$2000/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 \$20000/kg, respectively. Similarly, a variation in the 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. 10.2.

Figure 10.3 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

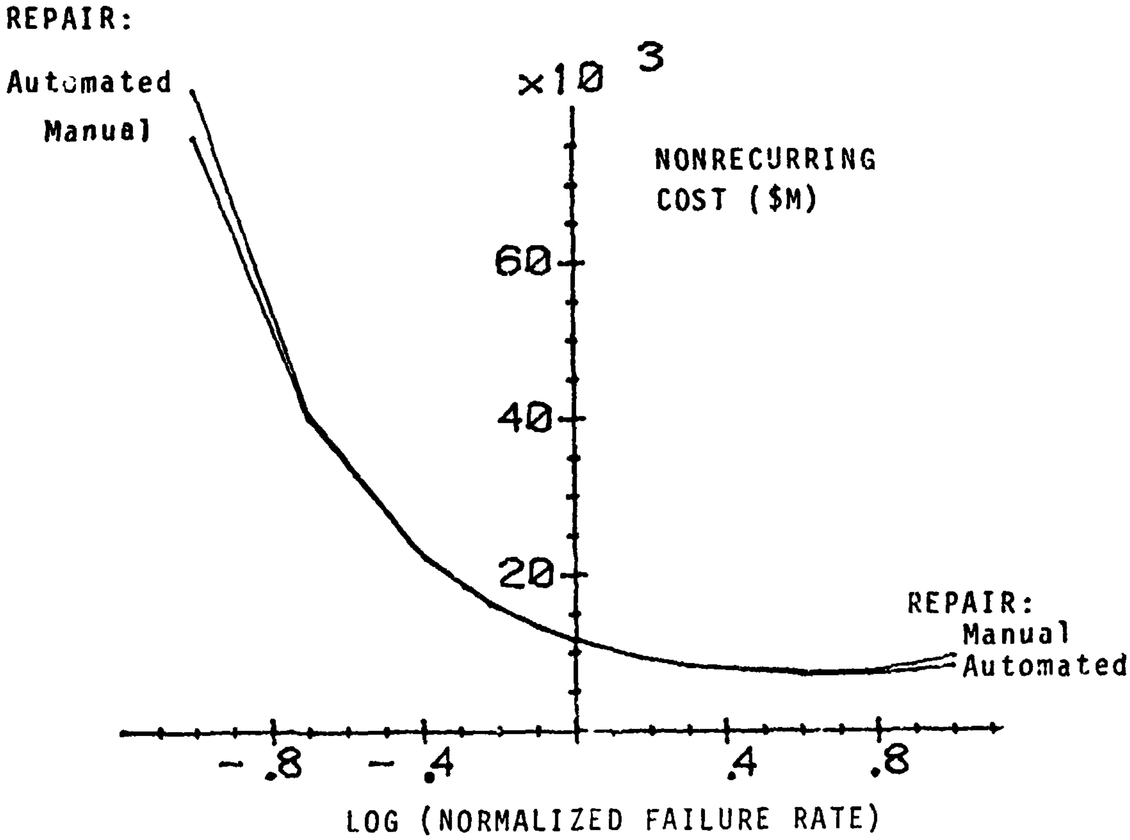


FIGURE 10.3

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, Figure 10.4 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.

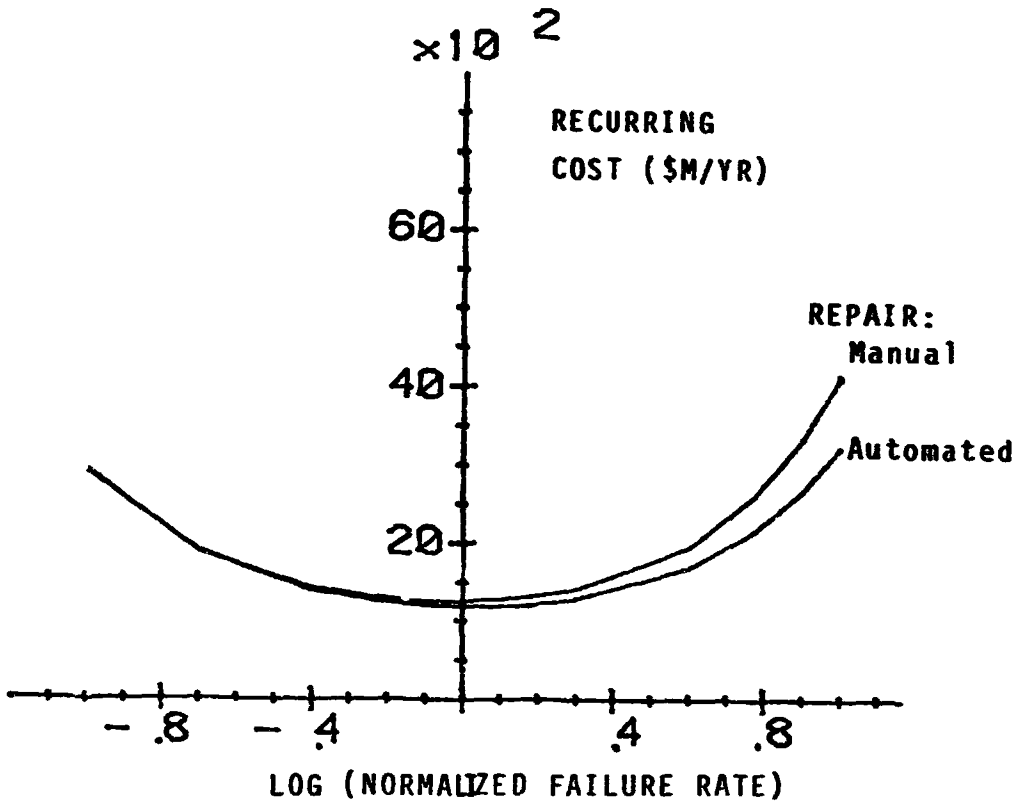


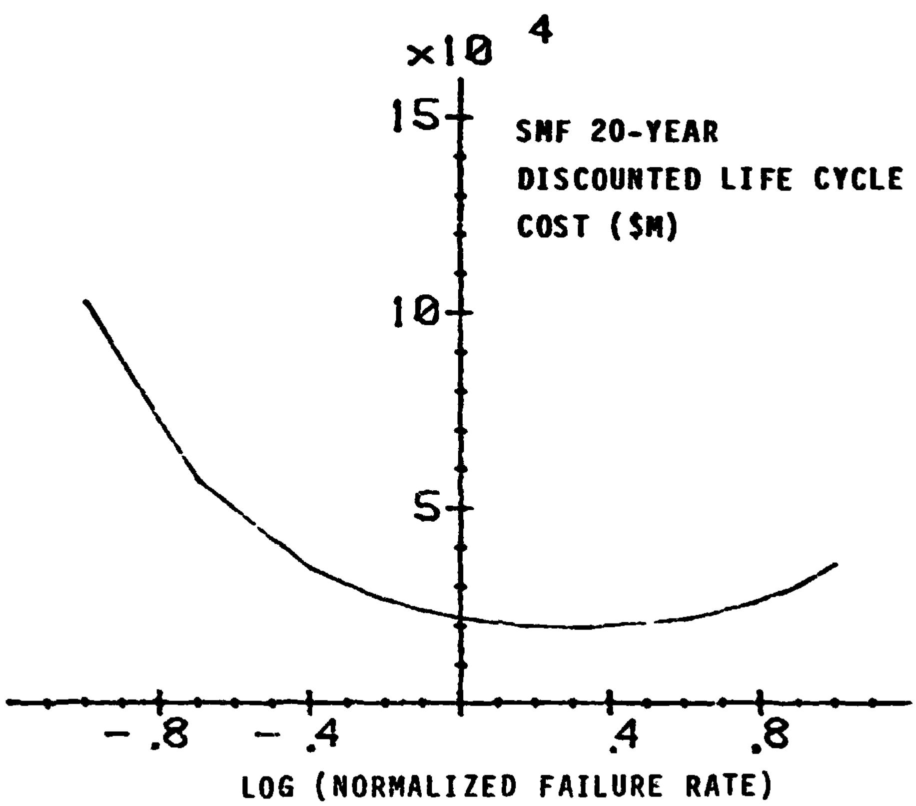
FIGURE 10.4

A minimum recurring cost coincidentlly 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 baseline SMF design, are $11.6 billion for nonrecurring, and $1.2 billion per year for recurring costs. These costs are competitive with ground-based 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 directly from Fig. 10.2 and is shown in Fig. 10.5. 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 system, 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 Chapters 12 and 13; however the above example is sufficiently illustrative of the



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

FIGURE 10.5

sensitivity of costs to the assumptions used in this analysis.

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 10.4 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 systems 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 costs.

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.

CHAPTER 11

OPTIMUM BUILDUP SCENARIO

Having derived a total SMF system in the preceeding chapters, and estimated the initial and yearly costs associated with it, a sufficient amount of information exists to examine various options in SMF deployment. The setup analysis in Chap. 10 assumed one year of space operations before SMF initial operational capability. This seems easily achievable, from Space Systems Lab experience in simulated weightless assembly.

However, this technical feasibility does not automatically imply practical feasibility. It is necessary to consider the SMF in the context of the total system of space industrialization.

It is unlikely, based on the results of the companion General Dynamics study (Ref. 11.1) that the point-design SMF would be a serious contender for funding until after SPS's had been built from terrestrial materials. It is conceivable that the SMF might be constructed as a single unit, and all SPS production suddenly switched over to nonterrestrial materials; it is much more likely that space-manufactured components would be slowly phased into SPS construction, and a gradual change form terrestrial to nonterrestrial materials would occur. The MIT study group proposed to study this lunar materials phase-in, using a linear program optimization technique.

Each element of the SMF can be characterized simply by three parameters: the non-recurring cost of the element, the production cost of one SPS ship-set of outputs from the element, and a fraction of SPS components which the element supplies. For example, the SMF can easily be broken down into a solar cell factory, a waveguide factory, a klystron factory, and a components (largely structural parts) factory. Although commonality between these factories is exploited in the MIT baseline SMF, minimal machine duplication would be necessary to separate the factory processes. Each factory would have its own initial and recurring costs and would supply a certain fraction of the SPS. An optimal build-up of the SMF might have an early switch to space-produced solar cells (due to the availability of the low-cost vapor deposition process), followed by components, waveguides, and finally by high-technology klystron components built in space. The reduction in cost of the SMF will be the motive for lead-in of space manufacturing; the gradual phasing is due to the advantage of delayed expenditures in discounted costs, and the use of early SPS power sales to pay for later factory developments.

The optimization technique used for this study was linear programming. This technique is often used for optimization of manufacturing systems where output costs can be considered to scale linearly with plant size. Those not familiar with linear programming are referred to some of the standard textbooks on systems optimization, such as Ref. 11.2.

As a means of verifying the implementation of this technique, a simpler problem was first analyzed: to choose between ground-based conventional, earth-sourced SPS, and non-terrestrial SPS generating systems, with the objective function to maximize discounted net income.

Each system was characterized by a nonrecurring cost (necessary for the use of the system), and an operating cost per SPS or per SPS-sized ground equivalent system. One hundred primal variables were thus defined: yearly investment in earth and lunar nonrecurring costs, and yearly investment in earth and lunar SPS and ground power plants, for a 20-year operational period. (It was assumed that all R & D has been returned on ground power systems, such as coal and fission). The objective function was to maximize net profits, measured as return from power plants minus investment in building and R & D. The objective function included a 10% discount rate, thus, there was economic advantage in achieving immediate returns and deferring expenditures. It was felt that the optimum would probably involve a progression from ground-based to terrestrial SPS to nonterrestrial SPS, as income supported further investment. A yearly budget limitation on outside capital entering the system was also included.

The computer program used is listed, together with the tableau matrix listed and solved, in the Appendix. Because of limitations in the standard linear program formulation, the program in its present form is not capable of finding an optimal solution which includes the constraint that all the R & D costs are expended before a system is used. This factor, and other non linear effects such as the need to include existance variables recognizing when no costs are accrued due to non-use of a system, requires additional reformulation of the of the problem, which is beyond the scope of the present contract. The development of the program is however continuing under separate funding, and considerations will also be given to the use of the more complex integer or dynamic programing techniques for circumventing the restrictions inherent in linear programming.

CHAPTER 12

TECHNOLOGY EVOLUTION PROGRAM

12.1: GENERAL REMARKS

This chapter describes the research and development steps required to establish the technology for the reference Space Manufacturing Facility. Although this program is keyed to the proposed reference SMF, it serves as a useful example of the scale and scope of R & D required for an SMF, and many of the steps described would be shared by other SMF designs.

The technology evolution program is actually a set of parallel programs. As described in Chap. 6, the reference SMF can be conceptually separated into the sections presented in Fig. 6.2, and repeated here in Fig. 12.1. Each section requires its own technology evolution program.

In general, these parallel programs have only minor effects on each other; for example, the development of waveguide production technology has little effect on research into furnaces and casters, and vice-versa. Even those sections which receive products from other sections can have separate technology evolution. For example, the ribbon and sheet operations, which begin with a rolling process, are little affected by the production techniques for the input slabs. However, if research on metals furnaces and casters indicates that the production of slabs is excessively difficult, then the ribbon and sheet operations must be modified to use different inputs

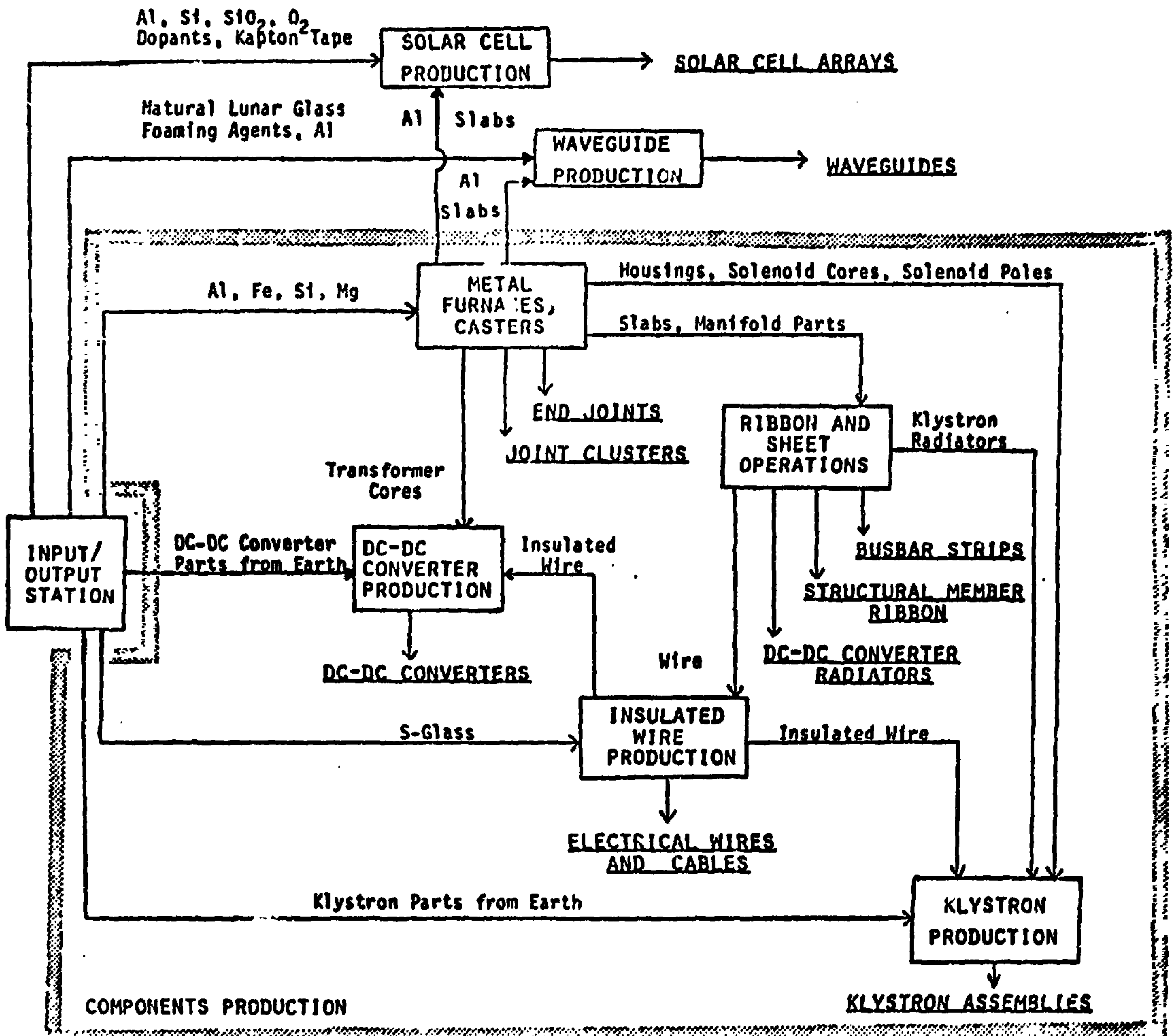


FIGURE 12.1: MAJOR OPERATIONS LAYOUT OF REFERENCE SP.

(e.g. vapor-deposited sheet). Therefore the technology evolution programs for the SMF sections can be separate provided that the various inputs can outputs between sections remain effectively unchanged (i.e. any changes do not significantly affect subsequent operations).

This separation of technology evolution programs should not lead to duplication, however. A number of SMF sections share processes (though not equipment), and R & D on these processes should be integrated. For example, electron beam guns are used in a wide variety of applications at the reference SMF: welding, cutting, vaporization, recrystallization. Basic research on electron beam guns can therefore be applied to all these operations. This commonality of equipment was considered an advantage in the choice of reference SMF processes (see Chap. 5).

While the technology evolution programs for the various sections of the SMF can proceed simultaneously, this is in general not true of the R & D steps within each program. For most sections of the SMF, the technology evolution for a given section is a sequence of research steps, each of which provides information and leads to a decision between alternative processes or equipment designs or operating procedures. Thus the information developed in the early steps has a significant impact on the later research in the program. Therefore the uncertainty in the definition of the programs increases through successive R & D steps.

The details of the technology evolution programs can also be affected by research in areas other than the SMF. First investigations in other aspects of space industrialization (e.g. lunar refining, transportation, SPS design) can change the specifications of inputs and outputs of the SMF.

Second, the SMF technology evolution program can benefit from research done on related industrial processes on Earth. For example, the study group anticipates that the next ten years will see intensive research on large-scale production of semiconductor materials and solar cells. Although the fundamental differences between the design environments in space and on Earth suggest that much of this research will not be applicable to space processes, the SMF technology evolution program can benefit greatly from the basic knowledge gained in solar cell performance, crystallography, doping, and array buildup. The technical challenge to the SMF designer will therefore be to apply the results of solar-cell production research on Earth to the development of space processes whenever possible.

The technology evolution programs for the individual sections of the SMF are each separated into three phases: conceptual studies, ground experiments, and Shuttle experiments. The research and development therefore progresses from an early general research program on the ground, including versatile prototypes, to a more specific development effort in the Shuttle using more specialized space hardware. At the conceptual stage, various options for SMF processes should be kept open, since the eventual success of any one option cannot be guaranteed. For example, the development of SMF furnaces could begin with studies of several furnace options (centrifugal, induction, gas-suspension) including potential designs for multipurpose furnaces (multi-material, or multi-input-shape).

Although there is no sharp transition between general and specialized R&D, each step in a technology evolution program aims at reducing the number of options to be investigated further, so that the complete program will produce finalized equipment. It is difficult to anticipate at what stages decisions between options should be made, because each step can uncover problems which may make the preferred options unworkable. The program therefore requires the flexibility to return to an earlier step if difficult problems develop. For example, if the Shuttle prototype for an aluminum-melting furnace demonstrates unforeseen problems, the technology evolution program should be flexible enough to return to other options studied on the ground, and to develop an alternative space prototype.

The example above also suggests that SMF equipment designs should not be finalized before testing in space. Unlike earlier space hardware development, when the design philosophy aimed at selection of options, construction and testing of prototypes, and finalization and fabrication of space hardware <u>before</u> launch, the SMF development should take advantage of the transportation cost reduction available from the Shuttle to do in-space prototype testing, even if the prototype is not guaranteed to be successful. This flexibility is particularly important for the

R&D on SMF processes which use the zero-g environment to advantage or which are seriously affected by the absence of gravity (e.g. induction furnaces, zone refining, human operations). For those processes, basic questions of feasibility may not be answerable without space experiments.

The technology evolution program is presented in the following sections as a series of tables, each detailing the R&D steps for a section of the reference SMF. The order of the steps is sequential, i.e., in most cases the early steps develop information useful in defining and executing the later ones. In some cases, certain R&D steps can benefit from hardware developed in other steps. For example, the testing of prototype casters in the Shuttle can use a previously developed prototype metal furnace to feed molten metal to the test articles.

Most of the suggested Shuttle experiments and prototypes are small enough to fit within a Spacelab payload (in most cases, several such experiments could fit in one flight). In fact, the in-space development articles could be flown as integrated multipurpose Spacelab missions. The study group feels that the Shuttle experiments in the technology evolution program could be performed with a small number of flights, at relatively little cost. At this level of investigation, however, definition of such integrated payloads is difficult, since experimental requirements and preferred process options are unknown.

Although the anticipated prototypes can fit within a Shuttle payload, in some cases the experimental requirements suggest a permanent orbital platform. Specifically, some prototypes might require sizeable power inputs (such as for furnaces, electron beam guns, lasers). These would therefore benefit from power sources parked in space, such as 25-kW or 100-kW modules. Similarly, some of these energy-intensive prototypes may require large heat-waste systems, and could therefore benefit from permanent cooling facilities and radiators. Finally, some of the experiments should be run several times with variation of experimental parameters. Such experiments could be left at an orbital platform between sets of runs, to allow return of output to Earth for examination and analysis; examples of such experiments include solar cell deposition processes and metal solidification processes. The orbital platform parking would avoid repeated Shuttle transportation.

The overall technology evolution program presented in the following sections details the R&D required for the SMF, but not for its outputs; the SPS or other satellite components produced by the SMF would require a separate technology evolution program. The program described in this chapter produces a set of working prototypes of the SMF hardware; in many cases, these prototypes are smaller than the SMF design components. The technology cutoff date is assumed to be the year 1990. Cost estimates for R&D are detailed in Chapter 10. "Line Item Costing."

The study group again emphasizes that the following descriptions are keyed to the reference SMF, and that other SMF designs would require different R&D steps. Furthermore, the descriptions also assume that the reference SMF processes chosen in Chapter 5 will be developed into space-rated hardware. However, should the chosen options prove unsatisfactory at any point in the R&D procedure, other options would be substituted, changing some of the steps in the development program. Like the reference SMF design, the technology evolution program described below is a point design in a very wide field of alternatives.

12.2: R&D: METALS FURNACES AND CASTERS

Table 12.1 presents a listing of research and development steps for reference SMF furnaces and casters. The furnaces are space-specific designs, requiring conceptual development. These preliminary design efforts should assess the usefulness of ground prototypes for furnaces, i.e. the extent to which such prototypes can accurately model the zero-g designs. Zero-g is expected to reduce the furnace masses considerably, and very small space prototypes (e.g. 1 ton, not including power supplies and heat waste systems) should be possible. Furnaces also require development of refractory materials adapted to the space environment.

Similarly, casters should benefit from mass reductions in zero-g, but require specialized refractories. The casters are modifications of earth designs.

The steps are listed in a time sequence from initial concepts, through design, ground prototype testing to final evaluation in a space environment.

TABLE 12.1: R & D: METALS FURNACES AND CASTERS

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Conceptual studies of furnace options	To produce preliminary designs of magnetic induction, solar trough, solar paraboloid, and rotating furnaces. Includes geometric design and sizing, static and dynamic load predictions, heating systems and temperature profiles, power and mass requirements, input/output systems design, estimation of maintenance, repair, and logistics, evaluation of technical uncertainty and required experiments, evaluation of operational safety, control requirements and systems, cost estimates, and comparisons of furnace options.	X		
Refractory material tests	To establish experimentally the tolerance of candidate refractory materials to molten metals and vacuum, and their thermal and magnetic properties. These materials are for casings and molds in furnaces, pipelines, continuous casters, and large piece casters. Emphasis on long-life, structural materials.	X	X	
Metal solidification experiments	To investigate the material microstructure and properties resulting from solidification in zero-g, specifically for metals and alloys in various casters. Development of relationships between casting parameters (mold shapes, thermal profiles, injection pressures, thermal conductivity of mold, mold material, alloy composition) and properties (structural, thermal, magnetic, electric) of cast output. Probably requires several sets of experiments.			X
Continuous caster design	To produce a preliminary design of a space-specific continuous caster for Al and Al alloy, based on earth designs, the metal solidification experiments, and the refractory material tests. Includes geometric design and sizing, structural design, choice of materials, cooling system design, thermal profiles, output handling systems, automatic monitoring and control equipment, estimation of maintenance, repair, logistics, and costs evaluation of operational safety and technical uncertainty.	X		

TABLE 12.1 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Die caster and large-piece caster design	To produce preliminary designs of space-specific die casters and large-piece casters, based on earth designs, the metal solidification experiments, and the refractory material tests. Casters receive molten Al, Al alloy, Fe, Fe alloy. Design includes structural design, choice of materials, estimation of injection pressures, thermal profiles, load histories, input/output systems, cooling systems, automatic monitoring and control, design of pipes, valves, and pumps, estimation of power, mass (reduced by zero-g), maintenance, repair, logistics, and costs evaluation of technical uncertainty and operational safety.	X		
Prototype furnaces	To develop useful ground prototypes of selected furnace options, if the zero-g effects can be adequately modeled or accounted for (otherwise space prototypes are required).		X	?
Prototype casters	To develop useful ground prototypes of the continuous caster, die casters, and large-piece caster, if the zero-g effects can be adequately modeled or accounted for (otherwise space prototypes are required).		X	?
Space prototypes of furnaces and casters	To develop and integrate space-rated furnaces, pipelines, pumps, continuous casters, die casters, and large-piece caster (casters can be integrated to furnaces and pipes one at a time). This effort may require stepwise verification of furnaces, then casters, with furnaces flown several times or parked in space. Includes development of automatic control systems, human maintenance and repair techniques in space, and long-term exposure to space environment. Output returned to Earth for analysis.			X
Prototype slab cutter	To develop a ground (but space-rated) prototype of a 128 kW electron beam cutter, including automatic filament replacement, cooling systems, automatic control, mechanical tracking. Tests on 2-cm-thick Al slab. Development of maintenance and repair techniques. Emphasis on reliability.		X	

12.3: R&D: RIBBON AND SHEET OPERATIONS

Table 12.2 presents the technology evolution program for ribbon and sheet equipment. All of these devices are modifications of existing earth equipment, replacing conventional cutting and welding equipment with electron beams. The rolling devices (rolling mill, ribbon slicer, and striator) are expected to have masses close to their earth counterparts, since the principal forces in such earth devices are tool-workpiece forces rather than gravitational forces.

However, the lack of a floor to anchor the machines (thus damping vibrations) requires the development of active damping systems; the designs must also be modified for maximum automation, compatibility with vacuum, and ease of in-space repair. These considerations also apply to the other ribbon and sheet operations devices.

TABLE 12.2: R & D: RIBBON AND SHEET OPERATIONS

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Prototype rolling mill	To produce design of space-specific reversing rolling mill for Al and Al alloy and to develop a ground prototype (which may be somewhat different than the design, due to its large mass). Includes structural design, estimation of power, mass, maintenance, repair, logistics, and costs, load predictions, operational safety, control requirements and systems. Prototype includes active vibration-damping, automatic control, in-space repair features, input/output systems. If possible, tests on space-cast slabs.	X	X	
Prototype electron beam cutters	To develop ground (but space-rated) prototypes of ribbon-cutting EB guns (research can benefit from development of slab cutter). Prototypes include automatic filament replacement, cooling systems, automatic control, tracking systems. Tests on Al and Al alloy ribbon. Development of maintenance and repair techniques. Emphasis on reliability and accuracy.		X	
Prototype electron beam welders	To develop ground (but space-rated) prototypes of sheet-wolding guns. Prototypes include same features as EB cutters. Tests include verification of weld properties. Development of maintenance and repair techniques. Emphasis on reliability, and on accuracy of control and tracking systems and techniques.		X	
Prototype ribbon slicer	To produce space-specific design of slicing-rollers device for Al and Al alloy ribbon, and to develop ground prototype (possibly different from design, due to high mass). This is a modification of the rolling mill design and rolling mill prototype, without reversing action. Tests of longevity, reliability. Development of techniques to vary output specifications.	X	X	
Development of striated heat pipes and heat pipe fluids	To verify the feasibility and assess the requirements of striated heat pipes for klystron radiators, including development of a heat pipe fluid compatible with aluminum and with suitable boiling temperature. Modifications to the heat pipe design should be made as needed. Effects of zero-g on heat pipe operation should be assessed (this may require space experiments).		X	?

TABLE 12.2 (Continued)

RESEARCH ITEM	OBJECTIVE	Component Definition	Ground Experiment	Shuttle Experiment
Prototype striator	To produce space-specific design of striation-rollers device for Al ribbon, and to develop ground prototype (possibly different from design, due to high mass). This is a modification of the rolling mill and ribbon slicer prototypes. Tests of longevity, reliability, output quality.	X	X	
Prototype form roller	To develop a ground (but space-rated) prototype of the form roller to produce heat pipes and radiator pipes from Al ribbon. This design is a modification of the Grumman beam-builder form roller. Tests of reliability, output quality, ease of repair.		X	
Design of sheet layout and klystron radiator assembly station	To produce a preliminary design of a fully automated sheet layout and radiator assembly device, based on the electron beam welder prototypes, and the output quality of ribbon slicer and form roller prototypes. Includes physical and structural design, estimation of mass, power, maintenance, repair, logistics, and costs, evaluation of technical uncertainty and operational safety, design of handling and control systems. Emphasis on maximum automation, minimum complexity, reliability, ease of repair.	X		
Prototype sheet layout and klystron radiator assembly station	To develop a ground (but space-rated) prototype of the sheet layout and klystron radiator assembly device. Prototype includes automatic control, active vibration damping systems, in-space repair features. Tests of equipment reliability and output quality.		X	
Design of DC-DC converter radiator assembly device	To produce a preliminary design of a fully automated device to produce large radiators, including radiator pipes and manifolds. Design work uses commonality of some features with klystron radiator assembly station, and develops similar parameters; structural handling of large sheets during welding is more difficult than for klystron radiators.	X		

TABLE 12.2 (Continued)

RESEARCH ITEM	OBJECTIVE	Component Definition	Ground Experiment	Shuttle Experiment
Prototype DC-DC converter radiator assembly device	To develop ground (but space-rated) prototype of large-radiator assembly device, including automatic control, active vibration damping, in-space repair features. Tests of reliability and output quality. Assessment of accuracy of ground simulation (high mass of radiator leads to different structural requirements on equipment).		X	
Integration of ribbon and sheet operations ground prototypes	To integrade the ground prototypes of rolling mill, EB cutters and welders, ribbon slicer, striator, form roller, and radiator assembly devices into a working, fully automated prototype of the reference SMF sheet and ribbon operations section. Includes development of handling systems (space-rated) and automatic control devices. Tests of system, including maintenance and repair.		X	
Space prototypes of rolling mill, ribbon slicer, and striator	To develop and test space prototypes of the related rolling devices. Includes tests of active damping systems, reliability, versatility, in-space repair. Due to mass of the prototypes (less than SMF machines, but still significant) these devices are candidates for orbital parking. Output returned to Earth for analysis.			X
Space prototypes of integrated sheet and ribbon devices	To develop space prototypes of the remaining devices in the sheet and ribbon operations section (many of the ground prototypes are already space rated) and to test these together with the space prototypes of rolling equipment. Includes tests of reliability, output quality, in-space maintenance and repair. Despite their number, these devices are not expected to mass more than one Shuttle payload; they may require additional power, however.			X

12.4: R&D: INSULATED WIRE PRODUCTION

The technology evolution program for the reference SMF insulated wire production section is detailed in Table 12.3. The glass fiber producer is an automated space-specific design, which therefore requires conceptual and experimental research. The wire wrapper is a relatively simple modification of existing earth equipment.

TABLE 12.3: R & D: INSULATED WIRE PRODUCTION

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Design of glass fiber producer	To produce a space-specific design of an automatic glass fiber producer. Includes investigation of suitable glass compositions available from lunar materials, alloys resistant to corrosion by molten glass and vacuum, heating systems, temperature and viscosity profiles, estimation of piston and tube loads, sizing and structural design, estimation of maintenance, repair, and costs, evaluation of technical uncertainty and operational safety, design of automatic spool threaders and control systems.	X		
Space experiment on fiber production	To investigate experimentally the effect of zero-g on the drawing of glass fibers through dies. Includes relationships between glass composition, molten glass pressure, die geometry, glass fiber diameter, drawing speed, and fiber quality. This is a small experiment; the output is returned to Earth for analysis. It may be advantageous to repeat the experiment after initial evaluation.			X
Prototype glass fiber producer	To develop ground (but space-rated) prototype of glass-fiber producer, based on preliminary design and Shuttle experiment results. Tests of equipment reliability, and of output quality (provided zero-g effects can be accounted for--otherwise in-space testing may be necessary).		X	?
Prototype insulation winder	To develop a ground (but space-rated) prototype of an insulation winder. This is a modification of an earth wire wrapper, adapted to vacuum operations and use of spools of glass fibers. Prototype includes automatic loading systems for spools. Tests of equipment reliability, ease of in-space repair.		X	

12.5: R&D: DC-DC CONVERTER PRODUCTION

Table 12.4 details the R&D steps for DC-DC converter production. Because only 461 DC-DC converters are required per year, the development of sophisticated automatic machinery is not warranted. Coolant channel drilling and coil winding are done by relatively simple modifications of existing earth equipment. The control circuitry for the converters is assembled to the cores manually. The procedures are simple enough that space prototypes should not be required.

TABLE 12.4: R & D: DC-DC CONVERTER PRODUCTION

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Prototype channel drill	To develop a ground (but space-rated) prototype of a numerically controlled deep drill (3m long bit) for drilling of coolant channels through SENDUST cores. This design is based on existing earth equipment, modified to emphasize tool longevity. Tests on equipment reliability.		X	
Prototype coil winder	To develop a ground (but space-rated) prototype of an automatic winder to wrap insulated wire around the transformer core limbs. Design is based on existing earth equipment, modified for operation in vacuum. Tests on equipment reliability.		X	
Definition and test of assembly tasks	To define required manual assembly tasks for control circuitry and to model these tasks in ground simulations.	X	X	

12.6: R&D: KLYSTRON PRODUCTION

In the absence of a detailed klystron design for the SPS, specific production equipment designs are not available, and therefore the technology evolution program listed in Table 12.5 is only general. The first item is therefore the detailed definition of a klystron design, optimized for SPS operation, use of lunar materials, and SMF manufacture.

Consultation by the study group on the subject of klystron manufacture indicate that the usual production steps can be performed by conventional precision equipment. The technology evolution program therefore requires the development of integrated, fully automated production devices for the klystron assemblies, followed by the adaptation of these ground prototypes into space prototypes. In view of the complexity and precision anticipated, the final space prototype should be tested in the Shuttle.

TABLE 12.5: R & D: KLYSTRON PRODUCTION

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Design of klystron and klystron assembly production sequence	To produce a klystron assembly design optimized for SPS operation, use of lunar materials, and SMF manufacture, and to define in detail the sequence of production steps, including allowable manufacturing tradeoffs and tolerances. Includes determination of components manufactured at SMF vs. produced on Earth.	X	X	
Prototype klystron assembly production equipment	To develop an integrated, fully automated set of ground prototypes for production machinery. Emphasis on maximum automation and reliability, ease of repair. Tests of output quality.		X	
Space prototypes of klystron assembly production equipment	To develop space-rated versions of the ground prototypes, including quality control systems and space-specific devices (e.g. EB welders). Shuttle tests to verify operation, reliability, in-space maintenance and repair, and output quality. Due to mass and complexity of equipment, integrated prototypes may benefit from in-space parking.			X

12.7: R&D: SOLAR CELL PRODUCTION

Table 12.6 details the steps in the R&D of the reference SMF solar cell production processes. As a first step, the study group recommends the establishment of a permanent task force to review the very considerable amount of new developments in solar cell production techniques. During this contract the study group received and reviewed published reports from a large number of research outfits in many countries; sources of information include many journals seldom found on aerospace shelves. Much of this information is not applicable to space operations; however, many concepts could be adapted to space use--in most cases, this is an option never considered by the concep s' authors.

The study group again emphasizes that this technology evolution program is keyed to the reference SMF, and therefore conceptual studies should keep alternative production options open. At this level of design, a final decision on a solar cell production scheme would be premature.

The suggested R&D steps include conceptual studies for those processes (zone refining, direct vaporization, recrystallization, laser cutting, glass layer production) which have not been applied in space before, and which carry some uncertainty about their feasibility or basic requirements. In most cases, these conceptual studies lead to ground prototypes, then to space prototypes. In a number of cases, however, the study group recommends following the conceptual study with a small-scale Shuttle experiment to assess the effect of zero-g on the process. This then leads to design of ground or space prototypes, as needed. In some cases, the suggested processes have been sufficiently researched and applied on Earth that development of prototypes can begin without extensive conceptual research.

TABLE 12.6: R & D: SOLAR CELL PRODUCTION

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Continuous review of developments in solar cell production techniques	To review the large number of current research findings on solar cell production alternatives (published by many research teams), and to assess the applicability of these developments to space operations.	X		
Conceptual studies of solar cell production systems	To investigate alternative processes and production sequence for the manufacture of solar cells at the SMF. Includes preliminary operations layouts and designs, estimation of mass, power, maintenance, repair, logistics, and costs, evaluation of technical uncertainty and operational safety, ease of automation and repair, output quality, and comparison of options. Definition of technology evolution programs for alternatives.	X		
Conceptual study and space experiments on zone refining	To investigate, theoretically and experimentally, the effect of zero-g on the zone refining process. Includes determination of optimum zone refining parameters to maximize zone travel rate and minimize number of passes required for purification and study of effects of types and concentrations of impurities on refining requirements. Output returned to Earth for analysis. Equipment is expected to be small.	X		X
Prototype zone refiner	To develop a prototype zone refiner for the reference SMF, to purify metallurgical grade Si from the Moon to semiconductor grade. This is a ground device, if the zero-g effects can be accurately modeled or accounted for (otherwise, a space prototype is required). Prototype includes feed and handling systems, heating and cooling systems, quality control sensors and automatic control systems. Tests of effects of operating parameters on output quality. Emphasis on maximum automation, ease of in-space repair.		X	?
Space prototype of zone refiner	To develop and test a space-rated prototype of the reference SMF zone refiner. This device may require a power source beyond the Shuttle's, and may benefit from in-orbit parking between test runs. Output is returned to Earth for analysis.			X

TABLE 12.6 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Conceptual study and space experiments on direct vaporization	To investigate, theoretically and experimentally, the effects of zero-g on direct vaporization of Al, Si, SiO_2, and to produce preliminary designs of direct vaporization devices. Includes evaluation of effects of deposition parameters (e.g. pressure of vapor, deposition surface temperature and morphology, thermal profiles) on properties of deposited output.	X		X
Prototype direct vaporization devices	To develop ground prototypes of DV devices for Al, Si, SiO_2, if zero-g effects can be accurately modeled or accounted for (otherwise space prototypes are required). Includes development of thermal belt, EB tracking control, slab feeding mechanisms, quality control systems, maintenance and repair techniques, cooling systems. Tests of equipment reliability and output properties.		X	?
Prototype ion implantation devices	To develop a ground (but space-rated) ion implantation device for boron and phosphorus, from existing equipment. Emphasis on deeper penetration (2-5 microns), full automation, longevity of equipment. Tests of equipment reliability, doping profiles, implantation damage. Assessment of compatibility with DV of silicon.		X	
Conceptual studies and experiments on recrystallization	To investigate, theoretically and experimentally on the ground, the feasibility and requirements for recrystallization of direct-vaporized layers of silicon. Includes studies of pulse and scan recrystallization, effects of silicon morphology, pulsing/scanning parameters, and environmental factors on recrystallized output. Production of preliminary designs for recrystallization devices, and of designs for space experiments.	X	X	
Space experiments on recrystallization	To investigate the effects of zero-g on recrystallization of silicon layers. Equipment is expected to be small. Output returned to Earth for analysis.			X
Prototype recrystallization devices	To develop ground prototypes of recrystallizers for the reference SMF, if zero-g effects can be accurately modeled or accounted for (otherwise space prototypes are required). Emphasis on automation, reliability, ease of repair. Tests of output quality.		X	?

TABLE 12.6 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Space experiments on ion implantation damage anneal	To assess the effect of zero-g on pulsed-beam annealing of ion implantation damage. Equipment is expected to be small. Output is returned to Earth for analysis.			X
Prototype ion implantation damage annealer	To develop a ground prototype of an ion implantation damage annealer, based on existing designs, if the zero-g effects can be accurately modeled or accounted for (otherwise a space prototype is required). Emphasis on automation, reliability, ease of repair. Tests of output quality.		X	?
Prototype of direct vaporizer with mask and mask cleanup device	To modify ground prototype of direct vaporizer for Al to operate through a shadow mask (to deposit top contact pattern). Includes development of space-rated mask with long life, and of device to brush deposited Al from mask automatically. Tests of output quality, equipment reliability.		X	
Space experiment on front contact sintering	To investigate the effect of zero-g on pulsed-beam sintering of solar cell front contacts. Equipment is expected to be small. Output is returned to Earth for analysis. Includes variation of sintering parameters.			X
Prototype front contact sintering device	To develop ground (or space, if needed) prototype of top contact sintering device, including tracking systems, in-space repair features, quality control systems, automatic control. Tests of equipment reliability and output quality.		X	?
Integrated space prototypes of solar cell deposition	To develop integrated, space-rated prototypes of thermal belt, direct vaporizers for Al and Si, ion implanters for boron and phosphorus, masking of front contact, recrystallizers and ion implantation damage anneal, and front contact sintering. Includes automated control, quality control, input/output and handling systems, tests of in-space maintenance and repair techniques. Output (operational solar cells, without glass layers) is returned to Earth for analysis. Equipment estimated at less than one Shuttle payload, not including power and heat waste systems.			X

TABLE 12.6 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Conceptual study and experiments on laser cutting of solar cells	To investigate, theoretically and experimentally on the ground, the use of lasers to cut solar cell material. Includes effects of cutting parameters (wavelength, focusing, tracking speed, power) on resulting degradation of cell near cut.	X	X	
Prototype solar cell crosscutter and longitudinal cutter	To develop ground prototypes of laser cutting systems for solar cells, including automatic control, tracking systems, quality control. Tests on space-produced solar cell material or equivalent. Emphasis on equipment accuracy and reliability.		X	
Prototype direct vaporizer for interconnects	To develop a ground (but space-rated) prototype of a direct vaporizer to produce 50-micron thick Al sheet, including systems to roll up the output, automatic controls, cooling systems for EB guns. This device is a modification of other DV prototypes. Emphasis on reliability, ease of repair, automation.		X	
Prototype solar cell interconnection device	To develop ground prototype of solar cell interconnection device (same as panel interconnection device). This is a sophisticated mechanical device, with tight tolerances. Emphasis on automation, reliability. Includes interconnect feed systems, sensor and alignment systems, electrostatic bonders. Tests on simulated solar cells and panels. Possible applications on Earth.		X	
Conceptual studies of optical cover and substrate production options	To review existing literature and to produce preliminary designs of production options for SiO_2 layers, including direct vaporization (reference SMF) and separate sheet production followed by electrostatic or laser bonding. Includes assessment of feasibility and operational requirements. Preliminary designs include thermal profiles, load histories, power and mass requirements, estimates of maintenance, repair, logistics, and costs, assessment of reliability and output quality.	X		

TABLE 12.6 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Prototype panel alignment and insertion device	To develop a ground (but space-rated) prototype of the panel alignment and spare panel insertion device. Includes full automation including sensing and control, in-space maintenance and repair features, maintenance and repair estimates. Tests of accuracy and reliability of equipment, and assessment of modifications required for zero-g use.		X	
Prototype kapton tape applicator	To develop a ground prototype of a kapton tape applicator to produce structurally connected solar array segments. Includes automatic sensing and control, tracking and loading systems, in-space repair features. Tests of reliability of equipment, using simulated solar cell panels. Assessment of modifications required for zero-g use.		X	
Prototype array segment packager	To develop a ground prototype of the array segment packager. Includes full automation (sensing, control, tracking), in-space repair features. Tests on simulated arrays, assessing equipment reliability, output quality, modifications required for zero-g.		X	
Integration of cell interconnection and panel/array buildup prototypes	To integrate the ground prototypes of devices to produce complete array segments from deposited solar cell material. Includes continuous processes, automated control, quality control, input/output and handling systems, maintenance and repair features. Tests on simulated or actual deposited solar cell material. Emphasis on reliability, ease of repair, integrated control. Possible applications on earth.		X	
Integrated space prototypes of cell interconnection and panel/array buildup devices	To space-rate and test the integrated prototypes for production of array segments. Equipment is expected to fill less than a Shuttle payload, not including power and heat waste systems. Output returned to Earth for analysis.			X

TABLE 12.6 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Space prototype of complete solar cell production strip	To develop and test full-scale prototype of 104 m-long solar cell production strip. Includes structural integration of components, full automation, tests of in-space repair and maintenance, return of output to Earth for analysis. Equipment requires more than one Shuttle payload, in-space assembly and checkout. Can be used to produce solar arrays for space use.			X

12.8: R&D: WAVEGUIDE PRODUCTION

The R&D steps for waveguide production in the reference SMF are detailed in Table 12.7. The study group recommends conceptual studies of the applicability of foamed glass to space components, and of the necessary properties of the material. Due to the proprietary nature of glass foaming processes, R&D requirements for a foaming facility are uncertain, as are the achievable foamed glass structural properties. There is also uncertainty on the feasibility of laser smoothing or fusing of the material. These uncertainties can probably be resolved only by experimental research.

TABLE 12.7: R & D: WAVEGUIDE PRODUCTION

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Conceptual studies and development of foamed glass for waveguides	To investigate alternative methods and to produce preliminary designs for foamed glass production options. Includes assessment of uses, properties, and production requirements for foamed glass for space applications. Emphasis on lunar material use.	X	X	
Design of space powder mixer	To produce a preliminary design of a mixing device to blend <5 micron powders suspended in vacuum. Emphasis on component longevity, automation, in-space maintenance and repair.	X		
Space prototype of powder mixer	To develop and test a space powder mixer. Equipment is expected to be small. Device and output are returned to Earth for analysis.			X
Space experiments on glass foaming	To investigate experimentally the effect of zero-g on glass foaming processes. Variation of operating parameters to study relationships affecting output properties.			X
Design of glass foaming facility	To produce preliminary design of a foaming/annealing furnace to produce foamed glass. Includes geometric design and sizing, static and dynamic load predictions, heating and cooling systems, temperature profiles, power and mass requirements, input/output systems, estimation of maintenance, repair, and logistics, evaluation of technical uncertainty, required experiments, operational safety, control requirements, cost estimates.	X		
Prototype glass foaming facility	To develop a ground (but space-rated) prototype of the glass foaming facility (if the earlier space experiments indicate that zero-g effects cannot be accounted for, a space prototype is required). Emphasis on equipment longevity, automation. Development of relationships between operating parameters and output characteristics.		X	?
Prototype foamed glass sawcutters	To develop ground (but space-rated) prototypes of multi-bladed band saws for slicing blocks of foamed glass. Includes chip removal systems, input/output and handling systems, maintenance and repair techniques, automatic control, quality control. Tests of blade longevity and output quality.		X	

TABLE 12.7 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Experiments on foamed glass smoothing	To investigate, experimentally on the ground, options for smoothing foamed-glass surfaces, including the use of lasers. Development of relationships between operating parameters and output quality. Tests are performed on space-produced foamed glass sheets or equivalent.		X	
Prototype foamed glass smoother	To develop a ground prototype of the foamed glass smoother. Includes sheet handling and tracking systems, quality control. Emphasis on automation, accuracy of output, ease of repair.		X	
Prototype waveguide Al direct vaporizer	To develop a ground (but space-rated) prototype of a DV device to apply Al interior coatings to waveguides. This is a modification of DV of Al devices for other SMF processes. Tests on smoothed foamed glass sheets, and evaluation of output quality.		X	
Prototype laser cutters for foamed glass	To develop ground prototypes of laser cutting systems for foamed glass sheets, including automatic control, tracking systems, quality control. Tests on Al-coated foamed glass sheets, using lasers to make straight cuts, slots, and holes. Emphasis on equipment accuracy and reliability.		X	
Design of waveguide assembler and waveguide packager	To produce preliminary designs of waveguide assembler and waveguide packager, including automatic manipulator systems, guide systems, laser fusing devices, quality control, packaging manipulators, and storage racks. Emphasis on full automation, accuracy of output, ease of repair.	X		
Prototype waveguide assembler and waveguide packager	To develop ground prototypes of waveguide assembler and packager, including full automation, handling systems, quality control devices, laser fusers. Tests of equipment accuracy and reliability, using Al-coated foamed glass strips as inputs, evaluation of output quality, and development of maintenance and repair techniques.		X	
Integration of waveguide production prototypes	To integrate the ground prototypes into a fully automated glass foaming and waveguide production line, including automatic handling and control, in-space maintenance and repair features. Emphasis on reliability, ease of repair, integrated control, accuracy of output.		X	

TABLE 12.7 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Space prototype of waveguide production system	To space-rate and test the integrated ground prototypes. Includes structural integration of components, full automation, tests of in-space maintenance and repair, return of output to Earth for analysis. Equipment requires roughly one Shuttle payload (not including power and heat waste systems) and in-space assembly.			X

12.9: R&D: SUPPORT EQUIPMENT

Table 12.8 describes the major steps in the technology evolution for reference SMF support equipment. In general, the development of the SMF support equipment shares a number of steps with SPS development and the development of likely near-term space hardware (e.g. orbital antenna farms, Shuttle service stations, space stations). Therefore some of the R&D may be shared with other programs.

For a number of support equipment sections, ground and space prototypes are useful for component verification, but the final verification requires the full-scale structure. Examples are the input/output station, power plant, production control systems, stationkeeping and attitude control, and structure. In these cases the technology evolution program aims at developing sufficient knowledge and experience with the prototypes to produce final designs for the sections, with confidence in their proper function after construction.

The study group feels that the most demanding technology evolution tasks for support equipment are the development of repair automata, the development of free-flying hybrid teleoperators, and the development and integration of the computer hardware and software for production control.

TABLE 12.8: R & D: SUPPORT EQUIPMENT

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Design & ground tests of input/output station	To produce a design of the cargo and personnel docking facilities, including structural design of damped impact-resistant structure, docking latches, manipulator cranes (with life-support pods, control computers, end effectors), androgyne docking rings, airlocks, and pressurized tunnel. Also ground tests on equipment components, stressing reliability, longevity, ease of repair.	X	X	
Design & ground tests of internal transport & storage devices	To produce a design for the magnetic cart internal transport system and for the internal storage device. Internal transport includes track, carts, magnetic drive components, control actuators, sensors, routing control hardware & software, & cart/cargo interfaces. Internal storage device includes holding racks, drive systems, input/output devices, labeling systems, control hardware & software. Design work includes load predictions, geometric design & sizing, estimates of maintenance & repair, evaluation of operational safety. Tests of component longevity, reliability, ease of repair. Evaluation of modifications required for zero-g use.	X	X	
Design & ground tests of crawlers	To produce & ground test designs for solar cell factory crawlers, including structural design, drive systems, tracks & support structure, sensors, computer hardware and software, communications, manipulators, end effectors. Crawlers are specialized to the sections they service, & therefore require variations on a basic design. Tests of component accuracy and reliability, & development of ground prototypes. Design of control software, crawler/internal transport interface, maintenance & repair techniques. Evaluation of modifications needed for zero-g use.	X	X	
Design & ground tests of power plant components	To produce a design for the reference SMF power plant, including solar array, DC-DC and DC-AC converters, power feed systems, emergency fuel cells, switching systems, & control hardware & software (much of this design matches components of the SPS). Includes mass, maintenance, repair, logistics, & cost estimates, structural design of solar array & busbars (design work interfaces with SMF structure development), sizing of fuel cells & converters. Tests on components, stressing reliability, ease of assembly (some of these tests probably done during SPS development). Investigation of bootstrapping possibilities.	X	X	

TABLE 12.8 (Continued)

RESEARCH ITEM	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Design & ground tests of production control systems	To investigate production control options and to produce preliminary designs of space-rated computers, monitoring sensors, data transmission systems, status display systems, routing control software, inventory control software, maintenance & repair scheduling software, computer hierarchies, damage-tolerance techniques (e.g. redundancy, distributed controls with self-reconfiguration), management structures. Simulations of various software options & ground tests of hardware, leading to full-scale simulation of SMF operations, including failures & changes in production objectives.	X	X	
Design & ground tests of habitation components	To produce a design for a modular zero-g habitat made from converted Shuttle external tanks, including interior structures, life-support systems (closed water cycle), airlocks, structural attachments, thermal control, shielding requirements, emergency systems. Design work includes load predictions, structural design, estimates of mass, power, maintenance, repair, logistics, & costs, in-space maintenance & repair features, evaluation of technical uncertainty & operational safety, development of space workers' nutritional, recreational, & physical requirements & work schedules. Tests of habitation components, with emphasis on reliability, & simulations of living conditions. Much of this research may be shared with near-term space station development.	X	X	
Design & ground tests of stationkeeping and attitude control equipment	To produce designs of stationkeeping equipment. Includes computation of orbital requirements, estimation of attitude control requirements, design of navigation & attitude sensors, guidance computers, oxygen thrusters (e.g. resistojets, ion). Ground tests of hardware, & computer simulations of orbital & attitude perturbations & software response. Some design work & tests common with SPS development.	X	X	
Design & ground tests of SMF structure component	To produce a design for the SMF structure, including central mast, solar array supports, factory equipment support structure, flexible joints with active damping systems. This design is interfaced with the design of internal transport tracks & power feed systems, which may be structural. Design includes	X	X	

(continued)

TABLE 12.8 (Continued)

RESEARCH ITEM	(continued) OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
	development of position and deformation sensors, maintenance & repair techniques, mass & cost estimates, evaluation of operational safety. Emphasis on ease of in-space assembly & repair. Tests of position sensors, active damping systems, assembly & repair techniq[illegible] & computer simulations to predict load histories & c[illegible]requirements.			
Design & ground tests of repair shop components	To produce designs for re[illegible] shops made from converted Shuttle external tan[illegible], including human work areas, life-support systems, airlocks, interior structures, emergency systems, structural attachments, repair automata, spare parts racks, input/output systems. Design work shares common efforts with habitat development; includes load predictions, structural design, estimates of mass, power, maintenance, repair, logistics, & costs, evaluation of operational safety, shielding requirements, development of versatile zero-g workshop machines, development of automated repair machinery (several types), development of thermal control systems & toxic-gas scrubbers. Tests of components, with emphasis on reliability & ease of repair in space, & simulations of work conditions. Assessment of modifications for use in zero-g.	X	X	
Design & ground tests of free-flying teleoperators	To produce a design for a versatile free-flying hybrid teleoperator for repair & maintenance operations in the solar-cell factory. Based on the Shuttle Teleoperator Retrieval System, this design includes multipurpose manipulators & end effectors, navigation systems, thrusters, communications hardware, sensors, computers, power supplies, propellant tanks, & a remote control station Design work includes definition of specific tasks & requirements, component design, system integration, development of complex software structures (including telemetry links to remote computers). Tests of components (emphasis on reliability) & simulations of integrated functions. Development of multi-media control station & communications links (video, audio, tactile). Assessment of modifications required for SMF use. May have some earth applications.	X	X	

TABLE 12.8 (Continued)

RESEARCH TYPE	OBJECTIVE	Concept Definition	Ground Experiment	Shuttle Experiment
Integrated space prototypes of habitation, input/output station, & repair shops	To develop and test a modified external tank (half habitation, half repair shop) with attached docking systems (incl. manipulator crane). Tests of component reliability, safety, worker productivity, repair automata requirements, emergency systems. This equipment could fit into one Shuttle flight, & has potential near-term space use (such as a Shuttle repair station). This can also serve as a parking facility for experiments.			X
Integrated space prototypes of internal transport & storage devices, crawlers, station-keeping & attitude control equipment, & structure	To develop & test an integrated space-rated prototype structure including crawlers, transport & storage systems, and SMF structure components (sensors, flexible joints, damping). This equipment can possibly fit in one Shuttle payload, but requires in-space assembly. Tests include in-space assembly, maintenance, & repair techniques, verification of dynamic behavior predictions, accuracy of component operation (including control hardware & software).			X
Space prototype of free-flying hybrid teleoperator	To develop & test a space-rated prototype of the free-flying hybrid teleoperator. Tests of all six command modes, device versatility and accuracy, operating range (time, distance, physical environment), operator learning curves. Tests can include teleoperator operations on structure/transport systems/etc. prototypes developed earlier, & should include tests in simulated thermal & radiation environment of the solar cell factory. Teleoperator has potential uses in near-term space operations.			X

CHAPTER 13

POSSIBLE SYSTEMS TRADEOFFS

13.1: INTRODUCTION

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. It is the purpose of this chapter to discuss briefly some of these tradeoffs.

13.2: OPTIMIZATION OF PRODUCT FOR USE OF LUNAR MATERIALS

One of the contractural guidelines of this study was that there would be no redesign of the SPS (chosen as an example product of the SMF) beyond lunar-material substitutions. This assumption forces unnecessary complexity on the SMF processes, and may lead to unrealistically high program costs. Significant reductions in SMF complexity can be obtained by designing the output specifically for lunar-material use and ease of space manufacture. Therefore a ful comparison of earth baseline and lunar material scenarios should include the option to optimize product designs within each scenario.

More generally, the study should assess the physical and economic characteristics of the space production environment which drive the optimum design of SMF outputs. Examples of such characteristics are the availability of raw materials, the relative difficulties in refining various minerals, the unsuitability of many traditional Earth processes, the advantages of processes unsuitable on Earth, the different cost patterns of energy, the availability of cheap vacuum, the effects of zero-g, and the relatively high cost of human labor. All of these factors tend to rewrite the list of do's and don't's used in product design on Earth, and a systematic assessment of the optimum trends in product design for lunar material space manufacture would be a useful tool.

One possible approach could be an inversion of the design philosophy used in studies to date. Rather than starting with a product design and asking "how can this be made in space from lunar materials?", a study could begin with a list of available materials and a list of processes suitable for lunar and space use, (the processes graded according to simplicity and adaptation to the physical and economic conditions), and ask "what useful products can be produced, and which are the simplest and least expensive to produce?".

13.3: EFFECT OF SPS MASS INCREASE

A likely result of tailoring the SPS design for ease of space manufacture from lunar materials is an increase in the SPS size and mass. For example, some of the complexity of the reference SMF presented in this study results from the requirement for production of solar cells with 12.5% efficiency. An alternative SPS design, using thin film cells or thermionic devices with 6% efficiency, might simplify the SMF design and therefore reduce the SMF costs. However, a 10-GW SPS would then require a collection area of 200 km^2 (rather than the baseline 100 km^2), and would therefore be more massive than the baseline.

The tradeoff to be evaluated is the cost reduction in the SMF design (due to the use of simpler solar cell manufacturing techniques) versus cost increases due to: possible increases in attitude control requirements (propellant) for the SPS; a required increase in the production of raw materials from the lunar base; increased transportation costs for these raw materials; a required increase in the production capacity of the SMF; an increase in the assembly required per SPS. While the SMF related cost reductions and increases can be estimated from the SMF design, the other contributors to the tradeoff require further study. What is the cost of increments in lunar mining, transportation, assembly?

13.4: TRADEOFFS IN LUNAR REFINING

There are many possible lunar refining options, and these candidates vary in the range of output minerals and the purities of the outputs. In general, the larger the number of different outputs and the higher the output purities, the more complex and costly the refining equipment. On the other hand, a reduction in the available list of materials can force substitutions which complicate the manufacturing processes and degrade the performance of the final product. Similarly, a reduction in available purities can also increase the complexity of manufacture and decrease the final output quality.

Therefore there are tradeoffs between lunar equipment complexity and SMF equipment complexity and final product performance. As an example, if the production of S-glass on the Moon were difficult or impossible, the reference SMF might have to be modified to produce S-glass from lunar SiO_2 and Earth inputs, thus increasing SMF complexity and earth material requirements. Or the system could be modified to avoid the need for S-glass, producting electrical insulation from other materials; this could degrade the performance of the SPS.

As another example, if semiconductor grade silicon were available from the Moon (rather than metallurgical grade) the reference SMF would not require a zone refining section. This example introduces another tradeoff: the location of refining processes. In the reference design, the refining of silicon is split between the Moon and the SMF, while the refining of other materials is done on the Moon. Each location offers different advantages in refining, however: the Moon benefits from gravity, which allows many Earth processes unsuitable for zero-g, such as separations by liquid or solid density variations, column exchange processes, solubility processes; and there are benefits in launching only pure materials from the Moon. However, labor may be more expensive on the Moon than in space, and the SMF benefits from continuous solar energy. Another consideration is the likelihood of c ntamination of purified materials during transportation from the Moon to the SMF. All of these issues require further study.

Another tradeoff in lunar refining is scaling, or the buildup sequence for lunar operations. Should a full-scale, full-capability lunar base be established early in the program, or should a limited lunar facility be set up and progressively uprated? If a small scale base is set up to refine oxygen for interorbital propellant, at what time should the facility be expanded to produce raw materials? For the early SMF outputs, which materials should come from the Moon, and which from Earth?

13.5: TRANSPORTATION FROM THE MOON

Several options have been suggested for transportation of raw materials from the Moon: liquid chemical rocket, mass-driver, nuclear rocket, aluminum powder/oxygen rocket, tethered satellite elevator. Besides the uncertainties in the R & D cost estimates for these options, several other issues also require study. The costs of several of these options are strongly dependent on the source of their propellant and/or energy. For example, the aluminum powder/oxygen rocket is a competitive option only if both Al powder and oxygen are available in large quantities from the lunar refining processes. Therefore the lunar base capabilities can affect the relative merits of transportation systems.

Another issue affecting the choice of transportation methods are the constraints they impose on their cargo. The mass-driver operates on blocks or pellets, while the other options allow other cargo shapes (such as rods, slabs, powder) which may simplify the SMF input systems.

Finally, as mentioned earlier, the necessity to avoid contamination of purified materials may significantly complicate some transportation options. All of these transportation-related issues should be further investigated.

13.6: SMF PRODUCTION CONTROL TRADEOFFS

Within the SMF, several production control tradeoffs can have significant effects on SMF program costs. These tradeoffs affect the design of support equipment and the methods of allocation of available resources.

One tradeoff currently under assessment but requiring further study is automation versus human labor. For the supervision and operation of machinery, automated systems appear adequate and cost-effective. However, automation in maintenance and repair needs further research. Repair functions require evaluation of uncertainty; therefore automated repair systems are sophisticated and expensive devices, and human labor may well be competitive. There also exists the compromise of remote-controlled teleoperators, with the operators on Earth. Evaluation of this tradeoff requires better estimates of costs and reliability of the basic equipment, of the automated repair systems, productivity of maintenance and repair labor in space, and productivity and costs of teleoperator systems.

From the systems point of view, below a certain range of population at the SMF, the human labor costs are low enough that they are not significant contributors to the SMF program costs. Therefore, if automation is used to the extent that the SMF personnel total is below this range, then further use of automation does not yield significant returns, while increasing technical uncertainty. Based on the work in this SMF design study, and other in-house studies in the Space Systems Laboratory, the study group has located this "knee" in the program cost versus SMF population curve at an SMF population of roughly 2500, well above the population of the reference SMF (Ref. 13.1). Since this finding involves a number of assumptions on transportation (which is the principal cost of SMF personnel) further research should refine the accuracy of these findings.

A related tradeoff is the choice of maintenance and repair strategies. Options include repair after breakdown, preventive maintenance, rotable spares, the use of throwaway components. Factors affecting the choice of options include costs of modular designs, reliability of the SMF equipment, tolerance of the SMF production layout to machine outages, response time of the repair system, cost of procurement and transportation of throwaway equipment spares. Further study of these issues is needed to determine the impact of each repair option or SMF program costs.

Another production control tradeoff is the location of the spares inventory. If the spares are warehoused in space, their procurement and transportation costs occur earlier in the program, adding to discounted costs, and the SMF requires warehousing facilities. But production outages are cut down, since spares are readily available. If the spares are bought and shipped from Earth as needed, production outages from broken equipment are lengthened, and the SMF therefore must have a larger production capacity. This brings in the issue of machine redundancy: if the system is sufficiently redundant, machine outages may be tolerable, and in-space spares inventory may be unnecessary.

All of the production control tradeoffs are interrelated, and should therefore be studied together. The challenge is to develop a production control philosophy well adapted to the economic and physical environment of the SMF.

13.7: WASTE REPROCESSING AT THE SMF

The reference SMF presented in this study wastes 50,000 tons of every 100,000 tons of material input. The solar cell factory wastes 36,000 of those tons. Therefore waste reprocessing options and low-waste design options should be considered for the SMF. The tradeoff to be studied is between the costs of the waste reprocessing equipment (or the incremental costs of substituting low-wasted designs in the reference SMF) and the costs associated with the input materials which will be wasted.

The latter costs consist of incremental costs of higher mining and refining output rates, larger transportation requirements from Moon to SMF, and higher material throughputs at the input end of the SMF.

On the other hand, if the waste is in a form suitable for radiation or micrometeorite shielding for space facilities (or more exotic uses such as large masses for inertial anchors), the product waste may be beneficial. The effect of this option is to reclassify the suitable waste as a useful product, and to assign a value to that waste. The tradeoff is then between using process waste versus unrefined lunar material for bulk shielding or other applications

13.8: SMF BUILDUP SEQUENCE

As discussed earlier for the lunar mining and refining, there may be cost advantages in setting up the SMF in incremental sections. In such a buildup scenario, the early SPS's would include significant fractions of Earth materials, which would be reduced in later outputs as the SMF becomes able to produce more components from lunar materials. This scenario has the disadvantage that it requires setting up earth manufacturing systems (for SPS components) which may be difficult to convert to production of earth outputs as the SMF is upgraded. However, the scenario also spreads the up-front costs of the program over a larger period, provides earlier economic returns, and reduces technical uncertainty by learning from the initial setup. Evaluation of these tradeoffs should include study of transportation and lunar base systems also, since a stepwise buildup of SMF capability suggests stepwise buildups of those system elements as well.

13.9: LOCATION OF FACILITIES

There are several possible orbital locations for the SMF, e.g. low-lunar, geosynchronous, Lagrange-point, resonant, high-earth. Choice of location for the SMF should be done by an overall systems analysis of the tradeoffs involved. For example, a low-lunar orbit reduces the velocity increment required between lunar surface and SMF. This is an advantage because the material wasted by the SMF does not have to travel to a higher orbit; however, the amount of this savings depends on the choice of transportation systems. On the other hand, locating the SMF in low-lunar orbit stretches the logistics and personnel routes between Earth and SMF; that cost increment also depends on the choice of transportation system, and the source of propellant (earth or lunar).

The SMF location tradeoffs also involve the eventual destination of the SMF products. For example, locating the facility in geosynchronous orbit could reduce the output transportation requirements, if the satellite assembly stations are also in GSO. Since this transportation requires more expensive packaging than the lunar-SMF transportation, this option can reduce costs.

In general, many of the facilities in the lunar-material scenario (lunar base, transportation transition points, SMF, assembly stations) have alternative locations, and the associated tradeoffs involve transportation costs, equipment design, availibility of energy, stationkeeping, worker safety, propellant and material sources. An overall systems analysis, including computer modeling and preliminary design of options, is needed to optimize the scenario.

A related set of tradeoffs is the location of individual processes. For example, material refining could be done in space rather than on the Moon. This tradeoff involves relative costs of equipment, transportation costs between the two locations, and the relative costs of maintaining and transporting personnel. Since logistics and personnel transportation to an orbital SMF is cheaper than to the Moon, this suggests that the lunar base should be kept as simple as possible; however, refining at the SMF requires transportation of larger quantities of lunar materials to the SMF. Furthermore, zero-g refining equipment is likely to be different than lunar equipment (including differences in power supply or power storage requirements), and will therefore have different costs. Similarly, some processes could be done on the Moon (slab or ribbon production) or at the satellite assembly sites (component subassembly) rather than at the SMF. These tradeoffs involve orbital locations, transportation capabilities, earth-material requirements, alternative equipment designs.

CHAPTER 14

CONCLUSIONS AND RECOMMENDATIONS

14.1: 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.

14.2: RECOMMENDATIONS

1. Conduct systems tradeoffs outlined in Chapter 13 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.

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.

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ADDENDUM I

DIRECT VAPORIZATION EXPERIMENTS

I.1: INTRODUCTION

The reference SMF design used Physical Vapor Deposition (PVD) as a key process in the fabrication of solar cells. In this process, atoms "boiled off" from source material (such as slabs of silicon) are deposited onto an exsisting surface, forming a "top" layer of new material. It is this layer by layer build up of materials which forms the solar cell (see Chap. 6).

PVD, or DV (direct vaporization), was selected for the SMF for the reasons discussed in full in Chap. 5. When considering the DV options, it was found that literature search and consultations with experts were insufficient to obtain the information required for detailed equipment designs. This was because the literature is very scant, expert opinions are limited by proprietary restrictions, and those expert opinions available contradict each other on significant factors, such as the relative effects of deposition rate and surface temperature, and the required annealing times and temperatures. Thus, the study group decided to perform experimental work on the DV of silicon and silica (SiO_2). This work had three purposes: 1) to investigate the feasibility of using DV for the various SMF processes, 2) to study the specific conditions necessary for the operation of the DV processes, and 3) to indicate the directions for future research, appropriate to the SMF DV processes.

The requirements for silicon deposition in the reference SMF are high deposition rates (4 microns/min) and columnar grains of 100-200 microns diameter (after processing). The technique used in the reference design involves deposition of a polycrystalline or amorphous silicon layer followed by a recrystallization process. As discussed in Chap. 5, direct vaporization cannot alone produce a monocrystalline silicon wafer. Some sources in the literature suggested estimated maximum practical deposition rates of .5 microns/min and suggested that a deposition surface temperature of 1200°C was necessary to get a crystalline deposit. If these estimates were accurate, the deposition section would require considerable lengthening, and the deposition temperature would destroy the rear aluminum contact. More specifically, the deposition process should be limited to a temperature low enough to avoid any significant diffusion of aluminum into the silicon (the Si-Al eutectic temperature is 578°C). The study was therefore needed to obtain quantitative information about the relationships between deposition rates, substrate temperature and the morphology of the deposited layer (particularly the grain size).

In these experiments, silicon and silica were vapor deposited onto 6061 aluminum alloy in a vacuum chamber. The power source fcr the experiments was a 6 kW Electron Beam gun. The tests investigated the effects of beam power on deposition rate, deposition rate on grain size, and substrate temperature on grain size when depositing silicon onto aluminum, and attempted to deposit silica onto an unheated aluminum substrate.

I.2: APARATUS

I.2.1 Deposition Equipment: A schematic representation of the equipment used in the vapor deposition experiments is shown in Fig. I.1. The apparatus may be divided into three sections: the vacuum system, the evaporator, and the substrate assembly; each of these is described below.

The vacuum system consists of a stainless steel chamber (with 2 lead glass viewing ports), a mechanical roughing pump, two oil diffusion pumps, and bourdon and ion pressure gauges. For these experiments, typical working pressures were in the low 10^{-6} Torr range.

The evaporator system consists of an electron beam gun, a magnetic deflection system, a power supply, and a lined hearth containing the source material (see Fig. I.2).

The electron beam gun consists of a tungsten filament cathode and a ground plate (which serves as an anode) which produces a stream of electrons directed vertically from the gun. An electromagnet is then used to "turn" the beam through 180° and direct the electrons towards the source material in the hearth. The gun is connected to a 10 kV/6kW power supply

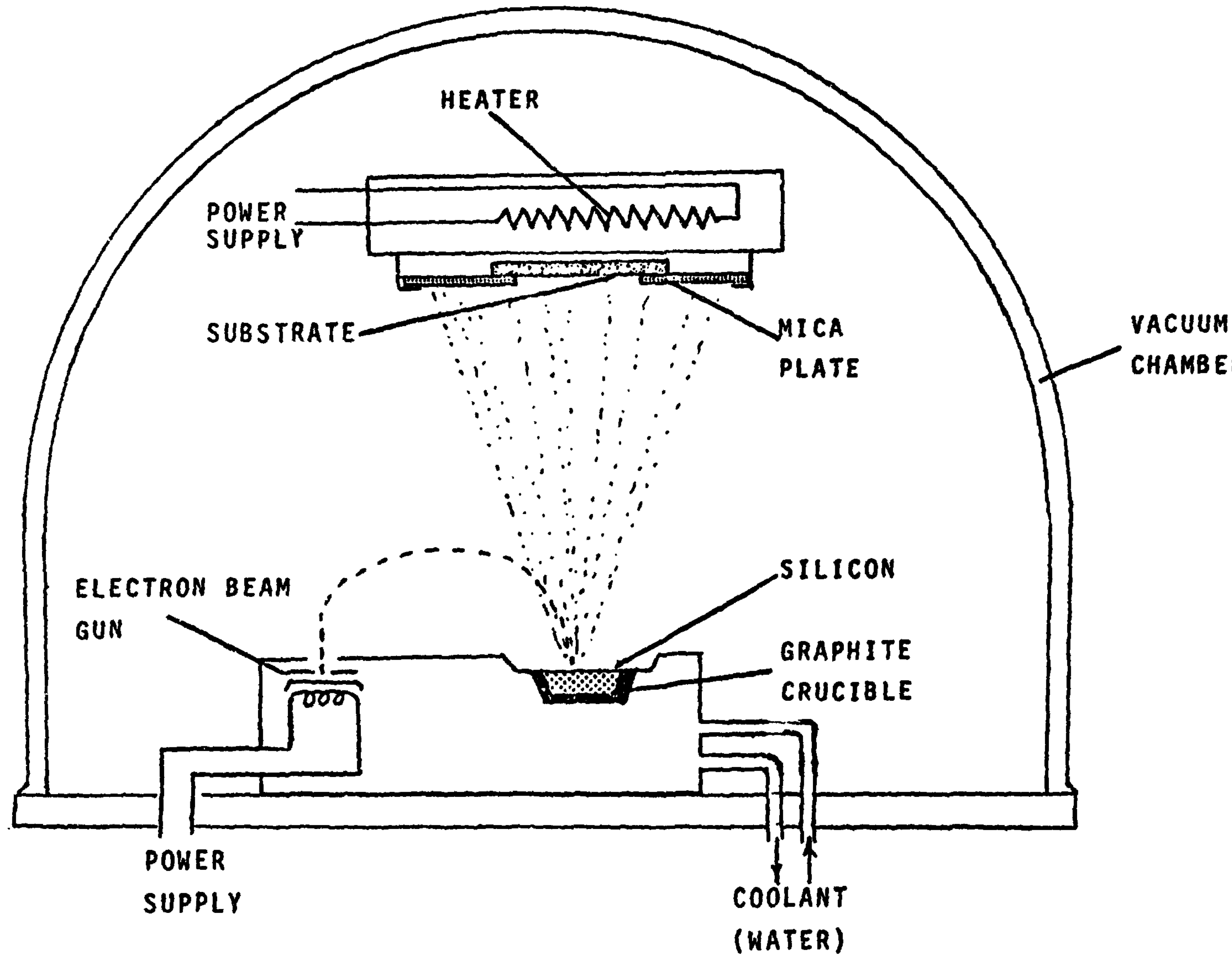

FIGURE I.1: SCHEMATIC OF EXPERIMENTAL SET-UP

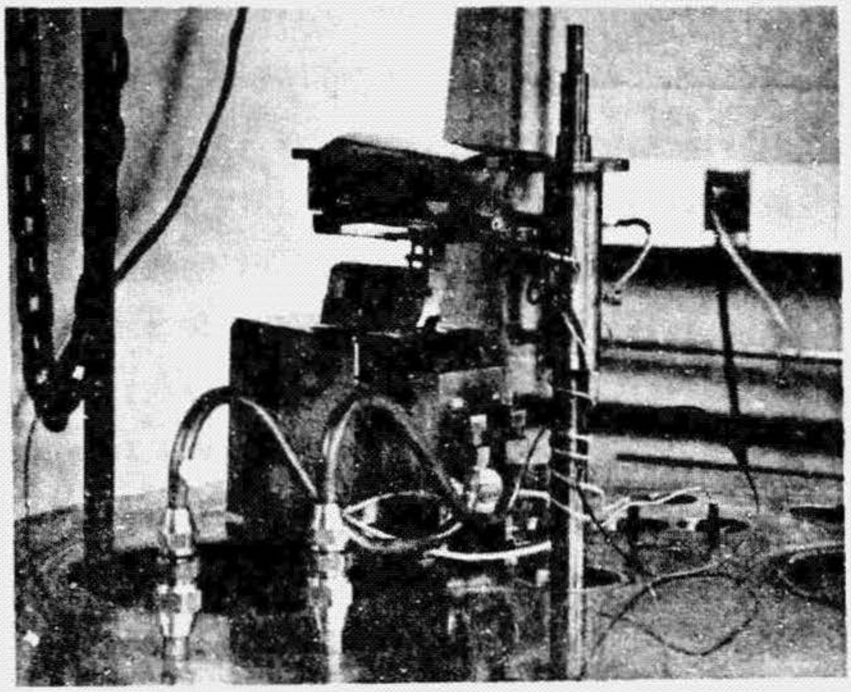

FIGURE I.2: APPARATUS FOR
VAPOR DEPOSITION EXPERIMENTS

outside the vacuum chamber via high voltage vacuum feed throughs.

The power supply allows some control over the way in which the source material is evaporated. First, a "position" control adjusts the electromagnetic field which deflects the electrons, allowing any point in the source material to be placed in the "focus" of the beam. Second, the input current into the gun may be varied, allowing variation of the the level of energy input into the source material. Third, a sweep control allows the beam to be swept across different proportions of the source material surface, giving a distributed energy input across the silicon surface.

The high energies involved mean that both the electron beam gun and the hearth containing the source material must be actively cooled by a water system. As can be seen from the figure, the gun and hearth are incorporated into a single unit requiring one inlet and one outlet pipe for the coolant.

The material to be deposited is placed inside a machined graphite crucible which acts as a liner for the hearth. Semiconductor grade silicon and quartz crystal, crushed into small pieces, degreased and cleaned, were used in the deposition experiments.

As shown in Fig. I.2 a nickel "guard" was built around the power lines and feed throughs in order to stop vaporized silicon from depositing itself onto the high voltage leads and causing a dangerous short circuit. Mounted on the guard was a mirror, angled to allow an observer at one of the windows to see the source material.

The <u>substrate assembly system</u> consists of a substrate holder, substrate heater, and thermocouple, all mounted on a spindle (see Fig. I.2). The spindle allowed the substrate assembly to be rotated in the horizontal plane so that the substrate was only positioned above the source material during the actual deposition.

The substrate holder was a mica sheet with a 2 cm x 2 cm square cut out of the center. The aluminum substrate (a polished disc 46 mm in diameter) was positioned over the hole and fastened to the mica by a steel strip. The mica was, in turn, fastened to the bottom of a steel frame which held a radiative heater directly above the substrate.

The substrate heater, used to control substrate temperature, consisted of thin tungsten wire wrapped around two aluminum rods. Two steel foil shields were positioned above the wire in order to deflect more energy onto the substrate. Power was supplied to the heater by a DC Variac unit outside the vacuum system.

A thermocouple, with one junction clipped to the substrate, was used to monitor substrate temperature.

I.2.2 Sample Analysis Equipment: In the silicon wafer of a solar cell, grain boundaries tend to inhibit the motion of charge carriers, and thus reduce cell efficiency. Therefore, an important measure of the quality of a silicon wafer is the average grain diameter. The deposited silicon films were analyzed to determine film thickness and average grain diameter.

Film thickness was measured using a Dektak; this machine measures the displacement of a diamond stylus which rides over the edge of the deposited film. Deformations in the substrate can lead to false readings, and so this method is limited to use on flat substrates (those showing less than .5 micron fluctuation across the substrate).

Average grain size was determined from micrographs taken using a scanning electron microscope (SEM). Average grain diameters were calculated by averaging several observed and measured grains -- films with no observable grains were considered amorphous. The SEM was also used in determining the thickness of deposits made onto substrates too deformed to use the Dektak. In this process, the sample was sliced, and a photograph of the cross-section taken through the SEM. The approximate film thickness could then be determined from the photograph.

I.3: EXPERIMENTAL PROCEDURE

In producing samples of deposited material, the study group followed the procedure outlined below.

The vacuum system was pumped down to the operating pressure -- in the low 10^{-6} Torr range -- and the EB gun switched on and adjusted to melt the material to be deposited (silicon or silica). Once the material was melted, power to the electron gun was adjusted to begin the vaporization process. Once vaporization had begun, the substrate (pre-heated to the desired temperature) was swung into position over the hearth. Deposition was allowed to continue for a measured time (typically 30 minutes), after which the system was shut down, and the sample removed for analysis.

I.4: RESULTS

The tests were exploratory in nature and conducted for the purpose of very preliminary investigations of the vapor deposition process. The time and equipment available precluded the production of a large number of measurable samples in this series of experiments. The results presented are, therefore, very rough estimates of possible performance, mainly confined to the effects of deposition rate on the grain structure of deposited silicon.

Table I.1 lists the measurable samples produced and their associated properties. A few of the samples produced were sufficiently deformed by thermal stresses (having been allowed to cool too rapidly after completion of the deposition process) so that they could not be analyzed; these samples are not listed.

TABLE I.1: SAMPLE MEASURMENTS

Sample Number	Deposition Rate (μ/min)	Substrate Temp. (°C)	Average Grain Diameter (μ)
3	0.29	510	0.4
5	0.25	505	0.44
8	0.04	500	1.04
9	0.83	500	amorphous
11	1.1	500	amorphous
16	0.15	450	0.22

Figure I.3 is a micrograph of sample number 3 at 3000x magnification. This is a polycrystalline sample, with each of the grains appearing as the small circles on the photograph.

FIGURE I.3: POLYCRYSTALLINE SILICON DEPOSIT

Figure I.4 is a micrograph of sample number 11 at 5000x magnification. This is an amorphous sample with no visible grain structure.

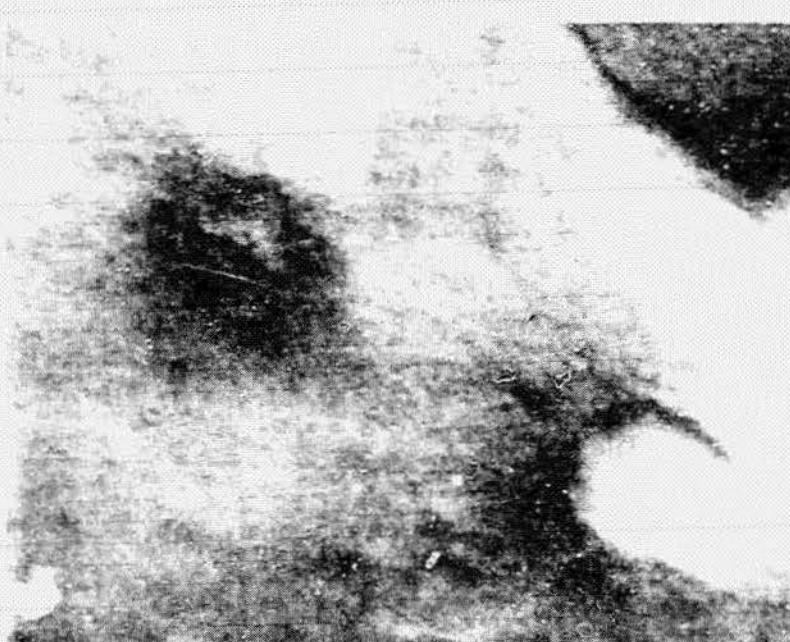

FIGURE I.4: AMORPHOUS SILICON DEPOSIT

Figure I.5 is a plot of grain size vs deposition rate for samples 3-11.

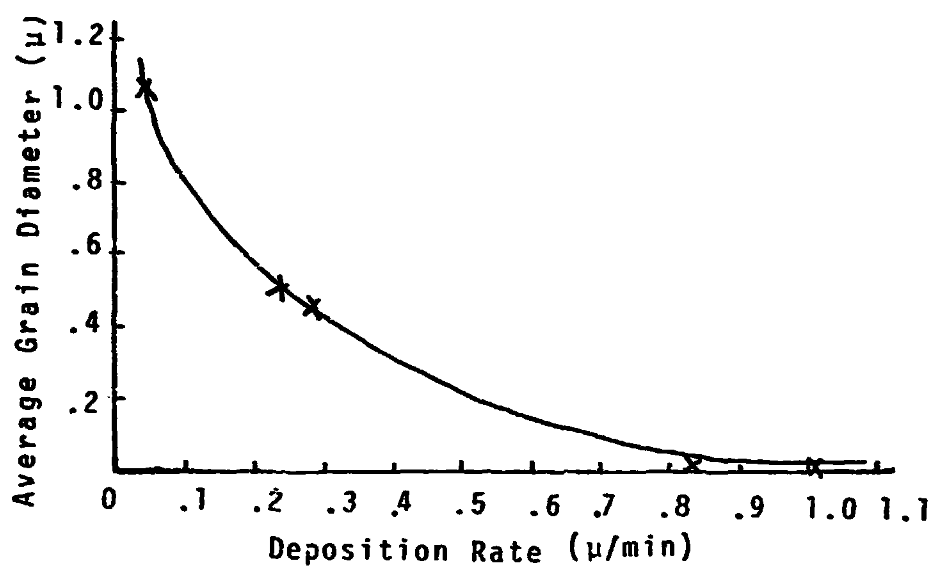

FIGURE I.5: AVERAGE GRAIN DIAMETER VS DEPOSITION RATES

A single attempt was made to deposit silica onto an unheated substrate by direct vaporization. After melting, the silica began to vaporize and a coating was deposited onto the aluminum. During the deposition process (a period of 15 min.) the substrate temperature rose through 215°C. With any thermal control, the stresses set up during cooling were sufficient to make the silica deposit separate from the substrate.

I.5: DISCUSSION OF RESULTS

From Table I.1 and Figs. I.3 and I.4 it can be seen that two types of deposit were made -- polycrystalline and amorphous. The amorphous deposit is in a higher potential energy configuration than the lattice structure of the polycrystalline deposit. Thus, in a recrystallization process, such as that used in the reference solar cell factory design, an initially amorphous deposit of silicon may be a better starting point than a polycrystalline one. This is an area in need of further research.

Figure I.5 shows that, for silicon deposited onto Al, the average grain diameter decreases with an increase in deposition rate. As the silicon atoms are initially deposited onto the substrate, a series of randomly oriented nucleation sites are formed. If there is sufficient time, the nucleation sites coalesce into a few large nucleation sites. The rate at which atoms are arriving at the surface initially determines the number of nucleation sites formed. Subsequently, as atoms arrive at the deposition surface they require a finite amount of time to find a vacancy in the developing lattice structure. As the rate at which the atoms are arriving is increased, there is less time for each atom to locate a vacancy, and some of the vacancies remain unfilled. Therefore, if the deposition rate is low, the atoms initially have time to coalesce and form a few large nucleation sites. Subsequent atoms fill most available lattice points at these nucleation sites and the grains grow outwards until they meet grains of different orientation -- thus determining the grain size. If the deposition rate is higher, initially many nucleation sites are formed leading to the growth of smaller grains. If the deposition race becomes sufficiently high, the atoms have insufficient time to assume a crystalline structure before subsequent atoms arrive and bury them -- this is an amorphous deposit.

The test to deposit silica by direct vaporization gave two results. First, it showed that silica may be deposited by direct vaporization. Second, it showed that there is a need to exercise thermal control over the substrate (to prevent the development of thermal stresses such as the ones encountered in the experiment).

I.6: CONCLUSIONS AND RECOMMENDATIONS

I.6.1 Conclusions:

1) Direct vapor deposition of either polycrystalline or amorphous silicon is feasible.
2) For silicon, an increased deposition rate tends to give a reduced average grain diameter.
3) Direct vaporization of silica is feasible.

I.6.2 Recommendations for further study:

1) Investigation of the requirements for optimum recrystallization (see Chap. 12).
2) Further investigation of the conditions for deposition of silicon onto aluminum. Of interest are the effects of substrate temperature, substrate morphology, and vapor pressure on the grain structure of the deposited silicon.
3) An investigation of the optimum conditions for the direct vaporization of silica.

ADDENDUM II

AUTOMATION AT THE SMF

II.1 INTRODUCTION

This automation addendum provides an explanation of how the designer should approach the configuration of the computer resource, using the solar cell factory (SCF) as an example. The philosophy presented is applicable to most of the other sections of the SMF.

A description of the free-flying hubrid teleoperator (FHT) remote repair system appears in Chapter 9, "Maintenance and Repair", because this is one of the principal repair devices used in the solar cell factory. Quality control sensors and the strategy for keeping inventory of factory materials and components is presented in Chapter 8, "Support Equipment Specifications". These items are therefore not covered in this addendum, although they involve issues of automation.

II.2: GENERAL CONCEPTS OF AUTOMATION

Because technology is moving so fast, one cannot accurately predict what computer capabilities will be just one decade into the future (Ref. 1,2); however, were advances in computer technology to halt today, the current state of the art is cause enough to make the computer resource a major consideration in space system design.

Recent advances in large scale integration (LSI) technology have changed the economics of computer system design and have led increasingly to the use of extremely small, inexpensive, yet powerful processing elements (PE's).

Computers in the 1990's resulting from the certain advances in integrated ciicuit (IC) technology will be available to the SMF designer for information storage, quality control, diagnosis of plant equipment, component control and coordination, and for the operation of teleoperators and crawlers. Decisions concerning the role of computers in components of a space system should not be relegated to the detailed design phase of the project, because such an approach would lead to lack of commonality between computer subsystems, reduced maintainability, and an inability to attain needed levels of fault tolerance (Ref. 3).

The computer resource for the Solar Cell Factory (SCF) is to be targeted for use in two areas of industrial automation: manufacturing control and robotics (Ref.3). Manufacturing control applies automation to the ti-- sequenced manipulation of the geometries of raw . .rials under computer supervision to form parts that are then assembled. A robot can be defined as a mobile manipulator not requiring the constant direction of an operator. Clearly, the SCF crawlers and teleoperators fall under this latter category. A description of the solar cell factory robots and the automated functions of the teleoperators is presented in Chapter 9.

Standardization of the hardware and software of the computer resource will help reduce system complexity and cost. This commonality would have obvious benefits if the computer resource were geographically distributed in the SCF. Taking an even wider view, on the scale of the SMF itself, Matelan (Ref. 4) suggests that the computer resource of the SCF and the habitat be designed as if they were joined so that if for some reason the connection is needed, such a task could be accomplished with ease.

All computers, whether fixed or mobile, are designed from the beginning to make them function as integral members of the resource. The computer resource should be thought of as a major system component itself, rather than as a group of elements in other components. This coordinated integration of computing power, cutting across subsystem boundaries, could be a unifying force in the overall design of a space manufacturing and habitation facility.

This addendum suggests the adoption of a distributed computer control scheme for the SCF. Ramamoorthy and Krishnanao (Ref. 5) define a distributed computer system as "an interconnection of digital systems called Processing Elements (PEs), each having certain processing capabilities, which are spatially either close or far apart, communicating with each other through a common memory, a bus or a communication line, and having either apparent or hidden hierarchical levels of control."

The adoption of a distributed control strategy must be justified for the application under design, the SCF. Ref. 6 suggests the following criteria which the application environment must satisfy to justify a distributed computer configuration:

(1) The application is amenable to logical division into autonomous units.

(2) The data collection and reduction functions are distributed in space.

(3) The resources required for a subset of functions can be predicted.

The first criterion can be seen to be satisfied upon examining Figure 6.8 illustrating the manufacturing process of the SCF. In this case the various machines could be considered the autonomous units. Data collection and reduction will occur locally at the component/machine level and the information will be made available periodically to the higher levels of control. The system is defined well enough so that the necessary means for control can be estimated.

The designer may be tempted to adopt a central computer to control all aspects of the facility; however, a comparison between a distributed computer resource and a central computer shows that the distributed approach has distinct advantages making it the more attractive choice. The use of one computer would require a complete backup in case of a computer failure--an expensive arrangement.

With a distributed configuration the failure of one PE will not shut down the entire system, and in addition, the computer resource can be designed to reconfigure itself around a failed processor.

This dispersed system makes early subsystem checkout and fault tracing easier to accomplish. The modular nature of the distributed system simplifies the hardware and software by dividing the system into units of manageable complexity and allows for easy tailoring of the computer resource to the application. A system with distributed PE's can be easily expanded without modifying the entire facility, while expansion of capabilities and modification of programs can be quite cumbersome in a central computer. Interestingly, the direct costs of a single, powerful central processing unit and its software are higher than the combined costs of multiple, lower-power central processing units and associated software that together provide equivalent performance (Ref. 7).

The most important step in the design of a distributed computer architecture that matches the application is the definition of the process and the possible failure modes of that process, i.e. one must know what is to be controlled before deciding on a control scheme (Ref. 8, 9, 10). This definition must include the normal functions of a component, assorted monitoring functions, the coordination of the components of a machine, the coordination of the machines of a strip and the coordination of 14 strips to form a package.

What needs to be coordinated will become obvious when the objectives of the facility are examined. Further, the modes of failure at all levels should be predicted, as well as the amount of time between the occurrence of a failure and when it is corrected. One should examine how long a process can continue within tolerable limits while it is not being controlled and what the "regret" is to the facility of completely losing a particular component/machine. How the process will be safely started and stopped is a very important matter to address. From this analysis the designer should be able to detect decision points in the control structure, e.g., when part of a strip should be stopped or when a crawler/teleoperator should be alerted for a replacement or repair job. Here the designer should realize that functions which inherently lend themselves to centralized decision, like those mentioned above, should not be distributed (Ref. 11). This careful analysis of the application will guide the designer to the correct architecture and thus lead to the design of a successful distributed system.

The designer is now confronted with the question of processor interconnection schemes, and thus with one of the most difficult issues in configuring the computer resource. Interconnection strategies will have to be dealt with at all levels of the hierarchy. Ref. 12, which discusses these issues at length, presents this important facet of the design under three broad categories:

(1) Physical aspects of the configuration

(2) Control and communication issues

(3) Reliability issues

The distributed systems research indicates clearly, though, that the three categories listed above cannot be considered alone; they impact each other. Here, again, the careful analysis of the requirements of the facility mentioned earlier will be the best guide to the designer on how these three issues should be resolved.

This addendum presumes that each component within a machine will be controlled by its own processing element, e.g., a microprocessor with sufficient memory and processing power to adequately regulate the component and also interact with the higher levels of control. The designer has the option of either physically imbedding a microprocessor into a component, which would simplify the interfaces between the processing element and the component instrumentation (Ref. 10, 13), or of putting all the microprocessors of a particular machine on a common board near the machine, which would facilitate replacement and repair of the processors (Ref. 11).

Ref. 14, the classic study of the taxonomy of inter-connected computer networks, lists the advantages and dis-advantages of several computer networks. How well a micro-processor is programmed and interfaced as part of an integral control system determines whether a particular microprocessor's advantages will be realized (Ref. 15). Further, maintaining microprocessor homogeneity throughout the system will enhance the design of an integrated computer resource that is fault recoverable.

The designer should be aware of the special conditions in earth orbit and in the SCF itself so that appropriate processing elements and bus lines can be chosen that will not degrade in such an environment.

II.3 COMPUTER CONTROL SYSTEM REQUIREMENTS

The kind of coordination and communication necessary for the SCF may become obvious with the following example. Tables 1 and 2 show a simple breakdown of control functions of the direct vaporization of aluminum [illegible]

Intercommunication needs between [illegible] processing elements are minimal; however, the components of a machine will need to be coordinated to meet the objectives of that particular machine. This could be accomplished by a machine processing element dedicated to overseeing the shutdown and startup of the components, alerting the level of control above it, the strip controller, that an intolerable condition in that machine has been encountered, and transferring data.

The application clearly reveals the requirement for a strip control (see Figure 6.8). The strip controller will be needed to halt all the machines prior to the panel alignment [illegible] insert machine if any one of these ceases to operate because of an intolerable condition. Further, with these machines shut down, the panel insert machine must be alerted

TABLE II.1

DV OF AL MACHINE COMPONENT
CONTROL FUNCTIONS

EB Gun
power, current, voltage levels
filament feed mechanism, filament use
beam direction
machinery health
Slab Feed
rate of feed
slab co[illegible]ction
need for more stock
machinery health
Thick[illegible]ss Monitor
data gathering
movement across width of belt
machinery health

TABLE II.2

DV OF AL MACHINE CONTROL

Messages Received

from component control

- need for replacement or non-urgent repair
- notice of intolerable condition
- data

from strip control

- notice for start-up
- notice for shutdown

Messages Given

to component control

- component(s) start-up
- component(s) shutdown
- confirmation of messages received

to strip control

- need for replacement or non-urgent repair (teleoperator/crawler)
- notice of intolerable condition
- data

to start providing spare panels. The appropriate teleoperator would then be alerted to redress the anomalous condition. A similar situation would occur with machines past the panel insert zone except that the panel insert machine would start collecting good panels from the previous machines. This instance also reveals the need for a higher level of control, namely a package section control, because when one of the production strips past the panel alignment and insert zone is stopped, this will require all fourteen strips past the insert zone to halt, unless a missing strip in a package can be tolerated. The above illustrates why central processors could be important at various levels within the computer resource hierarchy.

With respect to communication in a distributed computer resource, Ref. 16 gives the following explanation: "The key to distributed systems is the establishment of communications. In general, the sending of a message is equivalent to transmitting energy, and it is desirable to minimize the system energy. To put it another way, it is desirable to transmit a minimum amount of information, consistent with function, within and between systems. The distributed system is fundamentally intended to minimize transmission of information."

When unscheduled events like malfunctions occur requiring the [illegible]ing of machine(s), an interrupt in the programs can be employed that stores the state of the task in progress until the problem is rectified. Further, Ref. 18 suggests the use of an interrupt in all processors every few milliseconds to coordinate the timing of all functions in the system.

The designer will eventually need to decide how often local information, whether it be quality control data, e.g. thickness, composition and temperature, or a rundown on the state of a machine, should be provided to the higher levels of control. In general, the designer should move those functions that are done most frequently down the hierarchy, and those done less frequently up the hierarchy.

The communication paths in the SCF will most likely be exposed to a hostile environment that could garble messages. Use of optical communication paths may be attractive for this type of environment. Ref. 17 notes procedures for adding redundant bits to a message so that the receiver can detect an error in the message on its arrival. Some schemes not only detect errors at a receiver, but also correct them.

The analysis performed on the application should also examine the "regret" of losing a particular component/machine so the designer will have some idea about those functions requiring the greatest reliability.

One approach to making the distributed computer system more reliable is by simply duplicating the microprocessors wherever they occur, whether at the component level or at one of the control levels (Ref. 4, 17). This philosophy could extend to sensors and communication buses as well. One of the two processors would operate in a standby mode, ready to take over in the event of a failure. To decide when a processing element has failed, though, is not easy, and generally one cannot rely on the module itself to announce that it is failing (Ref. 12).

Another approach to making the system more reliable is to reconfigure the computer resource when a failure of a processor occurs. Reconfiguration is characterized by the ability of a system to adapt itself to changes in its status and to provide a variable organization. This could be accomplished with spare micro processors strategically located throughout the computer hierarchy, e.g. one spare processor for each machine (Ref. 2, 18). When a processor has been determined to fail, the appropriate spare would then assume its load until the necessary replacements had been made.

A reconfiguration strategy can be determined prior to the execution of a job based on predicted failure modes--this is known as static reconfiguration. Dynamic reconfiguration strategies could also respond to predefined situations, but would take into account the current status of the system. This latter reconfiguration scheme can complicate the software and the amount of processing needed, or as Ref. 12 explains, "...dynamic reconfiguration involves high overhead and may be restricted to the cases where reconfiguration is a must (e.g. failure modes), or to the cases where the overhead to determine a reconfiguration strategy is tolerable."

Some combination of duplicating processors and using spares at various levels may turn out to be the ideal configuration. A preliminary analysis of the SCF indicates that the greatest reliability will be needed at the panel insert machine, a "buffer" which can store good and defective panels and also provide spare panels when needed.

Even if the designer adheres to a simple and consistent design of the computer resource for the SCF, in all probability the software will be the most unreliable part of the configuration (Ref. 4). Bishop (Ref. 20) suggests the use of a simulation program to model the communication links between processors. If the model is realistic, the program should be able to detect and diagnose real-time software errors in the network.

II.4 EXAMPLES

II.4.1 Example of An Automated Control Computer Structure:

As is clear from the discussion of section II.2, it is extremely difficult to predict advances in computer technology a decade ahead. However, the current state of the art and the promise of improved capabilities (e.g. high-density integrated circuits, hologramic storage, vision, voice actuation) make computers a major system element in space hardware design. A computer structure at the space manufacturing facility can be used for automated control of machinery, inventory, routing, maintenance and repair scheduling, monitoring, quality control. Computers could also be used in robots, defined here as machines capable of dealing with some uncertainty in their environment.

<u>II.4.2 Example of An Automated Control System</u>: The basic requirements of computer structures at the SMF can be summarized as follows, based on the discussions of sections II.2 and II.3. The system must provide localized functions (monitoring, control, quality control) to a large number of machines spread throughout a large volume of space. The system must also provide intermediate functions (maintenance and repair scheduling, routing) to machines and groups of machines. The system must provide centralized functions to the entire SMF or to major sections of the SMF (inventory control, resource allocation, factory status monitoring and display). Finally, the entire system should be reprogrammable, to adjust for variations in production requirements. A single computer, tied to all sensory and control systems in the factory, has several disadvantages. First, most sensor systems and many control systems send out or receive analog signals, which are less reliable than digital signals. Therefore the machines should include analog/digital conversion devices and use digital communications with the master computer. Second, there is a critical need for damage tolerance in the [illegible] system, since a failure in the master computer could

lead to extensive damage in the suddenly uncontrolled factory. This argues for a fully redundant computer system or a set of decentralized emergency control units. The transition from primary master computer to a backup master computer can be a very delicate operation, especially if it requires the transfer of large amounts of information; it also requires a sophisticated arbitration system to decide when the primary computer is malfunctioning and to order the switch. Third, such a master computer would be very difficult to reprogram, due to the complexity of its algorithms. Thus even a minor change in production requirements could require a complex reworking of the control system. Fourth, the input/output systems of the master computer would have to handle very large amounts of data.

These criteria suggest a distributed computer structure consisting of several levels of centralization (localized, intermediate, centralized) with increasing levels of sophistication. The system should be connected by a network of communications paths, along which can travel sensor data, control commands, status information, emergency requests, reprogramming commands, and blocks of memory.

An example of such a computer structure for the solar cell factory appears Fig. II.1. At the local machine level, microprocessors (labeled A1, A2, A3,...B1, B2, B3,...) handle the functions necessary to the machine's operations (e.g. monitoring and diagnosis, control, quality assurance). The

A series watches over one production strip, the B series over another, etc.

Each set of microprocessors on a strip is tied to each other and to a "strip host." The strip host contains in memory all the software used by the strip microprocessors, as well as diagnostic programs. It can therefore monitor the proper function of the microprocessors, and correct software malfunctions. In addition, the strip host arbitrates between the requests for assistance of the microprocessors, and assigns the computer resources available. The strip host also regulates communications between the strip microprocessors and the other computers in the network.

The 14 strip hosts in a section of 14 production strips are tied to each other and to a section control computer. Based on information from the strip hosts, the section control schedules maintenance and repair. It also monitors the strip hosts and reprograms them as needed.

The 19 section control computers (for the solar cell factory's 19 production sections) are tied to each other and to the main solar cell factory control facility, which includes computers and human supervisors. This facility monitors and reprograms the section control units, and takes over problems which the localized computers have found too difficult.

Although Figure II.1 shows the separation between software sections of the computer structure, it does not indicate the location of the computers themselves. It is

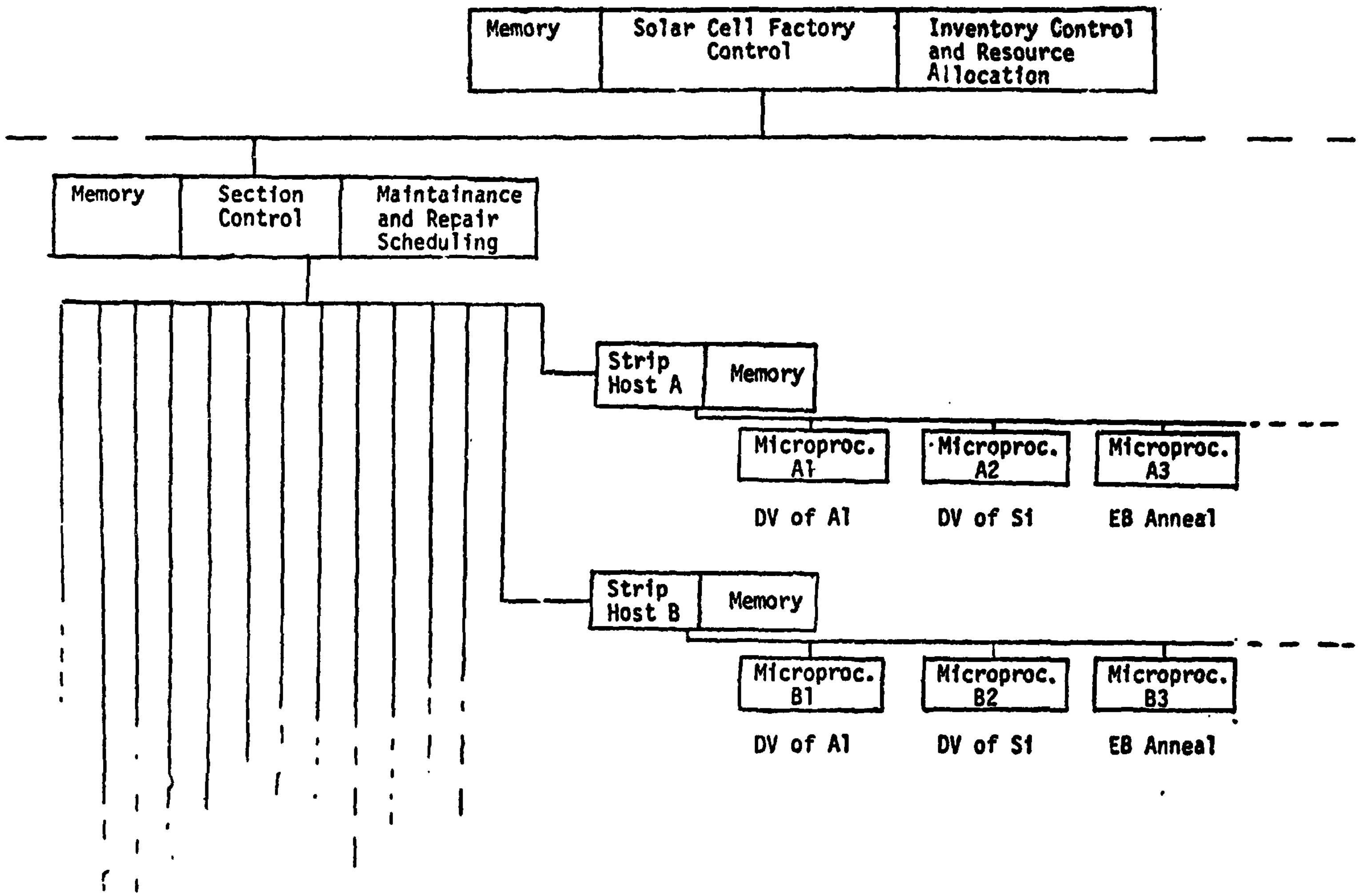

FIGURE II.1: EXAMPLE OF SCF COMPUTER CONTROL HIERARCHY possible to group the computers into clusters to simplify support services. However, this stretches the data transmission lines and increases the risk of a single physical accident damaging a substantial fraction of the computer capability. Although difficult to assess at this stage, some physical distribution of equipment seems desirable.

The most critical factor in the design of a computer system for the solar cell factory is ility and damage tolerance. Since loss of control can damage sections of the factory, or at least stop production in the affected section, the design of a fail-safe or, better yet, fail-operational computer system becomes a very worthwhile effort. By comparison, the mass and power consumption of the system are not significant criteria, since they are expected to be very small percentages of SMF mass and power.

Part of the solution to the problem of reliability is the development of long-life space-rated computer hardware. In addition the equipment should be modular and repairable by replacement of modules. This repair will probably be done by automatic equipment in the solar cell factory.

However, computer units will fail, and there are several operations to make the system tolerant to such failures, as discussed in section II.3. The first option is simple redundancy, in which each unit is backed by its twin, ready to take over when a malfunction is diagnosed. The diagnosis and switch command can be done either by a computer elsewhere in the hierarchy, or the unit itself and its redundant twin can keep track of each other, comparing functions to determine malfunctions. However, the possibility of conflict between the two may require another redundant unit and majority rule on malfunctions. Such systems are in development today. One disadvantage of this option is that it requires many computers, many of which do not operate very often.

Another option is backing up a local computer with a more centralized one. This requires that the centralized computer have all the functions of the local device in memory and sufficient data lines to take over the monitoring and control functions of the local computer. One disadvantage of this system is that several failures of local computers can overload a centralized computer; however, the centralized computer can be backed up by a more centralized computer, etc. A more serious drawback is that the failure of a centralized computer leaves the local computers without backup.

Section II.3 has discussed the concept of distributed, self-reconfigurating computer systems. These can provide "graceful degradation" and continuity in unaffected areas when malfunctions do occur. The key concept is a priority structure which allows the system to reassign computer resources to take over the functions of malfunctioning units. The significant advance over the state-of-the-art is that <u>any</u> computer in the network can be reprogrammed to take over at least <u>some</u> of the functions of any other computer.

This can be done by assigning each computer unit two types of functions. The first are "kernel functions," those functions required for the normal operation of the unit. For example, microprocessor A2 in Fig.II.1 has kernel functions which handle the monitoring and control of the DV of silicon in production strip A. These kernel functions are performed under any circumstances, provided that microprocessor A2 is not defective (however, the kernel functions can be reprogrammed to adjust production requirements). The second types of functions in the unit are those occasionally inserted to operate on other sections of the factory; in other words, the unit has extra capacity and capability beyond that required for its kernel functions, and that extra computation power can be loaded with other functions used to fill in for malfunctioning units.

Several examples from Fig. II.1 can illustrate the possibilities of such a system. Example 1: Microprocessor A3 malfunctions; strip host A diagnoses malfunction, ta'ᶜˢ A3 off-line, takes the proper functions of A3 from its memory, loads half of those func⁺·ˎ^, into A1 and half into A2, and commands both of these uᵢᵢ..ˎs to time-share the running of A3's machine with their own kernel functions. After these steps, the strip host sends a request for repair either to the section control or to the repair systems, and returns to normal operations. The microprocessors A1 and A2 do their kernel functions and A3's functions as well.

Example 2: Here again, microprocessor A3 malfunctions. Strip host A takes A3 off-line. Rather than reprogramming A1 and A2 as in Example 1, strip host A requests assistance from section control. Section control commands strip host B to program microprocessor B3 to time-share its kernel functions between its own machine and A3's machine. Since B3's and A3's kernel functions are the same, B3's capability is sufficient to run both machines. After these commands, the section control schedules a repair on A3 and returns to normal operations. Strip hosts A and B return to normal operations also, except that they route information between A3's machine and B3.

Example 3: Here again, microprocessor A3 malfunctions. Strip host A takes A3 off-line and requests assistance directly from strip host B. Strip host B then reprograms B3 as in Example 2. If strip host B or microprocessor B3 is too busy, strip host A switches its request to strip host C, etc. Simultaneous requests from several strip hosts (though unlikely) are arbitered by section control.

Example 4: Strip host B malfunctions. Section Control diagnoses this and takes strip host B off-line. Section control can then either: program microprocessors B1, B2,... to take over their strip host's functions; or program strip hosts A and C to time-share their strip host kernel functions to fill in for strip host B; or program other computers (microprocessors, strip hosts, section control computers) in some combination to take over the functions of strip host B. Section control then schedules repair for the damaged unit.

As these examples show, the distributed control system has the ability to reassign the functions of any damaged unit or units to other computers in the hierarchy. The system is therefore very damage-tolerant. However, this requires the ability to route data and commands from any unit to any other. The traditional method to do this is to provide a communication line between each pair of devices. On the scale of the solar cell factory system, this would require an enormous number of data lines. A more advanced approach is to provide a smaller number of trunk lines and switchboard systems to route the information. The trunk lines need not be wires, but can use microwaves or lasers instead. This option is currently used by the telephone company for long-distance calls. A disadvantage of this option is that switchboards are slow and can be overloaded. One option to eliminate some switchboard systems is to attach an identification code to each transmission and send it over common data lines to all units (or a large group of units). The code cues the destination unit to absorb the transmission. The other units ignore the data. This concept requires multiplexing the data lines to keep units from sending simultaneous messages. This in turn requires a common clock for all the units, and a set order of time increments allocated for sending. The number of messages sent by all the units then sizes how many units can be on the same trunk line. Also, centralized computers can allocate extra sending time to local computers requiring assistance. Systems of this type are currently in development (Ref. 19).

Another advantage of the distributed control concept is that test functions on computers can be applied by any other computer or group of computers. Therefore even the sophisticated factory control computers can be monitored by the less centralized devices.

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APPENDIX

COMPUTER PROGRAM LISTINGS AND OUTPUTS

A.1: PROGRAM SMFCOST

(LINE ITEM COSTING OF SMF)

LISTING

DATA

OUTPUT

```
C***********************************************************************
C*  LINE ITEM COSTING PROGRAM FOR A SPACE MANUFACTURING FACILITY
C*  DEVELOPED UNDER CONTRACT TO THE NASA MARSHALL SPACE FLIGHT CENTER
C*  M.I.T. SPACE SYSTEMS LAB
C*----------------------------------------------------------------------
C*  DAVID L. AKIN                      MARCH 13, 1979
C***********************************************************************
C*  PERFORM INITIAL HOUSEKEEPING
C*
      IMPLICIT REAL(K,L,P,M)
      DIMENSION COSTS(10,60),SUMM(2,60),TOTALS(12),RANDD(4),PROC(4),
     *TITLE(20),SUPER(5),MSCPM(60)
      DIMENSION NAME(7,60),NAMEC(7)
      DATA COSTS/600*0./,TOTALS/12*0./
C***********************************************************************
C*  READ IN SYSTEM PARAMETERS
C*
C*-------------------------------------------------------------------
C*  READ IN TITLE FOR PRINTOUT HEADING
C*
      READ(5,105)(TITLE(I),I=1,20)
C*----------------------------------------------------------------------
C*  READ IN:
C*     ALPHA    -  DUTY CYCLE MULTIPLIER
C*     HABM     -  HABITAT MASS (KG/PERSON)
C*     HABP     -  HABITAT POWER (KW/PERSON)
C*     HABRAD   -  HABITAT RESEARCH AND DEVELOPMENT COST ($M)
C*     HABPRC   -  HABITAT PROCUREMENT COST ($/KG)
C*     SUPER(1)-  HUMAN SUPERVISION OF TELEOPERATOR (HR/REPAIR HR)
C*     SUPER(2)-  HUMAN SUPERVISION OF AUTOMATED REPAIR
C*     SUPER(3)-  HUMAN SUPERVISION OF EXPENDABLES REPLACEMENT
C*     SUPER(4)-  HUMAN REPAIR OF REPLACED COMPONENTS
C*     SUPER(5)-  DIRECT HUMAN ON-SITE REPAIR (HR/REPAIR HR)
C*
      READ(5,101)ALPHA,HABM,HABP,HABRAD,HABPRC,(SUPER(I),I=1,5)
      HABRAD=HABRAD*1000000.
C*----------------------------------------------------------------------
C*  READ IN:
C*     TCARGO   -  CARGO TRANSPORT COST ($/KG)
C*     TPERS    -  PERSONNEL TRANSPORT COST ($/KG)
C*     FFACT    -  EMERGENCY SPARES FRACTION
C*     UTRAIN   -  CREW TRAINING COST ($/PERSON)
C*     QTRANM   -  CREW TRANSPORT MASS (KG/PERSON)
C*     XCHGM    -  CREW ROTATION RATE (TIMES/YEAR)
C*     W        -  LABOR WAGE ($/HR)
C*     LCONSM   -  LIFE SUPPORT EARTH CONSUMABLES (KG/CREW-DAY)
C*     S        -  SUPPORT OVERHEAD FACTOR
C*     YEARS    -  OPERATIONAL LIFETIME OF SMF (YEARS)
C*
      READ(5,101)TCARGO,TPERS,FFACT,UTRAIN,QTRANM,XCHGM,W,LCONSM,S,YEARS
C*----------------------------------------------------------------------
C*  READ IN:
C*     MSMF     -  SMF STRUCTURE MASS (KG)
```

```
C*     PSMF     -  SMF STRUCTURE POWER (KW)
C*     CSMF     -  SMF STRUCTURE PROCUREMENT COST ($/KG)
C*     EXSMF    -  SMF STRUCTURE EXPENDABLES (KG/YR)
C*     ALFA     -  SPECIFIC POWER OF POWERPLANT (KG/KW)
C*     GCOST    -  COST OF POWERPLANT ($/KW)
C*     K        -  NUMBER OF MACHINE TYPES IN SMF
C*     H        -  NUMBER OF HOURS IN YEARLY SMF OPERATIONS (HRS/YR)
C*     APROD    -  PRODUCTIVITY OF ASSEMBLY CREW (KG/CREW-HR)
C*     R        -  INTEREST RATE FOR COST DISCOUNTING
C*
      READ(5,101)MSMF,PSMF,CSMF,EXSMF,ALFA,GCOST,K,H,APROD,R
C*----------------------------------------------------------------------
C*  READ IN:
C*     RANDD(I)    -  (1) R&D COST FOR LOW TECHNOLOGY ($/KG)
C*                 -  (2) MEDIUM TECHNOLOGY
C*                 -  (3) HIGH TECHNOLOGY
C*                 -  (4) ULTRA-HIGH TECHNOLOGY
C*     PROC(I)     -  (1) PROCUREMENT COST FOR LOW TECHNOLOGY ($/KG)
C*                 -  (2) MEDIUM TECHNOLOGY
C*                 -  (3) HIGH TECHNOLOGY
C*                 -  (4) ULTRA-HIGH TECHNOLOGY
C*
      READ(5,104) (RANDD(I),I=1,4),(PROC(I),I=1,4)
C***********************************************************************
C*  WRITE OUT INITIAL PARAMETERS
C*
      WRITE(6,401) (TITLE(I),I=1,20)
      WRITE(6,402)TCARGO,TPERS
      WRITE(6,403)FRACT,UTRAIN
      WRITE(6,404)QTRANM,XCHGM
      WRITE(6,405)W,LCCNSM
      WRITE(6,406)S,YEARS
      WRITE(6,407)MSMF,PSMF
      WRITE(6,408)CSMF,EXSMF
      WRITE(6,409)ALFA,GCOST
      WRITE(6,410)K,H
      WRITE(6,411)APROD,R
      WRITE(6,417)HARM,HADP
      WRITE(6,418)HARRAD,HABPRC
      DO 1 I=1,4
 1    WRITE(6,419)I,RANDD(I),I,PROC(I)
      WRITE(6,420)SUPER(1),SUPER(2)
      WRITE(6,421)SUPER(3),SUPER(4)
      WRITE(6,422)SUPER(5)
      WRITE(6,416)ALPHA
      IMACH=IFIX(K)
C***********************************************************************
C*  INITIALIZE SOLAR CELL FACTORY DUTY CYCLE (DCTOT), AND CALCULATE
C*     THE AVERAGE LAUNCH COSTS FOR REPLACEMENT PARTS
C*
      IRUN=0.
      DCTOT=1.
      T=TPERS*FRACT+TCARGO*(1.-FRACT)
```

```
C*****************************************************************************
C*  READ IN MACHINE PARAMETERS
C*    EXPLANATION OF MACHINE PARAMETERS:
C*         QM  -  MACHINE THRUPUT (NOT USED)
C*         LM  -  OPERATING LABOR REQUIREMENT (CREW HR/OPERATING HR)
C*         EM  -  EARTH EXPENDABLES (KG/HR)
C*         BM  -  PROCESS R&D COST AND SYSTEMS INTEGRATION ($M)
C*         XM  -  COST OF EARTH EXPENDABLES ($/KG)
C*         NM  -  NUMBER OF THIS TYPE OF MACHINE
C*         KM  -  NUMBER OF COMPONENT TYPES
C*
      WRITE(6,412)
      WRITE(6,234)
      DO 4 J=1,IMACH
      READ(5,102)(NAME(I,J),I=1,7),QM,LM,EM,BM,XM,NM,KM
      IRUN=IRUN+KM+3
C*  KEEP TRACK OF PAGINATION
      IF (IRUN.GT.50) WRITE(6,233)
      IF (IRUN.GT.50) IRUN=0
C*  PRINT OUT MACHINE INPUT VARIABLES
      WRITE(6,413) (NAME(I,J),I=2,7),LM,EM,XM,BM,KM
      BM=BM*1000000.
C*
C*    EXPLANATION OF ARRAY 'COSTS':
C*      FOR THE J(TH) MACHINE TYPE -
C*
C*        NONRECURRING COSTS:
C*          COSTS(1,J)  -  RESEARCH AND DEVELOPMENT
C*          COSTS(2,J)  -  PROCUREMENT
C*          COSTS(3,J)  -  TRANSPORTATION
C*          COSTS(4,J)  -  POWERPLANT
C*
C*        RECURRING COSTS:
C*          COSTS(5,J)  -  OPERATING LABOR
C*          COSTS(6,J)  -  EXPENDABLES PROCUREMENT
C*          COSTS(7,J)  -  EXPENDABLES TRANSPORTATION
C*          COSTS(8,J)  -  REPAIR LABOR
C*          COSTS(9,J)  -  REPAIR PARTS PROCUREMENT
C*          COSTS(10,J) -  REPAIR PARTS TRANSPORTATION
C*
C*
      ICOMP=IFIX(KM)
      PROD=1.
      PROD1=1.
C*----------------------------------------------------------------------------
C*  READ IN COMPONENT PARAMETERS FOR EACH MACHINE
C*    EXPLANATION OF COMPONENT PARAMETERS:
C*         NC  -  NUMBER OF THIS TYPE OF COMPONENT
C*         MC  -  MASS OF INDIVIDUAL COMPONENT (KG)
C*         PC  -  POWER OF INDIVIDUAL COMPONENT (KW)
C*         CCC -  COMPONENT COMPLEXITY CODE (1-4)
C*         DC  -  DUTY CYCLE (%)
C*         LRC -  REPAIR CODE (1-5)
```

```
C*        RC  -  REPLACEMENT PARTS (KG/YR)
C*
      DO 3 I=1,ICOMP
      READ(5,102) (NAMEC(I1),I1=1,7),NC,MC,PC,CCC,DC,LRC,RC
C*  FIND NONRECURRING COSTS AND REPAIR PARAMETERS FROM CODES (CCC & LRC)
      CC=MC*PROC(IFIX(CCC))
      LC=SUPER(IFIX(LRC))
      IF (LRC.NE.5.) RC=.05*MC
C*  NCT= TOTAL NUMBER OF COMPONENT TYPE IN ALL OF THIS MACHINE TYPE
      NCT=NC*NM
C*  APPLY 90% LEARNING CURVE IF MORE THAN 100 UNITS ARE USED
      IF (NCT.GE.100.) CC=CC*NCT**(-.15)/(.85)
C*  ADJUST PROCUREMENT COSTS FOR MACHINE RELIABILITY
      CC=CC/ALPHA
C*
C*  MODIFICATION OF DUTY CYCLE FOR VARIATION OF PARAMETERS
C*
      DC1=DC
      DC=100.*(1.-(1.-DC/100.)*ALPHA)
C*  PRINT OUT COMPONENT PARAMETERS AND COSTS
      WRITE(6,414) (NAMEC(I1),I1=2,7),NC,MC,PC,CC,DC,LC,RC,CCC,LRC
      DC=DC*.01
      DC1=DC1/100.
C*
C*  BEGIN SUMMATION OF COMPONENT COST FACTORS
C*
      COSTS(1,J)=MC*RANDD(IFIX(CCC))+COSTS(1,J)
      COSTS(2,J)=CC*NC+COSTS(2,J)
      COSTS(3,J)=MC*NC+COSTS(3,J)
      COSTS(8,J)=(1.-DC)*LC*NC+COSTS(8,J)
      COSTS(9,J)=RC*CC*NC/MC+COSTS(9,J)
      COSTS(10,J)=RC*NC+COSTS(10,J)
      COSTS(4,J)=PC*NC+COSTS(4,J)
C*
C*  MULTIPLY COMPONENT FAILURE PROBABILITIES TO FIND MACHINE DUTY CYC.
C*
      IF (NC.LT.1.) GO TO 3
      PROD1=PROD1*(1.-(1.-DC1)**(AMIN1(3.,NC)))
      PROD=PROD*(1.-(1.-DC)**(AMIN1(3.,NC)))
 3    CONTINUE
C*
C*  END COMPONENT READ-IN LOOP
C*--------------------------------------------------------------------
      DM=PROD
C*  ADJUST COMPONENT R&D COSTS FOR RELIABILTY REQUIREMENTS, AND ADD
C*      PROCESS AND SYSTEMS INTEGRATION R&D COSTS
      COSTS(1,J)=COSTS(1,J)/ALPHA+BM
C*  ASSUME NO MACHINE WOULD HAVE A DUTY CYCLE LESS THAN 50%
      IF (DM.LT..5) DM=.5
C*
C*  CALCULATE COST ELEMENTS
C*
C*  WORKLOAD INCREASE FACTOR DUE TO MACHINE DOWNTIME
```

```
      FACTOR=PROD1/DM
C*    REVISE NUMBER OF MACHINES TO MAINTAIN THRUPUT
      NM=NM*FACTOR
C*   KEEP TRACK OF TOTAL DUTY CYCLE OF SOLAR CELL FACTORY
      NSCFM(J)=NM
      WRITE(6,230) DM,NM,COSTS(1,J)
      IF (J.LE.14) DCTOT=DCTOT+DM
      IF (J.NE.18) GO TO 8
C*   ADJUST NUMBER OF SOLAR CELL STRIPS TO MEET TOTAL SCF DUTY CYCLE
C*       REQUIREMENTS, AND TO FORM AN INTEGER NUMBER OF SECTORS
C*       (14 STRIPS/SECTOR)
      NM=14.*FLOAT(IFIX(246./(DCTOT*14.)+.965))
      WRITE(6,423) NM,DCTOT
      WRITE(6,233)
      IRUN=0
C*   ADJUST SOLAR CELL COSTS FOR REVISED NUMBER OF STRIPS
      DO 2 J2=1,17
      COSTS(2,J2)=COSTS(2,J2)*NM/NSCFM(J2)
      COSTS(3,J2)=COSTS(3,J2)*NM/NSCFM(J2)
      COSTS(5,J2)=COSTS(5,J2)*NM/NSCFM(J2)
      COSTS(6,J2)=COSTS(6,J2)*NM/NSCFM(J2)
      COSTS(7,J2)=COSTS(7,J2)*NM/NSCFM(J2)
      COSTS(8,J2)=COSTS(8,J2)*NM/NSCFM(J2)
      COSTS(9,J2)=COSTS(9,J2)*NM/NSCFM(J2)
    2 COSTS(10,J2)=COSTS(10,J2)*NM/NSCFM(J2)
C*   PERFORM FINAL COST ACCOUNTING FOR THIS MACHINE
    8 COSTS(5,J)=DM*LM*NM*H*W
      COSTS(6,J)=XM*EM*DM*NM*H
      COSTS(7,J)=EM*DM*NM*H*TCARGO
      COSTS(2,J)=COSTS(2,J)*NM
      COSTS(3,J)=COSTS(3,J)*NM*TCARGO
      COSTS(8,J)=COSTS(8,J)*NM*H*W
      COSTS(9,J)=COSTS(9,J)*NM
      COSTS(10,J)=COSTS(10,J)*NM*T
      COSTS(4,J)=COSTS(4,J)*NM*DM*(GCOST+ALFA*TCARGO)
C*
C*   SUM RECURRING AND NONRECURRING COSTS FOR EACH MACHINE
C*
      SUMM(1,J)=COSTS(1,J)+COSTS(2,J)+COSTS(3,J)+COSTS(4,J)
    4 SUMM(2,J)=COSTS(5,J)+COSTS(6,J)+COSTS(7,J)+COSTS(8,J)+COSTS(9,J)+
     +COSTS(10,J)
C*
C*   END MACHINE READ-IN LOOP
C******************************************************************
C*   PRINT OUT NONRECURRING COST TABLE
C*
      WRITE(6,201)
      DO 5 J=1,IMACH
      WRITE(6,202) (NAME(I,J),I=2,7),(COSTS(I,J),I=1,4),SUMM(1,J)
C******************************************************************
C*   FIND TOTAL COSTS BROKEN DOWN BY COST ELEMENT
C*
      TOTALS(11)=TOTALS(11)+SUMM(1,J)
```

```
      TOTALS(12)=TOTALS(12)+SUMM(2,J)
      IF (J.EQ.30) WRITE(6,231)
      DO 5 I=1,10
 5    TOTALS(I)=TOTALS(I)+CCSTS(I,J)
      WRITE(6,205) (TOTALS(I),I=1,4),TOTALS(11)
C**********************************************************************
C*  PRINT OUT RECURRING COST TABLE
C*
      WRITE(6,203)
      DO 6 J=1,IMACH
      WRITE(6,204) (NAME(I,J),I=2,7),(COSTS(I,J),I=5,10),SUMM(2,J)
      IF (J.EQ.30) WRITE(6,232)
 6    CONTINUE
      WRITE(6,206) (TOTALS(I),I=5,10),TOTALS(12)
C*  BEGIN TYPING SUMMARY PAGE
      WRITE(6,209) TOTALS(11)
      WRITE(6,210) TOTALS(12)
C**********************************************************************
C*  FIND TOTAL LABOR FORCE (LTOT), YEARLY LABOR TRANSPORT MASS (MLABOR)
C*      AND COST (TRANSL), AND YEARLY MASS AND COST OF CREW CONSUMABLES
C*      (MCONSM AND TRANSC)
C*
C*  FIND TOTAL PRODUCTION MASS (MPRODT), POWER (PPRODT), AND
C*    LABOR (LPRODT)
      MPRODT=TOTALS(3)/TCARGO
      WRITE(6,211) MPRODT
      PPRODT=TOTALS(4)/(GCOST+ALFA*TCARGO)
      WRITE(6,212) PPRODT
      LPRODT=(TOTALS(5)+TOTALS(8))/(H*W)*3.
      WRITE(6,213) LPRODT
C*********************************************************************
      LTOT=S*LPRODT
      MLABOR=LTOT*QTRANM*XCHGS
      TRANSL=MLABOR*TPERS
      MCONSM=LCONSM*365.*LTOT
      TRANSC=MCONSM*TCARGO
      WRITE(6,214) LTOT
      WRITE(6,215) MLABOR,MCONSM
      WRITE(6,216) TRANSL,TRANSC
C**********************************************************************
C*  FIND YEARLY TRAINING COSTS (CTRAIN), WAGES OF SUPPORT CREW (WSUP),
C*      AND EXPENDABLES TRANSPORT COST FOR THE SMF STRUCTURE (CEXSMF)
C*
      CTRAIN=UTRAIN*LTOT
      WRITE(6,217) CTRAIN
      WSUP=LPRODT*(S-1.)*H*W
      WRITE(6,218) WSUP
      CEXSMF=EXSMF*TCARGO
      WRITE(6,220) CEXSMF
C**********************************************************************
C*  FIND HABITAT MASS (MHAB), TRANSPORT COST (THAB), INITIAL COST
C*      (CHAB), POWER (PHAB), AND POWER COST (PCHAB)
C*
```

```
      MHAB=HABM*ITCT
      THAB=TCARGO*MHAB
      CHAB=HABRAD+PHAB*HABPRC
      PHAB=HABP*LTOT
      PCHAB=(GCOST+ALFA*TCARGO)*PHAB
      WRITE(6,228) MHAB,PHAB
      WRITE(6,229) CHAB,THAB,PCHAB
      PTOT=PPRODT+PSMF+PHAB
C***********************************************************************
C*  FIND TOTAL SMF POWER (PTOT) AND MASS (MTOT), AND PROCUREMENT COST
C*     FOR THE NONPRODUCTION SMF (STRUCTURE, ATTITUDE CONTROLS, ETC.)
C*
      MTOT=MPRODT+MSMF+PTOT*ALFA+MHAB
      CTSMF=CSMF*MSMF
      WRITE(6,219) CTSMF
      WRITE(6,221) MTOT,PTOT
C***********************************************************************
C*  FIND NONPRODUCTION SMF TRANSPORT COST (SMFSTC) AND POWER COST
C*     (PWRCST)
C*
      SMFSTC=(MSMF+PSMF*ALFA)*TCARGO
      WRITE(6,222) SMFSTC
      PWRCST=PSMF*GCOST
      WRITE(6,223) PWRCST
C***********************************************************************
C*  FIND SMF SET-UP CREW SIZE (PSETUP) AND COST (DSETUP)
C*
      PSETUP=MTOT/(6000.*APRCD)
      DSETUP=PSETUP*(W*6000.+UTRAIN+1250.*LCONSM*TCARGO+XCHGM*TPERS*4.)
      WRITE(6,224) DSETUP,PSETUP
C***********************************************************************
C*  FIND COST TOTALS: DIRECT NONRECURRING (CDIRNR)
C*                    DIRECT RECURRING (CDIRRC)
C*                    INDIRECT NONRECURRING (CINDNR)
C*                    INDIRECT RECURRING (CINDRC)
C*
      CDIRNR=TOTALS(11)
      CDIRRC=TOTALS(12)
      CINDNR=CTSMF+SMFSTC+PWRCST+DSETUP+CHAB+THAB+PCHAB
      CINDRC=CEXSMF+WSUP+UTRAIN+TRANSL+TRANSC
      WRITE(6,225) CDIRNR,CDIRRC,CINDNR,CINDRC
C***********************************************************************
C*  FIND TOTAL RECURRING AND NONRECURRING COSTS (CRC AND CNR)  AND
C*     USE COST DISCOUNTING TO FIND SMF LIFE CYCLE COSTS (LIFCYC)
C*     AND DISCOUNTED AVERAGE SPS COSTS (SPSCST)
C*
      CNR=CDIRNR+CINDNR
      CRC=CDIRRC+CINDRC
      DISCNT=0.
      IYRS=IFIX(YEARS)
      DO 7 I=1,IYRS
    7 DISCNT=DISCNT+(1.+R)**(-I)
      LIFCYC=CNR+CRC*DISCNT
```

```
      SPSCST=LIFCYC/YEARS
      WRITE(6,226) LIFCYC
      WRITE(6,227) SPSCST
C**********************************************************************
      STOP
C**********************************************************************
C*  FORMAT STATEMENTS
C*
  101 FORMAT(10F8.3)
  102 FORMAT(A1,5A4,A3,7F8.3)
  103 FORMAT(5F8.3)
  104 FORMAT(8F8.0)
  105 FORMAT(20A4)
  201 FORMAT(1H1///30X,'$$$$$$$$  NONRECURRING COSTS  $$$$$$$$'/
     +T32,'R & D',T44,'PROCUREMENT',T60,'TRANSPORT',T78,'POWER',T92,
     +'TOTALS'/)
  202 FORMAT(1X,5A4,A3,7F15.0)
  203 FORMAT(1H1///40X,'$$$$$$$$  RECURRING COSTS  $$$$$$$$'//
     +T31,'OPERATING',T53,'EXPENDABLES',T92,'REPAIR',T122,'TOTALS'/
     +T33,'LABOR',T45,'PROCUREMENT',T61,'TRANSPORT',T79,'LABOR',
     +T90,'PROCUREMENT',T105,'TRANSPORT'/)
  204 FORMAT(1X,5A4,A3,7F15.0)
  205 FORMAT(/10X,'TOTALS',8X,5F15.0)
  206 FORMAT(/10X,'TOTALS',8X,7F15.0)
  209 FORMAT(1H1,'TOTAL DIRECT NON-RECURRING COST =$',F12.0)
  210 FORMAT(' TOTAL DIRECT RECURRING COST =$',F12.0)
  211 FORMAT(/' TOTAL DIRECT PRODUCTION MASS (KG) =',F10.0)
  212 FORMAT(' TOTAL DIRECT PRODUCTION POWER (KW) = ',F10.0)
  213 FORMAT(' TOTAL DIRECT PRODUCTION CREW = ',F6.0,' PEOPLE')
  214 FORMAT(/' TOTAL SMF CREW = ',F6.0)
  215 FORMAT(' CREW TRANSPORT MASS = ',F8.0,' KG, CONSUMABLE MASS = ',
     +F8.0,' KG')
  216 FORMAT(' CREW TRANSPORT COST=$',F11.0,' CONSUMABLES COST=',F11.0)
  217 FORMAT(/' CREW TRAINING COSTS =$',F11.0)
  218 FORMAT(' SUPPORT CREW WAGES =$',F11.0)
  219 FORMAT(' NONRECURRING COST OF NONPRODUCTION SMF =$',F10.0)
  220 FORMAT(' SUPPORT EXPENDABLES TRANSPORT COST =$',F10.0)
  221 FORMAT(/' TOTAL SMF MASS (KG) =',F10.0
     +/' TOTAL SMF POWER (KW) = ',F8.0)
  222 FORMAT(/' SMF SUPPORT TRANSPORT COST =$',F10.0)
  223 FORMAT(' SMF SUPPORT POWER COST =$',F10.0)
  224 FORMAT(/' SETUP COSTS =$',F9.0,' FOR ',F5.0,' PEOPLE')
  225 FORMAT(///10X,'$$$$$$$$    DIRECT COSTS: NONRECURRING =$',F12.0,
     +', RECURRING =$',F12.0//10X,
     +'$$$$$$$$  INDIRECT COSTS: NONRECURRING =$',F12.0,', RECURRING =$'
     +,F12.0)
  226 FORMAT(//10X,'$$$$$$$$  SMF LIFE CYCLE COSTS=$',F14.0)
  227 FORMAT(/10X,'$$$$$$$$  DISCOUNTED AVERAGE SPS COST=$',F12.0)
  228 FORMAT(/' HABITAT MASS (KG) = ',F10.0/
     +' HABITAT POWER (KW) = ',F10.0)
  229 FORMAT(' R&D AND PROCUREMENT COST OF HABITAT ($) = ',F12.0/
     +' TRANSPORT COST OF HABITAT ($) = ',F12.0/
     +' POWER COST OF HABITAT ($) = ',F12.0)
```

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230  FORMAT(25X,'DUTY CYCLE = ',F6.4,' REQUIRING ',F6.0,' MACHINES',
    +5X,'R&D = $',E12.0)
231  FORMAT(1H1///30X,'$$$$$$$$ NONRECURRING COSTS (CONT.) $$$$$$$$'//
    +T32,'R & D',T44,'PROCUREMENT',T60,'TRANSPORT',T78,'POWER',T92,
    +'TOTALS'/)
232  FORMAT(1H1///40X,'$$$$$$$$ RECURRING COSTS (CONT.) $$$$$$$$'//
    +T31,'OPERATING',T53,'EXPENDABLES',T92,'REPAIR',T122,'TOTALS'/
    +T33,'LABOR',T45,'PROCUREMENT',T61,'TRANSPORT',T79,'LABOR',
    +T90,'PROCUREMENT',T105,'TRANSPORT'/)
233  FORMAT(1H1,T38,'NUMBER',T50,'MASS',T62,'POWER',T70,'PROCUREMENT',
    +T84,'DUTY CYC',T97,'REP. LABOR',T110,'PARTS',T117,'CCC',T123,'LRC'
    +/)
234  FORMAT(T38,'NUMBER',T50,'MASS',T62,'POWER',T70,'PROCUREMENT',
    +T84,'DUTY CYC',T97,'REP. LABOR',T110,'PARTS',T117,'CCC',T123,'LRC'
    +/)
401  FORMAT(1H1,51X,'SPACE MANUFACTURING FACILITY'
    +/53X,'LINE ITEM COSTING PROGRAM'
    +/50X,'M.I.T. SPACE SYSTEMS LABORATORY'
    +///51X,'INPUT VARIABLE SPECIFICATION'//20X,20A4
    +//10X,'SMF GLOBAL PARAMETERS:'/)
402  FORMAT(' CARGO TRANSPORT COST ($/KG) =',F6.0,
    +T50,'PERSONNEL TRANSPORT COST ($/KG) =',F6.0)
403  FORMAT(' PAYLOAD FRACTION ON PERSONNEL SHIPS =',F6.2,
    +T50,'TRAINING COST ($/PERSON) =',F8.0)
404  FORMAT(' CREW TRANSPORT MASS (KG/PERSON) =',F6.0,
    +T50,'CREW ROTATION RATE (TIMES/YEAR) =',F6.1)
405  FORMAT(' CREW WAGE ($/HR) =',F7.2,
    +T50,'CONSUMABLES FLOW RATE (KG/PERSON-DAY) =',F6.2)
406  FORMAT(' SUPPORT OVERHEAD FACTOR =',F5.1,
    +T50,'SMF OPERATIONAL PERIOD (YRS) =',F6.0)
407  FORMAT(' SMF NONPRODUCTION MASS (KG) =',F8.0,
    +T50,'SMF NONPRODUCTION POWER (KW) =',F8.0)
408  FORMAT(' SMF NONPRODUCTION COST  ($) =',F8.0,
    +T50,'SMF NONPRODUCTION EXPENDABLES (KG/YR) =',F8.0)
409  FORMAT(' POWERPLANT SPECIFIC MASS (KG/KW) =',F6.0,
    +T50,'POWERPLANT PROCUREMENT COST ($/KW) =',F6.0)
410  FORMAT(' NUMBER OF MACHINES IN SMF =',F5.0,
    +T50,'PRODUCTION HOURS/YEAR =',F6.0)
411  FORMAT(' ASSEMBLY PRODUCTIVITY (KG/PERSON-HR) =',F6.1,
    +T50,'COST DISCOUNTING RATE =',F5.2)
412  FORMAT(1H1//10X,'MACHINE AND COMPONENT PARAMETERS:')
414  FORMAT(4X,5A4,A3,7F12.2,2(2X,F3.0))
413  FORMAT(/1X,5A4,A3,7X,'LABOR = ',F8.3,7X,'EXPEND. = ',F8.3,
    +' KG/HR AT $',F5.0,'/KG      COMPONENTS =',F5.1)
415  FORMAT(F8.3)
416  FORMAT(' DUTY CYCLE MULTIPLIER = ',F8.3)
417  FORMAT(' HABITAT MASS (KG/PERSON) = ',F7.0,
    +T50,'HABITAT POWER (KW/PERSON) = ',F6.1)
418  FORMAT(' HABITAT R&D ($M) = ',F12.2,
    +T50,'HABITAT PROCURMENT ($/KG) = ',F7.1)
419  FORMAT(' R&D, LEVEL ',I1,' = $',F7.0,'/KG',
    +T50,'PROCUREMENT, LEVEL ',I1,' = $',F6.0,'/KG')
420  FORMAT(' HUMAN SUPERVISION (HR/HR DOWN):'/
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     +T20,'TELEOPERATOR REPAIR = ',F7.3,
     +T60,'CRAWLER/AUTOMATIC REPAIR = ',F7.3)
 421 FORMAT(T20,'CRAWLER/SCHEDULED REPLACEMENT = ',F7.3,
     +T60,'CRAWLER/HUMAN REPAIR = ',F7.3)
 422 FORMAT(T20,'MANUAL REPAIR = ',F7.3)
 423 FORMAT(///5X,'ALL ABOVE MACHINES HAVE BEEN CORRECTED TO FORM ',
     +F6.0,' STRIPS NEEDED FOR SOLAR CELL FACTORY DUTY CYCLE OF ',F6.4)
     END
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BASELINE SMF CASE: 1 SPS PRODUCED/YEAR, AUTOMATIC REPAIR OF SCP MACHINERY
1.        3040.    9.        377.      100.      .25       .1        .05       .5        1.
100.      450.     .1        50000.    100.      4.        34.34     .83       2.        20.
2000000.1000.      25.       0.        10.       2000.     60.       8766.     300.      .1
500.      5000.    20000.    100000.   50.       500.      2000.     10000.
MTHERMAL BELT                0.        0.        .005      10.       20.       246.      4.
CCOPPER BELT                 1.        4000.     0.        2.        99.9      1.        200.
CMOTOR AND DRIVE             1.        1000.     20.       2.        99.9      1.        50.
CEND ROLLERS                 2.        50.       0.        2.        99.9      1.        2.5
CTHERMAL CONTROL             1.        200.      20.       3.        99.9      1.        10.
MDV OF AL REAR CONTACT       0.        0.        .005      10.       10.       246.      7.
CEB GUN                      2.        20.       3.1       3.        99.9      2.        1.
CFILAMENT MAGAZINE           2.        .04       0.        2.        99.9      3.        .4
CSLAB FEEDER                 2.        50.       .01       3.        99.9      2.        2.5
CPANEL BAFFLES               1.        .05       0.        1.        99.9      3.        4.
CSIDE BAFFLE                 .14       1.        0.        1.        99.9      3.        40.
CSIDE BAFFLE GUIDE           .14       2.5       .01       2.        99.9      1.        .1
CCOOLING SYSTEM              1.        22.       .01       3.        99.9      2.        1.
MDV OF SI AND P-DOPANT       0.        0.        .005      20.       10.       246.      8.
CEB GUN                      20.       25.       7.3       3.        99.9      2.        1.25
CFILAMENT MAGAZINE           20.       .04       0.        2.        99.9      3.        .4
CSLAB FEEDER                 20.       60.       .01       3.        99.9      2.        3.
CPANEL BAFFLES               4.        .25       0.        1.        99.9      3.        80.
CSIDE BAFFLE                 .29       1.        0.        1.        99.9      3.        160.
CSIDE BAFFLE GUIDE           .29       2.5       .01       2.        99.9      1.        .15
CBORON ION IMPLANTER         20.       25.       1.75      3.        99.9      2.        1.3
CCOOLING SYSTEM              1.        360.      .15       3.        99.9      2.        18.
MPULSE RECRYSTALLIZATION0.             0.        .005      100.      10.       246.      3.
CEB GUN                      2.        10.       1.8       3.        99.9      2.        .5
CFILAMENT MAGAZINE           2.        .04       0.        2.        99.9      3.        .2
CCOOLING SYSTEM              1.        24.       .008      3.        99.9      2.        1.
MSCAN RECRYSTALLIZATION 0.             0.        .005      100.      10.       246.      3.
CEB GUN                      2.        5.        .6        3.        99.9      2         .25
CFILAMENT MAGAZINE           2.        .04       0.        2.        99.9      3         .12
CCOOLING SYSTEM              1.        14.       .003      3.        99.9      2         .7
MN-DOPANT IMPLANTATION       0.        0.        .001      10.       200.      246.      1.
CPHOSPH. ION IMPLANTER       2.        25.       1.75      3.        99.9      2.        1.3
MANNEAL                      0.        0.        .005      10.       10.       246.      3.
CEB GUN                      2.        5.        .4        3.        99.9      2.        .25
CFILAMENT MAGAZINE           2.        .04       0.        2.        99.9      3.        .12
CCOOLING SYSTEM              1.        14.       .001      3.        99.9      2.        .7
MDV OF AL FRONT CONTACT 0.             0.        .05       10.       10.       246.      9.
CEB GUN                      4.        10.       1.6       3.        99.9      2.        .5
CFILAMENT MAGAZINE           4.        .04       0.        2.        99.9      3.        .16
CSLAB FEEDER                 4.        50.       .01       3.        99.9      2.        2.5
CMASK                        2.        300.      0.        3.        99.9      3.        15.
CMASK GUIDE & ROLLUP         2.        250.      2.        3.        99.9      1.        12.5
CPANEL BAFFLES               2.        .05       0.        1.        99.9      3.        2.
CSIDE BAFFLE                 .29       1.        0.        1.        99.9      3.        20.
CSIDE BAFFLE GUIDE           .29       2.5       .01       2.        99.9      1.        .13
CCOOLING SYSTEM              1.        30.       .006      3.        99.9      2.        1.5
MFRONT CONTACT SINTERING0.             0.        .005      10.       10.       246.      3.
CEB GUN                      2.        5.        .2        3.        99.9      2.        .25
CFILAMENT MAGAZINE           2.        .04       0.        2.        99.9      3.        .12
CCOOLING SYSTEM              1.        14.       .001      3.        99.9      2.        .7
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4CELL CROSSCUT	0.	0.	.005	10.	25.	246.	4.
LASER	1.	20.	2.5	3.	99.9	2.	1.
KR. LAMP MAGAZINE	1.	.1	0.	3.	99.9	3.	.2
CGUIDE ROLLERS	2.	.5	0.	2.	99.9	2.	.03
CSHIELD	1.	1.	0.	1.	99.9	1.	0.
8CELL INTERCONNECTION	0.	0.	.001	20.	15.	246.	7.
CELECTROSTATIC WELDER	1.	10.	.5	3.	99.9	2.	.5
CINTERCONNECT FEEDER	1.	20.	1.	3.	99.9	2.	1.
CINTERCONNECT ROLL	1.	15.	0.	2.	99.9	3.	.75
CSENSORS	2.	.1	.1	3.	99.9	4.	.01
VARIABLE SPEED ROLLERS	4.	.8	.1	3.	99.9	2.	.2
MOTOR AND TRACKING	1.	10.	1.	2.	99.9	2.	.5
GUIDE ROLLERS	4.	.5	0.	2.	99.9	2.	.01
DV SIO2 OPTICAL COVER	0.	0.	.01	100.	10.	246.	13.
EB GUN	30.	25.	7.	3.	99.9	2.	1.25
CFILAMENT MAGAZINE	30.	.04	0.	2.	99.9	3.	.44
CSLAB FEEDER	30.	60.	.01	3.	99.9	2.	3.
CMASKING DEVICE	1.	50.	1.	3.	99.9	2.	2.5
CT-STRIP MASK PACKAGE	1.	5.	0.	2.	99.9	3.	.25
COXYGEN DISPERSER	6.	5.	.01	1.	99.9	1.	.25
CPANEL BAFFLES	6.	.25	0.	1.	99.9	3.	80.
CSIDE BAFFLE	.43	1.0	0.	1.	99.9	3.	160.
CSIDE BAFFLE GUIDE	.43	2.5	.01	2.	99.9	1.	.13
CSOFT SURFACE BELT	1.	3000.	0.	2.	99.9	1.	150.
CMOTOR DRIVE	1.	700.	15.	2.	99.9	1.	35.
CEND ROLLERS	1.	100.	5.	2.	99.9	1.	5.
CCOOLING SYSTEM	1.	550.	.25	3.	99.9	2.	28.
RDV OF SIO2 SUBSTRATE	0.	0.	.01	10.	10.	246.	13.
CEB GUN	20.	25.	7.	3.	99.9	2.	1.3
CFILAMENT MAGAZINE	20.	.04	0.	2.	99.9	3.	.44
CSLAB FEEDER	20.	60.	.01	3.	99.9	2.	3.
CMASKING DEVICE	1.	50.	1.	3.	99.9	2.	2.5
CT-STRIP MASK PACKAGE	1.	5.	0.	2.	99.9	3.	.25
COXYGEN DISPERSER	4.	5.	.01	1.	99.9	1.	.25
CPANEL BAFFLES	4.	.25	0.	1.	99.9	3.	80.
CSIDE BAFFLE	.29	1.0	0.	1.	99.9	3.	160.
CSIDE BAFFLE GUIDE	.29	2.5	.01	2.	99.9	1.	.13
CSOFT SURFACE BELT	1.	2000.	0.	2.	99.9	1.	100.
CMOTOR DRIVE	1.	500.	10.	2.	99.9	1.	25.
CEND ROLLER	1.	100.	5.	2.	99.9	1.	5.
CCOOLING SYSTEM	1.	400.	.15	3.	99.9	2.	20.
MPANEL ALIGN & INSERT	0.	0.	.001	20.	15.	246.	7.
CACCELERATOR BELT	1.	70.	5.	3.	99.9	1.	3.5
CVARIABLE SPEED ROLLERS	32.	.8	.1	3.	99.9	2.	.04
CPANEL REMOVER	2.	25.	.7	2.	99.9	2.	1.25
CPANEL INSERTER	1.	25.	.7	2.	99.9	2.	1.25
CPANEL HOPPER	3.	30.	1.	2.	99.9	2.	1.5
CSENSORS	10.	.1	.1	3.	99.9	4.	.01
CGUIDE ROLLERS	60.	.5	0.	2.	99.9	2.	.03
8PANEL INTERCONNECTION	0.	0.	.001	10.	15.	246.	7.
CELECTROSTATIC WELDER	1.	10.	.5	3.	99.9	2.	.5
CINTERCONNECT FEEDER	1.	20.	1.	3.	99.9	2.	1.
INTERCONNECT ROLL	1.	15.	0.	2.	99.9	3.	.75
SENSORS	2.	.1	.1	3.	99.9	4.	.01
CVARIABLE SPEED ROLLERS	4.	.8	.1	3.	99.9	2.	.04

CMOTOR	1.	15.	5.	2.	99.9	2.	.75
CGUIDE ROLLERS	4.	.5	0.	2.	99.9	2.	.03
MLONGITUDINAL CUT	0.	0.	.005	10.	25.	246.	4.
CLASER	1.	20.	2.5	3.	99.9	2.	1.
CKR. LAMP MAGAZINE	1.	.1	0.	3.	99.9	3.	.2
CGUIDE ROLLERS	2.	.5	0.	2.	99.9	2.	.03
CSHIELD	1.	1.	0.	1.	99.9	1.	0.
MKAPTON TAPE APPLICATION	0.	0.	.001	20.	15.	246.	7.
CSTATIONARY TAPER	.93	.5	.5	2.	99.9	2.	.03
CSTATIONARY TAPE REFILL	.93	.06	0.	2.	99.9	3.	43.
CCROSS TAPER	.07	2.5	.5	2.	99.9	2.	.13
CCROSS TAPE REFILL	.07	.06	0.	2.	99.9	3.	43.
CSOFT ROLLER	1.57	.05	0.	2.	99.9	2.	.01
CGUIDE ROLLERS	8.	.05	0.	2.	99.9	2.	.01
CCROSS TAPE MOTOR	.07	5.	5.	2.	99.9	2.	.25
MARRAY SIG. FOLD & PACK	0.	0.	.001	10.	15.	246.	5.
CGUIDE ROLLERS	11.	.05	0.	2.	99.9	2.	.01
CVERTICAL DEFLECTORS	.07	2.	1.	2.	99.9	1.	.1
CBOX ALIGNMENT	.07	30.	4.	2.	99.9	1.	1.5
CBOX LABELLING	.07	.5	.01	2.	99.9	4.	.03
CTRAILING EDGE GUIDE	.07	5.	.01	2.	99.9	1.	.25
MTELEOPERATOR	0.	0.	0.	100.	0.	2.	2.
CTELEOPERATOR	1.	750.	10.	4.	90.	5.	75.
CCONTROL STATION	1.	600.	10.	3.	99.	5.	60.
MCRAWLER SYSTEM	0.	0.	.01	50.	20.	1.	6.
CSTRUCTURE AND DRIVE	54.	1500.	20.	2.	95.	5.	150.
CTRACKS	42.	2500.	0.	1.	100.	2.	0.
CCONTROL UNITS & SENSORS	54.	30.	5.	4.	99.	5.	1.5
CCOMPUTER HARDWARE	54.	10.	.2	4.	99.	5.	1.
CMANIPULATORS	216.	250.	3.	3.	99.	5.	12.5
CCONTROL CENTER	1.	3000.	20.	3.	99.	5.	300.
MZONE REFINES	0.	0.	.01	100.	20.	60.	12.
CINDUCTION COIL	10.	35.	25.	3.	99.9	5.	.5
CGAS JET RING & PUMP	10.	10.	1.	3.	99.9	5.	.25
CSLAB CLAMPS & DRIVE	1.	150.	.2	2.	99.9	5.	.5
CHANDLING EQUIPMENT	1.	50.	.5	2.	99.9	5.	2.5
CACTIVE COOL FOR COILS	1.	200.	.3	2.	99.9	5.	1.5
CRADIATOR	1.	33.	0.	1.	100.	5.	0.
CPRESS. CONT. & AIRLOCK	.167	6000.	0.	2.	99.9	5.	2.5
CEB CUTTER	.067	40.	128.	3.	99.9	5.	0.
CCOOLING FOR EB GUNS	.067	100.	.1	2.	99.	5.	0.
CPACKING CONTAINERS	2.	2.	0.	1.	99.9	5.	0.
CMAGNETIC CONTAINMENT	10.	30.	3.	3.	99.9	5.	0.
CACTIVE COOL FOR ARGON	.167	30.	1.	2.	99.9	5.	0.
MMASK CLEANUP DEVICE	0.	0.	0.	100.	0.	25.	4.
CMASK THREADER	1.	10.	1.	3.	95.	5.	.5
CCLEANUP BRUSHES & DRIVE	10.	5.	1.	2.	99.9	5.	5.
CGAS CIRCULATION PUMP	1.	10.	5.	2.	99.9	5.	.5
CPARTICLE FILTER SYSTEM	1.	1.	0.	3.	95.	5.	300.
MDV OF INTERCONNECTS	0.	0.	.001	10.	20.	5.	8.
CEB GUNS	10.	25.	34.7	3.	99.9	5.	.44
CFILAMENT MAGAZINE	10.	.04	0.	1.	100.	5.	0.
CSLAB FEEDERS	10.	50.	.01	3.	99.9	5.	50.
CBAFFLES	4.	1.	0.	1.	100.	5.	970.
CROLL WINDING EQUIPMENT	1.	50.	.1	3.	99.9	5.	0.

CSIDE BAFFLE GUIDE	2.	25.	.01	2.	99.9	5.	0.
CBELT	1.	1400.	10.	2.	99.9	5.	0.
CCOOLING SYSTEM	1.	500.	1.	2.	99.9	5.	0.
MLIQUID AL PIPELINE	0.	0.	0.	20.	0.	4.	3.
CPIPE SECTIONS	13.	3.	0.	2.	99.	5.	3.
CPIPE JOINTS	11.	.5	0.	2.	99.	5.	.5
CEM PUMPS	7.	10.	.01	2.	99.	5.	1.
MIRON PIPELINE	0.	0.	0.	20.	0.	1.	3.
CPIPE SECTION	5.	10.	0.	2.	99.	5.	10.
CPIPE JOINTS	3.	1.5	0.	2.	99.	5.	1.5
CEM PUMP	2.	10.	.001	2.	99.	5.	1.
MAL ALLOYING FURNACE	0.	0.	0.	50.	0.	3.	4.
CCASING	1.	150.	0.	3.	95.	5.	150.
CCOILS	1.	60.	1150.	2.	95.	5.	0.
CRADIATOR & PIPING	1.	1000.	10.	2.	99.	5.	10.
CCONTROLLER	1.	5.	.1	3.	99.	5.	0.
MIRON ALLOYING FURNACE	0.	0.	0.	50.	0.	1.	4.
CCASING	1.	150.	0.	3.	95.	5.	150.
CCOILS	1.	60.	1150.	2.	95.	5.	0.
CRADIATOR & PIPING	1.	1000.	10.	2.	99.	5.	10.
CCONTROLLER	1.	5.	.1	3.	99.	5.	0.
MCONTINUOUS CASTER	0.	0.	0.	20.	0.	2.	5.
CMOLD	1.	100.	0.	3.	95.	5.	5.
CFLUID	1.	100.	0.	1.	99.	5.	5.
CPIPING SYSTEM	1.	150.	0.	2.	99.	5.	7.
CPUMP	4.	10.	20.	1.	99.	5.	1.
CRADIATOR	1.	500.	0.	1.	100.	5.	0.
MAL SLAB CUTTER	0.	0.	0.	10.	0.	2.	3.
CEB GUN	1.	10.	20.	3.	99.	5.	2.5
CFOCUSING	1.	15.	30.	3.	99.	5.	0.
CEB GUN TRACKING	1.	25.	1.	3.	99.	5.	1.3
MAL DIE CASTER	0.	.25	0.	20.	0.	1.	4.
CPISTON AND CHAMBER	1.	15000.	75.	2.	99.	5.	750.
CMOLDS	19.	1000.	5.	2.	99.	5.	50.
CACTIVE COOLING SYSTEM	1.	1000.	60.	2.	99.	5.	50.
CRADIATORS	1.	500.	0.	1.	100.	5.	0.
MFE DIE CASTER	0.	.25	0.	20.	0.	1.	4.
CPISTON AND CHAMBER	1.	2000.	10.	2.	99.	5.	0.
CMOLDS	1.	1000.	5.	2.	99.	5.	0.
CACTIVE COOLING SYSTEM	1.	100.	8.	2.	99.	5.	0.
CRADIATOR	1.	50.	0.	1.	100.	5.	0.
MTRANSFORMER CORE CASTER	0.	.04	0.	20.	0.	1.	3.
CCASTER	1.	10000.	50.	2.	99.	5.	500.
CACTIVE COOLING SYSTEM	1.	1000.	60.	2.	99.	5.	50.
CRADIATOR	1.	500.	0.	1.	100.	5.	0.
MROLLING MILL	0.	0.	.01	10.	20.	1.	6.
CROUGHING STAND	1.	105000.	225.	1.	95.	5.	1000.
CSLAB COOLING SYSTEM	1.	10000.	5.	2.	95.	5.	500.
CRADIATOR AND PUMP	1.	100.	10.	1.	99.	5.	5.
CHANDLING & CONTROL	1.	2000.	10.	2.	95.	5.	100.
CFINISHING STAND	1.	70000.	150.	1.	95.	5.	1000.
CPREHEAT SYSTEM	1.	100.	10.	2.	100.	5.	5.
MEND TRIM/WELD/ROLL WIND	2.	0.	0.	10.	0.	2.	7.
CEB END TRIMMER	1.	6.	10.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	1.	2.	3.	3.	99.	5.	.5

CEB WELDER	1.	2.	1.	3.	99.	5.	.44
CACTIVE COOLING SYSTEM	1.	14.	1.	2.	99.	5.	0.
CROLL WINDER	1.	500.	50.	2.	99.	5.	25.
CTEFLON FILM ROLLS	3000.	280.	0.	1.	100.	5.	5.
CHANDLING EQUIPMENT	1.	100.	5.	2.	99.	5.	10.
MSHEET TRIMMER	0.	0.	0.	10.	0.	1.	6.
CEB CUTTERS	3.	6.	10.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	3.	2.	3.	3.	99.	5.	.5
CHANDLING EQUIPMENT	1.	30.	.1	2.	99.	5.	3.
CACTIVE COOLING SYSTEM	1.	30.	1.5	2.	99.	5.	0.
MRIBBON SLICER	0.	0.	0.	10.	0.	1.	4.
CROLLING STAND	1.	70000.	225.	1.	95.	5.	1000.
CHANDLING EQUIPMENT	1.	30.	1.	2.	99.	5.	3.
CSPOOL WINDER	1.	50.	5.	2.	99.	5.	5.
CSPOOLS	100.	2.	0.	1.	99.	5.	0.
MRIBBON TRIMMER	0.	0.	0.	10.	0.	1.	3.
CEB CUTTER	1.	8.	3.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	1.	2.	1.	3.	99.	5.	.5
CHANDLING EQUIPMENT	1.	20.	.1	2.	99.	5.	2.
MSTRIATOR	0.	0.	0.	10.	0.	1.	1.
CSTRIATOR	1.	20000.	50.	1.	99.	5.	1000.
MFORM ROLLER	0.	0.	0.	20.	0.	1.	[illegible]
CEB CUTTER	1.	7.	3.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	1.	2.	1.	3.	99.	5.	.5
CFORM ROLLER	1.	300.	30.	2.	99.	5.	150.
CHANDLING EQUIPMENT	1.	30.	1.	2.	99.	5.	1.5
MKLYSTRON RAD. ASSEMBLY	0.	0.	0.	20.	0.	7.	8.
CEB WELDER	49.	3.	1.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	49.	1.	.5	3.	99.	5.	.15
CSHEET MAGAZINE	2.	10.	.5	2.	99.	5.	.5
CSHEET TRACK & TRANSPORT	6.	10.	.5	2.	99.	5.	.5
CPIPE MAG. & TRANSPORT	6.	10.	.5	2.	99.	5.	.5
CRIBBON MAG. & TRANS.	6.	5.	.5	2.	99.	5.	.3
CPIPE SEGMENT BENDER	6.	30.	1.	2.	99.	5.	1.5
CPIPE RIBBON BENDER	6.	15.	.5	2.	99.	5.	.75
MDC-DC CONV. PRODUCER	0.	.2	80.8	10.	100.	1.	2.
CCOOLANT CHANNEL DRILL	1.	2000.	2.	2.	99.	5.	200.
CWINDING MACHINE	1.	2000.	.5	2.	99.	5.	100.
MINSULATION WINDER	0.	0.	0.	10.	0.	8.	1.
CINSULATION WINDER	1.	500.	2.	2.	95.	5.	25.
MGLASS FIBER PRODUCER	0.	0.	0.	10.	0.	61.	7.
CPLATINUM ALLOY TUBE	1.	40.	8.2	3.	95.	5.	0.
CPISTON & CYLINDER	1.	100.	0.	3.	99.	5.	5.
CGAS PUMP	1.	30.	.5	2.	99.	5.	1.5
CGAS CYLINDER	1.	45.	0.	1.	99.9	5.	2.
CSPOOL	6.	.5	0.	1.	99.9	5.	.03
CSPOOL MOTOR	1.	10.	.1	2.	99.	5.	.75
CSPOOL THREADER	4.	10.	.05	3.	99.	5.	1.
MDC CONV. RAD. ASSEMBLY	0.	0.	0.	20.	0.	1.	6.
CEB WELDER	20.	2.	1.	3.	99.	5.	.44
CFOCUSING & DEFLECTION	20.	1.	.5	3.	99.	5.	.15
CSHEET MAGAZINE	1.	15.	1.	2.	99.	5.	.75
CTRACK & TRANSPORT	1.	300.	5.	2.	99.	5.	1.5
CPIPE SEGMENT MAGAZINE	9.	10.	.5	2.	99.	5.	.5
CMANIFOLD ASSEMBLER	10.	10.	1.	2.	99.	5.	.5

BKLYSTRCN PLANT	0.	0.	500.	100.	25.	1.	1.
CKLYSTRCN PLANT	1.	305000.	40000.	2.	80.	5.	15300.
BGLASS FCAMING FACILITY	0.	1.	17.	50.	1.	1.	3.
CPOWDER MIXER	1.	75000.	35.	2.	90.	5.	7500.
CTHERMAL CCNTROL UNIT	7.	850.	80.	2.	99.	5.	17.
CMOLD	7.	21000.	1000.	2.	90.	5.	1000.
BFOAMED GLASS CUTTER	0.	0.	0.	10.	0.	1.	4.
CEIGHT BLADE SAW	1.	1700.	5.	2.	99.	5.	0.
CTWENTY BLADE SAW	1.	4000.	12.	2.	99.	5.	0.
CHANDLING EQUIPMENT	1.	170.	5.	1.	99.	5.	0.
CKERF REMOVAL SYSTEM	1.	20.	.5	2.	99.	5.	0.
BSHEET CUTTER & SLOTTER	0.	0.	0.	20.	0.	2.	3.
CLASER	14.	4000.	10.	3.	99.	5.	75.
CRADIATOR AND PUMP	1.	20.	1.	2.	99.	5.	1.
CCONVEYOR BELT SYSTEM	1.	170.	5.	1.	99.	5.	5.
BFOAMED GLASS SMOOTHER	0.	0.	0.	20.	0.	3.	3.
CSMOOTHING LASER	2.	4000.	10.	3.	99.	5.	75.
CRADIATOR AND PUMP	1.	40.	1.	2.	100.	5.	2.
CCONVEYOR BELT SYSTEM	1.	210.	5.	2.	99.	5.	5.
BWAVEGUIDE DV CF AL	0.	0.	0.	10.	0.	3.	5.
CEB GUN	5.	17.	17.	3.	99.9	5.	.44
CGUN COOLING SYSTEM	5.	20.	.3	2.	99.9	5.	0.
CSLAB FEEDERS	5.	50.	.01	3.	99.9	5.	50.
CBAFFLES	4.	.25	0.	1.	99.	5.	15.
CBELT & COOLING SYSTEM	1.	500.	2.	2.	99.5	5.	0.
BWAVEGUIDE PACKAGER	0.	0.	0.	10	0.	3.	3.
CHANDLING EQUIPMENT	1.	100.	5.	3.	99.	5.	5.
CWAVEGUIDE RACKS	850.	10.	0.	1.	99.9	5.	250.
CQUALITY CCNTROL	1.	50.	5.	3.	99.	5.	0.
BWAVEGUIDE ASSEMBLER	0.	0.	0.	20.	0.	12.	4.
CASSEMBLY ARMS	8.	10.	1.	3.	99.	5.	25.
CINTERIOR GUIDE	2.	15.	0.	2.	100.	5.	0.
CLASER	4.	4000.	10.	3.	99.	5.	75.
CRADIATOR AND PUMP	1.	80.	4.	2.	99.	5.	4.
BPERSCNNEL DOCKING MECH.	0.	0.	0.	10.	0.	4.	1.
CDOCKING MECHANISM	1.	1000.	1.	2.	99.	5.	50.
BPRESSURIZED TUNNEL	0.	0.	0.	10.	0.	2.	2.
CTHE TUNNEL	1.	5000.	.1	2.	99.	5.	250.
CAIRLOCKS	5.	5000.	.5	2.	99.	5.	0.
BCARGO DCCKING MECH.	0.	0.	0.	20.	0.	2.	2.
CRETENTICN LATCHES	4.	100.	.1	3.	99.	5.	5.
CSTRUCTURE & DAMPING	1.	1800.	0.	2.	99.9	5.	0.
BLOAD-UNLOAD MANIPULATOR	0.	1.	0.	50.	0.	4.	2.
CMANIPULATOR ARM	1.	5000.	10.	3.	95.	5.	250.
CCREW OPERATING STATICN	1.	2000.	1.	3.	99.	5.	100.
BMAGNETIC TRANSPORTER	0.	0.	0.	50.	0.	130.	4.
CFRAME	1.	50.	0.	1.	99.9	5.	2.5
CHIGH PERMEABILITY PLUG	4.	6.	0.	2.	100.	5.	0.
CTEFLCN SKIDS	8.	1.	0.	2.	99.9	5.	.2
CCONTAINER	6.	30.	0.	2.	99.5	5.	1.5
BTRANSPORTER TRACK	0.	0.	0.	10.	0.	1.	4.
CTRACK	4.	9000.	0.	1.	99.9	5.	90.
CMAGNETIC DRIVERS	1280.	30.	.01	2.	99.9	5.	1.5
CBUSSBARS	2.	45000.	0.	1.	100.	5.	0.
CROUTING CONTROL	1.	2000.	10.	3.	99.	5.	100.

MINTERNAL STORAGE DEVICE	0.	0.	0.	10.	0.	8.	3.
CBODY & CONTROL CIRCUIT	1.	200.	1.	2.	99.	5.	10.
CCONTAINER TUBES	8.	30.	0.	2.	99.	5.	1.5
CPUSH ARM	1.	150.	1.	2.	99.	5.	7.5
MREPAIR AUTOMATONS	0.	0.	.001	100.	20.	42.	1.
CAUTOMATIC REPAIR DEVICE	1.	200.	5.	4.	80.	5.	0.

SPACE MANUFACTURING FACILITY
LINE ITEM COSTING PROGRAM
M.I.T. SPACE SYSTEMS LABORATORY

INPUT VARIABLE SPECIFICATION

BASELINE SMF CASE: 1 SPS PRODUCED/YEAR, AUTOMATIC REPAIR OF SCF MACHINERY

SMF GLOBAL PARAMETERS:

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CARGO TRANSPORT COST ($/KG) =  100.                PERSONNEL TRANSPORT COST ($/KG) =  450.
PAYLOAD FRACTION ON PERSONNEL SHIPS =  0.10        TRAINING COST ($/PERSON) =  50000.
CREW TRANSPORT MASS (KG/PERSON) =  100.            CREW ROTATION RATE (TIMES/YEAR) =   4.0
CREW WAGE (K/HR) =  34.34                          CONSUMABLES FLOW RATE (KG/PERSON-DAY) =  0.83
SUPPORT OVERHEAD FACTOR =  2.0                     SMF OPERATIONAL PERIOD (YRS) =   20.
SMF NONPRODUCTION MASS (KG) =2000000.              SMF NONPRODUCTION POWER (KW) =   1000.
SMF NONPRODUCTION COST  ($) =      25.             SMF NONPRODUCTION EXPENDABLES (KG/YR) =      0.
POWERPLANT SPECIFIC MASS (KG/KW) =   10.           POWERPLANT PROCUREMENT COST ($/KW) = 2000.
NUMBER OF MACHINES IN SMF =  60.                   PRODUCTION HOURS/YEAR = 8766.
ASSEMBLY PRODUCTIVITY (KG/PERSON-HR) = 300.0       COST DISCOUNTING RATE = 0.10
HABITAT MASS (KG/PERSON) =   3040.                 HABITAT POWER (KW/PERSON) =    9.0
HABITAT R&D ($M) = 376999936.                      HABITAT PROCUREMENT ($/KG) =   100.0
R&D, LEVEL 1 = $   500./KG                         PROCUREMENT, LEVEL 1 = $   50./KG
R&D, LEVEL 2 = $  5000./KG                         PROCUREMENT, LEVEL 2 = $  500./KG
R&D, LEVEL 3 = $ 20000./KG                         PROCUREMENT, LEVEL 3 = $ 2000./KG
R&D, LEVEL 4 = $100000./KG                         PROCUREMENT, LEVEL 4 = $10000./KG
HUMAN SUPERVISION (HR/HR DOWN):
                 TELEOPERATOR REPAIR =   0.250          CRAWLER/AUTOMATIC REPAIR =   0.100
                 CRAWLER/SCHEDULED REPLACEMENT =   0.050 CRAWLER/HUMAN REPAIR =   0.500
                 MANUAL REPAIR =   1.000
DUTY CYCLE MULTIPLIER =    1.000
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MACHINE AND COMPONENT PARAMETERS:

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
THERMAL BELT	LABOR = 0.0		EXPEND. = 0.005 KG/HR AT $ 20./KG			COMPONENTS = 10.0			
COPPER BELT	1.00	4000.00	0.0	1030316.87	99.90	0.25	200.00	2.	1.
MOTOR AND DRIVE	1.00	1000.00	20.00	257579.12	99.90	0.25	50.00	2.	1.
END ROLLERS	2.00	50.00	0.0	11607.17	99.90	0.25	2.50	2.	1.
THERMAL CONTROL	1.00	200.00	20.00	206063.37	99.90	0.25	10.00	3.	1.
DUTY CYCLE = 0.9970 REQUIRING 246. MACHINES			R&D = $ 39250000.						
DV OF AL REAR CONTACT	LABOR = 0.0		EXPEND. = 0.005 KG/HR AT $ 10./KG			COMPONENTS = 10.0			
EB GUN	2.00	20.00	3.10	18571.47	99.90	0.10	1.00	3.	2.
FILAMENT MAGAZINE	2.00	0.04	0.0	9.29	99.90	0.05	0.00	2.	3.
SLAB FEEDER	2.00	50.00	0.01	46428.68	99.90	0.10	2.50	3.	2.
PANEL BAFFLES	1.00	0.05	0.0	1.29	99.90	0.05	0.00	1.	3.
SIDE BAFFLE	0.14	1.00	0.0	50.00	99.90	0.05	0.05	1.	3
SIDE BAFFLE GUIDE	0.14	2.50	0.01	1250.00	99.90	0.25	0.13	2.	1.
COOLING SYSTEM	1.00	22.00	0.01	22666.97	99.90	0.10	1.10	3.	2.
DUTY CYCLE = 0.9980 REQUIRING 246. MACHINES			R&D = $ 11853224.						
DV OF SI AND P-DOPANT	LABOR = 0.0		EXPEND. = 0.005 KG/HR AT $ 10./KG			COMPONENTS = 20.0			
EB GUN	20.00	25.00	7.30	16434.50	99.90	0.10	1.25	3.	2.
FILAMENT MAGAZINE	20.00	0.04	0.0	6.57	99.90	0.05	0.00	2.	3.
SLAB FEEDER	20.00	60.00	0.01	39442.80	99.90	0.10	3.00	3.	2.
PANEL BAFFLES	4.00	0.25	0.0	5.23	99.90	0.05	0.01	1.	3.
SIDE BAFFLE	0.29	1.00	0.0	50.00	99.90	0.05	0.05	1.	3.
SIDE BAFFLE GUIDE	0.29	2.50	0.01	1250.00	99.90	0.25	0.13	2.	1.
BORON ION IMPLANTER	20.00	25.00	1.75	16434.50	99.90	0.10	1.25	3.	2.
COOLING SYSTEM	1.00	360.00	0.15	370914.00	99.90	0.10	18.00	3.	2.
DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES			R&D = $ 29413312.						
PULSE RECRYSTALLIZATION	LABOR = 0.0		EXPEND. = 0.005 KG/HR AT $ 10./KG			COMPONENTS =100.0			
EB GUN	2.00	10.00	1.80	9285.73	99.90	0.10	0.50	3.	2.
FILAMENT MAGAZINE	2.00	0.04	0.0	9.29	99.90	0.05	0.00	2.	3.
COOLING SYSTEM	1.00	24.00	0.01	24727.60	99.90	0.10	1.20	3.	2.
DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES			R&D = $ 100680192.						
SCAN RECRYSTALLIZATION	LABOR = 0.0		EXPEND. = 0.005 KG/HR AT $ 10./KG			COMPONENTS =100.0			
EB GUN	2.00	5.00	0.60	4642.87	99.90	0.10	0.25	3.	2.
FILAMENT MAGAZINE	2.00	0.04	0.0	9.29	99.90	0.05	0.00	2.	3.
COOLING SYSTEM	1.00	14.00	0.00	14424.43	99.90	0.10	0.70	3.	2.
DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES			R&D = $ 100380192.						

N-DOPANT IMPLANTATION LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 200./KG COMPONENTS = 10.0

PHOSPH. ION IMPLANTER	2.00	25.00	1.75	23214.34	99.90	0.10	1.25	3.	2.

DUTY CYCLE = 1.0000 REQUIRING 246. MACHINES R&D = $ 10500000.

ANNEAL LABOR = 0.0 EXPEND. = 0.005 KG/HR AT $ 10./KG COMPONENTS = 10.0

EB GUN	2.00	5.00	0.40	4642.87	99.90	0.10	0.25	3.	2.
FILAMENT MAGAZINE	2.00	0.04	0.0	9.29	99.90	0.05	0.00	2.	3.
COOLING SYSTEM	1.00	14.00	0.00	14424.43	99.90	0.10	0.70	3.	2.

DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES R&D = $ 10380199.

DV OF AL FRONT CONTACT LABOR = 0.0 EXPEND. = 0.050 KG/HR AT $ 10./KG COMPONENTS = 10.0

EB GUN	4.00	10.00	1.60	8368.77	99.90	0.10	0.50	3.	2.
FILAMENT MAGAZINE	4.00	0.04	0.0	8.37	99.90	0.05	0.00	2.	3.
SLAB FEEDER	4.00	50.00	0.01	41843.90	99.90	0.10	2.50	3.	2.
MASK	2.00	300.00	0.0	278572.00	99.90	0.05	15.00	3.	3.
MASK GUIDE & ROLLUP	2.00	250.00	2.00	232143.37	99.90	0.25	12.50	3.	1.
PANEL BAFFLES	2.00	0.05	0.0	1.16	99.90	0.05	0.00	1.	3.
SIDE BAFFLE	0.29	1.00	0.0	50.00	99.90	0.05	0.05	1.	3.
SIDE BAFFLE GUIDE	0.29	2.50	0.01	1250.00	99.90	0.25	0.13	2.	1.
COOLING SYSTEM	1.00	30.00	0.01	30909.50	99.90	0.10	1.50	3.	2.

DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES R&D = $ 22813216.

FRONT CONTACT SINTERING LABOR = 0.0 EXPEND. = 0.005 KG/HR AT $ 10./KG COMPONENTS = 10.0

EB GUN	2.00	5.00	0.20	4642.87	99.90	0.10	0.25	3.	2.
FILAMENT MAGAZINE	2.00	0.04	0.0	9.29	99.90	0.05	0.00	2.	3.
COOLING SYSTEM	1.00	14.00	0.00	14424.43	99.90	0.10	0.70	3.	2.

DUTY CYCLE = 0.9990 REQUIRING 246. MACHINES R&D = $ 10380199.

CELL CROSSCUT LABOR = 0.0 EXPEND. = 0.005 KG/HR AT $ 25./KG COMPONENTS = 10.0

LASER	1.00	20.00	2.50	20606.34	99.90	0.10	1.00	3.	2.
KR. LAMP MAGAZINE	1.00	0.10	0.0	103.03	99.90	0.05	0.00	3.	3.
GUIDE ROLLERS	2.00	0.50	0.0	116.07	99.90	0.10	0.02	2.	2.
SHIELD	1.00	1.00	0.0	25.76	99.90	0.25	0.05	1.	1.

DUTY CYCLE = 0.9970 REQUIRING 246. MACHINES R&D = $ 10405000.

CELL INTERCONNECTION LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 15./KG COMPONENTS = 20.0

ELECTROSTATIC WELDER	1.00	10.00	0.50	10303.16	90	0.10	0.50	3.	2.
INTERCONNECT FEEDER	1.00	20.00	1.00	20606.34	99.90	0.10	1.00	3.	2.
INTERCONNECT ROLL	1.00	15.00	0.0	3063.69	99.90	0.05	0.75	2.	3.
SENSORS	2.00	0.10	0.10	92.86	99.90	0.50	0.00	3.	4.
VARIABLE SPEED ROLLERS	4.00	0.80	0.10	669.50	99.90	0.10	0.04	3.	2.
MOTOR AND TRACKING	1.00	10.00	1.00	2575.79	99.90	0.10	0.50	2.	2.
GUIDE ROLLERS	4.00	0.50	0.0	104.61	99.90	0.10	0.02	2.	2.

DUTY CYCLE = 0.9960 REQUIRING 246. MACHINES R&D = $ 20745488.

DV SIO2 OPTICAL COVER   LABOR = 0.0   EXPEND. = 0.010 KG/HR AT $ 10./KG   COMPONENTS =100.0

EB GUN	30.00	25.00	7.00	15464.75	99.90	0.10	1.25	3.	2.
FILAMENT MAGAZINE	30.00	0.04	0.0	6.19	99.90	0.05	0.00	2.	3.
SLAB FEEDER	30.00	60.00	0.01	37115.41	99.90	0.10	3.00	3.	2.
MASKING DEVICE	1.00	50.00	1.00	51515.84	99.90	0.10	2.50	3.	2.
T-STRIP MASK PACKAGE	1.00	5.00	0.0	1287.90	99.90	0.05	0.25	2.	3.
OXYGEN DISPERSER	6.00	5.00	0.01	98.44	99.90	0.25	0.25	1.	1.
PANEL BAFFLES	6.00	0.25	0.0	4.92	99.90	0.05	0.01	1.	3.
SIDE BAFFLE	0.43	1.00	0.0	29.23	99.90	0.05	0.05	1.	3.
SIDE BAFFLE GUIDE	0.43	2.50	0.01	730.85	99.90	0.25	0.13	2.	1.
SOFT SURFACE BELT	1.00	3000.00	0.0	772737.62	99.90	0.25	150.00	2.	1.
MOTOR DRIVE	1.00	700.00	15.00	180305.37	99.90	0.25	35.00	2.	1.
END ROLLERS	1.00	100.00	5.00	25757.92	99.90	0.25	5.00	2.	1.
COOLING SYSTEM	1.00	550.00	0.25	566674.19	99.90	0.10	27.50	3.	2.

DUTY CYCLE = 0.9940 REQUIRING 246. MACHINES R&D = $ 132740816.

DV OF SIO2 SUBSTRATE   LABOR = 0.0   EXPEND. = 0.010 KG/HR AT $ 10./KG   COMPONENTS = 10.0

EB GUN	20.00	25.00	7.00	16434.50	99.90	0.10	1.25	3.	2.
FILAMENT MAGAZINE	20.00	0.04	0.0	6.57	99.90	0.05	0.00	2.	3.
SLAB FEEDER	20.00	60.00	0.01	39442.80	99.90	0.10	3.00	3.	2.
MASKING DEVICE	1.00	50.00	1.00	51515.84	99.90	0.10	2.50	3.	2.
T-STRIP MASK PACKAGE	1.00	5.00	0.0	1287.90	99.90	0.05	0.25	2.	3.
OXYGEN DISPERSER	4.00	5.00	0.01	104.61	99.90	0.25	0.25	1.	1.
PANEL BAFFLES	4.00	0.25	0.0	5.23	99.90	0.05	0.01	1.	3.
SIDE BAFFLE	0.29	1.00	0.0	50.00	99.90	0.05	0.05	1.	3.
SIDE BAFFLE GUIDE	0.29	2.50	0.01	1250.00	99.90	0.25	0.1[illegible]	2.	1.
SOFT SURFACE BELT	1.00	2000.00	0.0	515158.44	99.90	0.25	100.00	2.	1.
MOTOR DRIVE	1.00	500.00	10.00	128789.50	99.90	0.25	25.00	2.	1.
END ROLLER	1.00	100.00	5.00	25757.92	99.90	0.25	5.00	2.	1.
COOLING SYSTEM	1.00	400.00	0.15	412126.75	99.90	0.10	20.00	3.	2.

DUTY CYCLE = 0.9940 REQUIRING 246. MACHINES R&D = $ 33740816.

PANEL ALIGN & INSERT   LABOR = 0.0   EXPEND. = 0.001 KG/HR AT $ 15./KG   COMPONENTS = 20.0

ACCELERATOR [illegible]	1.00	70.00	5.00	72122.12	99.90	0.25	3.50	3.	1.
VARIABLE SPEED RO[illegible]ERS	32.00	0.80	0.10	490.10	99.90	0.10	0.04	3.	2.
PANEL REMOVER	2.00	25.00	0.70	5803.58	99.90	0.10	1.25	2.	2.
PANEL INSERTER	1.00	25.00	0.70	6439.48	99.90	0.10	1.25	2.	2.
PANEL HOPPER	3.00	30.00	1.00	6[illegible]53.35	99.90	0.10	1.50	2.	3.
SENSORS	10.00	0.10	0.10	72.94	99.90	0.50	0.00	3.	4.
GUIDE ROLLERS	60.00	0.50	0.0	69.69	99.90	0.10	0.02	2.	2.

DUTY CYCLE = 0.9980 REQUIRING 246. MACHINES R&D = $ 21820496.

PANEL INTERCONNECTION LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 15./KG COMPONENTS = 10.0

ELECTROSTATIC WELDER	1.00	10.00	0.50	10303.16	99.90	0.10	0.50	3.	2.
INTERCONNECT FEEDER	1.00	20.00	1.00	20606.34	99.90	0.10	1.00	3.	2.
INTERCONNECT ROLL	1.00	15.00	0.0	3863.69	99.90	0.05	0.75	2.	3.
SENSORS	2.00	0.10	0.10	92.86	99.90	0.50	0.00	3.	4.
VARIABLE SPEED ROLLERS	4.00	0.80	0.10	669.50	99.90	0.10	0.04	3.	2.
MOTOR	1.00	15.00	5.00	3863.69	99.90	0.10	0.75	2.	2.
GUIDE ROLLERS	4.00	0.50	0.0	104.61	99.90	0.10	0.02	2.	2.

DUTY CYCLE = 0.9960 REQUIRING 246. MACHINES R&D = $ 10770500.

LONGITUDINAL CUT LABOR = 0.0 EXPEND. = 0.005 KG/HR AT $ 25./KG COMPONENTS = 10.0

LASER	1.00	20.00	2.50	20606.34	99.90	0.10	1.00	3.	2.
KR. LAMP MAGAZINE	1.00	0.10	0.0	103.03	99.90	0.05	0.00	3.	3.
GUIDE ROLLERS	2.00	0.50	0.0	116.07	99.90	0.10	0.02	2.	2.
SHIELD	1.00	1.00	0.0	25.76	99.90	0.25	0.05	1.	1.

DUTY CYCLE = 0.9970 REQUIRING 246. MACHINES R&D = $ 10405000.

KAPTON TAPE APPLICATION LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 15./KG COMPONENTS = 20.0

STATIONARY TAPER	0.93	0.50	0.50	130.20	99.90	0.10	0.02	2.	2.
STATIONARY TAPE REFILL	0.93	0.06	0.0	15.62	99.90	0.05	0.00	2.	3.
CROSS TAPER	0.07	2.50	0.50	1250.00	99.90	0.10	0.13	2.	2.
CROSS TAPE REFILL	0.07	0.06	0.0	30.00	99.90	0.05	0.00	2.	3.
SOFT ROLLER	1.57	0.05	0.0	12.04	99.90	0.10	0.00	2.	2.
GUIDE ROLLERS	8.00	0.05	0.0	9.43	99.90	0.10	0.00	2.	2.
CROSS TAPE MOTOR	0.07	5.00	5.00	2500.00	99.90	0.10	0.25	2.	2.

DUTY CYCLE = 1.0000 REQUIRING 246. MACHINES R&D = $ 20041088.

ARRAY SEG. FOLD & PACK LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 15./KG COMPONENTS = 10.0

GUIDE ROLLERS	11.00	0.05	0.0	8.99	99.90	0.10	0.00	2.	2.
VERTICAL DEFLECTORS	0.07	2.00	1.00	1000.00	99.90	0.25	0.10	2.	1.
BOX ALIGNMENT	0.07	30.00	4.00	15000.00	99.90	0.25	1.50	2.	1.
BOX LABELLING	0.07	0.50	0.01	250.00	99.90	0.50	0.02	2.	4.
TRAILING EDGE GUIDE	0.07	5.00	0.01	2500.00	99.90	0.25	0.25	2.	1.

DUTY CYCLE = 1.0000 REQUIRING 246. MACHINES R&D = $ 10187750.

ALL ABOVE MACHINES HAVE BEEN CORRECTED TO FORM 266. STRIPS NEEDED FOR SOLAR CELL FACTORY DUTY CYCLE OF 0.9685

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LEC
TELEOPERATOR LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS =100.0									
TELEOPERATOR	1.00	750.00	10.00	7500000.00	90.00	1.00	75.00	4.	5.
CONTROL STATION	1.00	600.00	10.00	1200000.00	99.00	1.00	60.00	3.	5.
DUTY CYCLE = 0.8910 REQUIRING 2. MACHINES R&D = $ 187000000.									
CRAWLER SYSTEM LABOR = 0.0 EXPEND. = 0.010 KG/HR AT $ 20./KG COMPONENTS = 50.0									
STRUCTURE AND DRIVE	54.00	1500.00	20.00	750000.00	95.00	1.00	150.00	2.	5.
TRACKS	42.00	2500.00	0.0	125000.00	100.00	0.10	125.00	1.	2.
CONTROL UNITS & SENSORS	54.00	30.00	5.00	300000.00	99.00	1.00	1.50	4.	5.
COMPUTER HARDWARE	54.00	10.00	0.20	100000.00	99.00	1.00	1.00	4.	5.
MANIPULATORS	216.00	250.00	3.00	262653.31	99.00	1.00	12.50	3.	5.
CONTROL CENTER	1.00	3000.00	20.00	6000000.00	99.00	1.00	300.00	3.	5.
DUTY CYCLE = 0.9899 REQUIRING 1. MACHINES R&D = $ 127750000.									
ZONE REFINER LABOR = 0.0 EXPEND. = 0.010 KG/HR AT $ 20./KG COMPONENTS =100.0									
INDUCTION COIL	10.00	35.00	25.00	31546.88	99.90	1.00	0.50	3.	5.
GAS JET RING & PUMP	10.00	10.00	1.00	9313.39	99.90	1.00	0.25	3.	5.
SLAB CLAMPS & DRIVE	1.00	150.00	0.20	75000.00	99.90	1.00	0.50	2.	5.
H HOLDING EQUIPMENT	1.00	50.00	0.50	25000.00	99.90	1.00	2.50	2.	5.
ACTIVE COOL FOR COILS	1.00	200.00	0.30	100000.00	99.90	1.00	1.50	2.	5.
RADIATOR	1.00	33.00	0.0	1650.00	100.00	1.00	0.0	1.	5.
PRESS. CONT. & AIRLOCK	0.17	6000.00	0.0	3000000.00	99.90	1.00	2.50	2.	5.
EB CUTTER	0.07	40.00	120.00	80000.00	99.90	1.00	0.0	3.	5.
COOLING FOR EB GUNS	0.07	100.00	0.10	50000.00	99.00	1.00	0.0	2.	5.
PACKING CONTAINERS	2.00	2.00	0.0	57.37	99.90	1.00	0.0	1.	5.
MAGNETIC CONTAINMENT	10.00	30.00	3.00	27040.19	99.90	1.00	0.0	3.	5.
ACTIVE COOL FOR AIRLCK	0.17	30.00	1.00	15000.00	99.90	1.00	0.0	2.	5.
DUTY CYCLE = 0.9970 REQUIRING 60. MACHINES R&D = $ 134967488.									
MASK CLEANUP DEVICE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS =100.0									
MASK THREADER	1.00	10.00	1.00	20000.00	95.00	1.00	0.50	3.	5.
CLEANUP BRUSHES & DRIVE	10.00	5.00	1.00	1284.78	99.90	1.00	5.00	2.	5.
GAS CIRCULATION PUMP	1.00	10.00	5.00	5000.00	99.90	1.00	0.50	2.	5.
PARTICLE FILTER SYSTEM	1.00	1.00	0.0	2000.00	95.00	1.00	300.00	3.	5.
DUTY CYCLE = 0.9016 REQUIRING 25. MACHINES R&D = $ 100294992.									
DV OF INTERCONNECTS LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 20./KG COMPONENTS = 10.0									
EB GUNS	10.00	25.00	34.70	50000.00	99.90	1.00	0.44	3.	5.
FILAMENT MAGAZINE	10.00	0.04	0.0	2.00	100.00	1.00	0.0	1.	5.
SLAB FEEDERS	10.00	50.00	0.01	100000.00	99.90	1.00	50.00	3.	5.
BAFFLES	4.00	1.00	0.0	50.00	100.00	1.00	970.00	1.	5.
ROLL WINDING EQUIPMENT	1.00	50.00	0.10	100000.00	99.90	1.00	0.0	3.	5.
SIDE BAFFLE GUIDE	2.00	25.00	0.01	12500.00	99.90	1.00	0.0	2.	5.
BELT	1.00	1400.00	10.00	700000.00	99.90	1.00	0.0	2.	5.
COOLING SYSTEM	1.00	500.00	1.00	250000.00	99.90	1.00	0.0	2.	5.
DUTY CYCLE = 0.9970 REQUIRING 5. MACHINES R&D = $ 22125504.									

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
LIQUID AL PIPELINE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 30.0									
PIPE SECTIONS	13.00	3.00	0.0	1500.00	99.00	1.00	3.00	2.	5.
PIPE JOINTS	11.00	0.50	0.0	250.00	99.00	1.00	0.50	2.	5.
EM PUMPS	7.00	10.00	0.01	5000.00	99.00	1.00	1.00	2.	5.
DUTY CYCLE = 1.0000 REQUIRING 4. MACHINES R&D = $ 20067488.									
IRON PIPELINE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0									
PIPE SECTION	5.00	10.00	0.0	5000.00	99.00	1.00	10.00	2.	5.
PIPE JOINTS	3.00	1.50	0.0	750.00	99.00	1.00	1.50	2.	5.
EM PUMP	2.00	10.00	0.00	5000.00	99.00	1.00	1.00	2.	5.
DUTY CYCLE = 0.5999 REQUIRING 1. MACHINES R&D = $ 20107488.									
AL ALLOYING FURNACE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 50.0									
CASING	1.00	150.00	0.0	300000.00	95.00	1.00	150.00	3.	5.
COILS	1.00	60.00	1150.00	30000.00	95.00	1.00	0.0	2.	5.
RADIATOR & PIPING	1.00	1000.00	10.00	500000.00	99.00	1.00	10.00	2.	5.
CONTROLLER	1.00	5.00	0.10	10000.00	99.00	1.00	0.0	3.	5.
DUTY CYCLE = 0.8045 REQUIRING 3. MACHINES R&D = $ 58400000.									
IRON ALLOYING FURNACE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 50.0									
CASING	1.00	150.00	0.0	300000.00	95.00	1.00	150.00	3.	5.
COILS	1.00	60.00	1150.00	30000.00	95.00	1.00	0.0	2.	5.
RADIATOR & PIPING	1.00	1000.00	10.00	500000.00	99.00	1.00	10.00	2.	5.
CONTROLLER	1.00	5.00	0.10	10000.00	99.00	1.00	0.0	3.	5.
DUTY CYCLE = 0.2845 REQUIRING 1. MACHINES R&D = $ 58400000.									
CONTINUOUS CASTER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0									
MOLD	1.00	100.00	0.0	200000.00	95.00	1.00	5.00	3.	5.
FLUID	1.00	100.00	0.0	5000.00	99.00	1.00	5.00	1.	5.
PIPING SYSTEM	1.00	150.00	0.0	75000.00	99.00	1.00	7.00	2.	5.
PUMP	4.00	10.00	20.00	500.00	99.00	1.00	1.00	1.	5.
RADIATOR	1.00	500.00	0.0	25000.00	100.00	1.00	0.0	1.	5.
DUTY CYCLE = 0.9311 REQUIRING 2. MACHINES R&D = $ 23054992.									
AL SLAB CUTTER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0									
ED GUN	1.00	10.00	20.00	20000.00	99.00	1.00	2.50	3.	5.
FOCUSING	1.00	15.00	30.00	30000.00	99.00	1.00	0.0	3.	5.
ED GUN TRACKING	1.00	25.00	1.00	50000.00	99.00	1.00	1.30	3.	5.
DUTY CYCLE = 0.9703 REQUIRING 2. MACHINES R&D = $ 11000000.									

AL DIE CASTER   LABOR = 0.250   EXPEND. = 0.0 KG/HR AT $ 0./KG   COMPONENTS = 20.0

PISTON AND CHAMBER	1.00	15000.00	75.00	7500000.00	99.00	1.00	750.00	2.	5.
MOLDS	19.00	1000.00	5.00	500000.00	99.00	1.00	50.00	2.	5.
ACTIVE COOLING SYSTEM	1.00	1000.00	60.00	500000.00	99.00	1.00	50.00	2.	5.
RADIATORS	1.00	500.00	0.0	25000.00	100.00	1.00	0.0	1.	5.

DUTY CYCLE = 0.5801 REQUIRING 1. MACHINES R&D = $ 105250000.

PB DIE CASTER   LABOR = 0.250   EXPEND. = 0.0 KG/HR AT $ 0./KG   COMPONENTS = 20.0

PISTON AND CHAMBER	1.00	2000.00	10.00	1000000.00	99.00	1.00	0.0	2.	5.
MOLDS	1.00	1000.00	5.00	500000.00	99.00	1.00	0.0	2.	5.
ACTIVE COOLING SYSTEM	1.00	100.00	8.00	50000.00	99.00	1.00	0.0	2.	5.
RADIATOR	1.00	50.00	0.0	2500.00	100.00	1.00	0.0	1.	5.

DUTY CYCLE = 0.5703 REQUIRING 1. MACHINES R&D = $ 35524992.

TRANSFORMER CORE CASTER   LABOR = 0.040   EXPEND. = 0.0 KG/HR AT $ 0./KG   COMPONENTS = 20.0

CASTER	1.00	10000.00	50.00	5000000.00	99.00	1.00	500.00	2.	5.
ACTIVE COOLING SYSTEM	1.00	1000.00	60.00	500000.00	99.00	1.00	50.00	2.	5.
RADIATOR	1.00	500.00	0.0	25000.00	100.00	1.00	0.0	1.	5.

DUTY CYCLE = 0.9801 REQUIRING 1. MACHINES R&D = $ 75250000.

ROLLING MILL   LABOR = 0.0   EXPEND. = 0.010 KG/HR AT $ 20./KG   COMPONENTS = 10.0

ROUGHING STAND	1.00	105000.00	225.00	5250000.00	95.00	1.00	1000.00	1.	5.
SLAB COOLING SYSTEM	1.00	10000.00	5.00	5000000.00	95.00	1.00	500.00	2.	5.
RADIATOR AND PUMP	1.00	100.00	10.00	5000.00	99.00	1.00	5.00	1.	5.
HANDLING & CONTROL	1.00	2000.00	10.00	1000000.00	95.00	1.00	100.00	2.	5.
FINISHING STAND	1.00	70000.00	150.00	3500000.00	95.00	1.00	1000.00	1.	5.
PREHEAT SYSTEM	1.00	100.00	10.00	50000.00	100.00	1.00	5.00	2.	5.

DUTY CYCLE = 0.8064 REQUIRING 1. MACHINES R&D = $ 158050003.

END TRIM/WELD/ROLL WIND   LABOR = 0.0   EXPEND. = 0.0 KG/HR AT $ 0./KG   COMPONENTS = 10.0

EB END TRIMMER	1.00	6.00	10.00	12000.00	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	1.00	2.00	3.00	4000.00	99.00	1.00	0.50	3.	5.
EB WELDER	1.00	2.00	1.00	4000.00	99.00	1.00	0.44	3.	5.
ACTIVE COOLING SYSTEM	1.00	14.00	1.00	7000.00	99.00	1.00	0.0	2.	5.
ROLL WINDER	1.00	500.00	50.00	250000.00	99.00	1.00	25.00	2.	5.
TEFLON FILM ROLLS	3000.00	280.00	0.0	4466.70	100.00	1.00	5.00	1.	5.
HANDLING EQUIPMENT	1.00	100.00	5.00	50000.00	99.00	1.00	10.00	2.	5.

DUTY CYCLE = 0.9415 REQUIRING 2. MACHINES R&D = $ 13410000.

SHEET TRIMMER   LABOR = 0.0   EXPEND. = 0.0 KG/HR AT $ 0./KG   COMPONENTS = 10.0

EB CUTTERS	3.00	6.00	10.00	12000.00	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	3.00	2.00	3.00	4000.00	99.00	1.00	0.50	3.	5.
HANDLING EQUIPMENT	1.00	30.00	1.00	15000.00	99.00	1.00	3.00	2.	5.
ACTIVE COOLING SYSTEM	1.00	30.00	1.50	15000.00	99.00	1.00	0.0	2.	5.

DUTY CYCLE = 0.9801 REQUIRING 1. MACHINES R&D = $ 10460000.

RIBBON SLICER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

ROLLING STAND	1.00	70000.00	225.00	3500000.00	95.00	1.00	1000.00	1.	5.
HANDLING EQUIPMENT	1.00	30.00	1.00	15000.00	99.00	1.00	3.00	2.	5.
SPOOL WINDER	1.00	50.00	5.00	25000.00	99.00	1.00	5.00	2.	5.
SPOOLS	100.00	2.00	0.0	58.96	99.00	1.00	0.0	1.	5.

DUTY CYCLE = 0.9311 REQUIRING 1. MACHINES R&D = $ 45400992.

RIBBON TRIMMER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

EB CUTTER	1.00	8.00	3.00	16000.00	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	1.00	2.00	1.00	4000.00	99.00	1.00	0.50	3.	5.
HANDLING EQUIPMENT	1.00	20.00	0.10	10000.00	99.00	1.00	2.00	2.	5.

DUTY CYCLE = 0.9703 REQUIRING 1. MACHINES R&D = $ 10300000.

STRIATOR LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

STRIATOR	1.00	20000.00	50.00	1000000.00	99.00	1.00	1000.00	1.	5.

DUTY CYCLE = 0.9900 REQUIRING 1. MACHINES R&D = $ 20000000.

FORM ROLLER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

EB CUTTER	1.00	7.00	3.00	14000.00	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	1.00	2.00	1.00	4000.00	99.00	1.00	0.50	3.	5.
FORM ROLLER	1.00	300.00	30.00	150000.00	99.00	1.00	150.00	2.	5.
HANDLING EQUIPMENT	1.00	30.00	1.00	15000.00	99.00	1.00	1.50	2.	5.

DUTY CYCLE = 0.5606 REQUIRING 1. MACHINES R&D = $ 21830000.

ELYSTRON RAD. ASSEMBLY LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

EB WELDER	49.00	3.00	1.00	2940.62	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	49.00	1.00	0.50	980.20	99.00	1.00	0.15	3.	5.
SHEET MAGAZINE	2.00	10.00	0.50	5000.00	99.00	1.00	0.50	2.	5.
SHEET TRACK & TRANSPORT	6.00	10.00	0.50	5000.00	99.00	1.00	0.50	2.	5.
PIPE MAG. & TRANSPORT	6.00	10.00	0.50	5000.00	99.00	1.00	0.50	2.	5.
RIBBON MAG. & TRANS.	6.00	5.00	0.50	2500.00	99.00	1.00	0.30	2.	5.
PIPE SEGMENT BENDER	6.00	30.00	1.00	15000.00	99.00	1.00	1.50	2.	5.
PIPE RIBBON BENDER	6.00	15.00	0.50	7500.00	99.00	1.00	0.75	2.	5.

DUTY CYCLE = 0.9999 REQUIRING 7. MACHINES R&D = $ [illegible]044[illegible]000.

DC-DC CONV. PRODUCER LABOR = 0.200 EXPEND. = 80.800 KG/HR AT $ 100./KG COMPONENTS = 10.0

COOLANT CHANNEL DRILL	1.00	2000.00	2.00	1000000.00	99.00	1.00	200.00	2.	5.
WINDING MACHINE	1.00	2000.00	0.50	1000000.00	99.00	1.00	100.00	2.	5.

DUTY CYCLE = 0.9801 REQUIRING 1. MACHINES R&D = $ 30000000.

INSULATION WINDER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

INSULATION WINDER	1.00	500.00	2.00	250000.00	95.00	1.00	25.00	2.	5.

DUTY CYCLE = 0.9500 REQUIRING 8. MACHINES R&D = $ 12500000.

GLASS FIBER PRODUCER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

PLATINUM ALLOY TUBE	1.00	40.00	8.20	80000.00	99.00	1.00	0.0	3.	5.
PISTON & CYLINDER	1.00	100.00	0.0	200000.00	99.00	1.00	5.00	3.	5.
GAS PUMP	1.00	30.00	6.50	15000.00	99.00	1.00	1.50	2.	5.
GAS CYLINDER	1.00	45.00	0.0	2250.00	99.90	1.00	2.00	1.	5.
SPOOL	6.00	0.50	0.0	12.13	99.90	1.00	0.03	1.	5.
SPOOL MOTOR	1.00	10.00	0.10	5000.00	99.00	1.00	0.75	2.	5.
SPOOL THREADER	4.00	10.00	0.05	10315.79	99.00	1.00	1.00	3.	5.

DUTY CYCLE = 0.9596 REQUIRING 61. MACHINES R&D = $ 13222750.

DC CONV. RAD. ASSEMBLY LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

EB WELDER	20.00	2.00	1.00	4000.00	99.00	1.00	0.44	3.	5.
FOCUSING & DEFLECTION	20.00	1.00	0.50	2000.00	99.00	1.00	0.15	3.	5.
SHEET MAGAZINE	1.00	15.00	1.00	7500.00	99.00	1.00	0.75	2.	5.
TRACK & TRANSPORT	1.00	300.00	5.00	150000.00	99.00	1.00	1.50	2.	5.
PIPE SEGMENT MAGAZINE	5.00	10.00	0.50	5000.00	99.00	1.00	0.50	2.	5.
MANIFOLD ASSEMBLER	10.00	10.00	1.00	5000.00	99.00	1.00	0.50	2.	5.

DUTY CYCLE = 0.5801 REQUIRING 1. MACHINES R&D = $ 21734992.

KLYSTRON PLANT LABOR = 0.0 EXPEND. = 500.000 KG/HR AT $ 25./KG COMPONENTS =100.0

KLYSTRON PLANT	1.00	305000.00	40000.00	152500000.	80.00	1.00	15300.00	2.	5.

DUTY CYCLE = 0.8000 REQUIRING 1. MACHINES R&D = $ 1624999940.

GLASS FOAMING FACILITY LABOR = 1.000 EXPEND. = 17.000 KG/HR AT $ 1./KG COMPONENTS = 50.0

POWDER MIXER	1.00	75000.00	35.00	37500000.0	90.00	1.00	7500.00	2.	5.
THERMAL CONTROL UNIT	7.00	850.00	80.00	425000.00	99.00	1.00	17.00	2.	5.
MOLD	7.00	21000.00	1000.00	10500000.0	90.00	1.00	1000.00	2.	5.

DUTY CYCLE = 0.8991 REQUIRING 1. MACHINES R&D = $ 534249472.

FOAMED GLASS CUTTER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

EIGHT BLADE SAW	1.00	1700.00	5.00	850000.00	99.00	1.00	0.0	2.	5.
TWENTY BLADE SAW	1.00	4000.00	12.00	2000000.00	99.00	1.00	0.0	2.	5.
HANDLING EQUIPMENT	1.00	170.00	5.00	8500.00	99.00	1.00	0.0	1.	5.
KERF REMOVAL SYSTEM	1.00	20.00	0.50	10000.00	99.00	1.00	0.0	2.	5.

DUTY CYCLE = 0.5606 REQUIRING 1. MACHINES R&D = $ 38684992.

SHEET CUTTER & SLOTTER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
LASER	14.00	4000.00	10.00	8000000.00	99.00	1.00	75.00	3.	5.
RADIATOR AND PUMP	1.00	20.00	1.00	10000.00	99.00	1.00	1.00	2.	5.
CONVEYOR BELT SYSTEM	1.00	170.00	5.00	8500.00	99.00	1.00	5.00	1.	5.

DUTY CYCLE = 0.9001 REQUIRING 2. MACHINES R&D = $ 100184992.

FOAMED GLASS SMOOTHER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
SMOOTHING LASER	2.00	4000.00	10.00	8000000.00	99.00	1.00	75.00	3.	5.
RADIATOR AND PUMP	1.00	40.00	1.00	20000.00	100.00	1.00	2.00	2.	5.
CONVEYOR BELT SYSTEM	1.00	210.00	5.00	105000.00	99.00	1.00	5.00	2.	5.

DUTY CYCLE = 0.9899 REQUIRING 3. MACHINES R&D = $ 101250000.

WAVEGUIDE DV OF AL LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
EB GUN	5.00	17.00	17.00	34000.00	99.90	1.00	0.44	3.	5.
GUN COOLING SYSTEM	5.00	20.00	0.30	10000.00	99.90	1.00	0.0	2.	5.
SLAB FEEDERS	5.00	50.00	0.01	100000.00	99.90	1.00	50.00	3.	5.
BAFFLES	4.00	0.25	0.0	12.50	99.00	1.00	[illegible]5.00	1.	5.
BELT & COOLING SYSTEM	1.00	500.00	2.00	250000.00	99.50	1.00	0.0	2.	5.

DUTY CYCLE = 0.9950 REQUIRING 3. MACHINES R&D = $ 13940125.

WAVEGUIDE PACKAGER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
HANDLING EQUIPMENT	1.00	100.00	5.00	200000.00	99.00	1.00	5.00	3.	5.
WAVEGUIDE RACKS	850.00	10.00	0.0	181.37	99.90	1.00	250.00	1.	5.
QUALITY CONTROL	1.00	50.00	5.00	100000.00	99.00	1.00	0.0	3.	5.

DUTY CYCLE = 0.9801 REQUIRING 3. MACHINES R&D = $ 13005000.

WAVEGUIDE ASSEMBLER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
ASSEMBLY ARMS	8.00	10.00	1.00	20000.00	99.00	1.00	25.00	3.	5.
INTERIOR GUIDE	2.00	15.00	0.0	7500.00	100.00	1.00	0.0	2.	5.
LASER	4.00	4000.00	10.00	8000000.00	99.00	1.00	75.00	3.	5.
RADIATOR AND PUMP	1.00	80.00	4.00	40000.00	99.00	1.00	4.00	2.	5.

DUTY CYCLE = 0.9900 REQUIRING 12. MACHINES R&D = $ 100674992.

	NUMBER	MASS	POWER	PROCUREMENT	DUTY CYC	REP. LABOR	PARTS	CCC	LRC
PERSONNEL DOCKING MECH. LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0									
DOCKING MECHANISM	1.00	1000.00	1.00	500000.00	99.00	1.00	50.00	2.	5.
DUTY CYCLE = 0.9900 REQUIRING 4. MACHINES R&D = $ 15000000.									
PRESSURIZED TUNNEL LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0									
THE TUNNEL	1.00	5000.00	0.10	2500000.00	99.00	1.00	250.00	2.	5.
AIRLOCKS	5.00	5000.00	0.50	2500000.00	99.00	1.00	0.0	2.	5.
DUTY CYCLE = 0.9900 REQUIRING [illegible]. MACHINES R&D = $ [illegible]0000000.									
CARGO DOCKING MECH. LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 20.0									
RETENTION LATCHES	4.00	100.00	0.10	200000.00	99.00	1.00	5.00	3.	5.
STRUCTURE & DAMPING	1.00	1800.00	0.[illegible]	900000.00	99.90	1.00	0.0	2.	5.
DUTY CYCLE = 0.9990 REQUIRING 2. MACHINES R&D = $ 31000000.									
LOAD-UNLOAD MANIPULATOR LABOR = 1.000 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 50.0									
MANIPULATOR ARM	1.00	5000.00	10.00	10000000.0	95.00	1.00	250.00	3.	5.
CREW OPERATING STATION	1.00	2000.00	1.00	4000000.00	99.00	1.00	100.00	3.	5.
DUTY CYCLE = 0.9405 REQUIRING 4. MACHINES R&D = $ 190000000.									
MAGNETIC TRANSPORTER LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 50.0									
FRAME	1.00	50.00	0.0	1417.19	99.90	1.00	2.50	1.	5.
HIGH PERMEABILITY PLUG	4.00	6.00	0.0	1301.34	100.00	1.00	0.0	2.	5.
TEFLON SKIDS	8.00	1.00	0.0	207.49	99.90	1.00	0.20	2.	5.
CONTAINER	6.00	30.00	0.0	6499.17	99.50	1.00	1.50	2.	5.
DUTY CYCLE = 0.9990 REQUIRING 130. MACHINES R&D = $ 50210000.									
TRANSPORTER TRACK LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0									
TRACK	4.00	5000.00	0.0	450000.00	99.90	1.00	90.00	1.	5.
MAGNETIC DRIVERS	1280.00	30.00	0.01	6033.80	99.90	1.00	1.50	2.	5.
BUSSBARS	2.00	45000.00	0.0	2250000.00	100.00	1.00	0.0	1.	5.
ROUTING CONTROL	1.00	2000.00	11.00	4000000.00	99.00	1.00	100.00	3.	5.
DUTY CYCLE = 0.9900 REQUIRING 1. MACHINES R&D = $ 77150000.									
INTERNAL STORAGE DEVICE LABOR = 0.0 EXPEND. = 0.0 KG/HR AT $ 0./KG COMPONENTS = 10.0									
BODY & CONTROL CIRCUIT	1.00	200.00	1.00	100000.00	99.00	1.00	10.00	2.	5.
CONTAINER TUBES	8.00	30.00	0.0	15000.00	99.00	1.00	1.50	2.	5.
PUSH ARM	1.00	150.00	1.00	75000.00	99.00	1.00	7.50	2.	5.
DUTY CYCLE = 0.5801 REQUIRING 8. MACHINES R&D = $ 11900000.									
REPAIR AUTOMATONS LABOR = 0.0 EXPEND. = 0.001 KG/HR AT $ 20./KG COMPONENTS =100.0									
AUTOMATIC REPAIR DEVICE	1.00	200.00	5.00	2000000.00	80.00	1.00	0.0	[illegible]	5.
DUTY CYCLE = 0.8000 REQUIRING 42. MACHINES R&D = $ 120000000.									

	$$$$$$$$ NONRECURRING COSTS $$$$$$$$ R & D	PROCUREMENT	TRANSPORT	POWER	TOTALS
THERMAL BELT	39250000.	403567616.	140979984.	29431488.	572285440.
DV OF AL REAR CONTACT	11853224.	40663088.	4325689.	4589564.	58048944.
DV OF SI AND P-DOPANT	29413312.	483501568.	68170816.	133704560.	673310976.
PULSE RECRYSTALLIZATION	100660192.	11522491.	1172526.	2660035.	115080704.
SCAN RECRYSTALLIZATION	100380192.	6311843.	640527.	886923.	107696720.
N-DOPANT IMPLANTATION	10500000.	12350027.	1329999.	2582997.	25734432.
ANNEAL	10380199.	6311843.	640527.	590546.	17400368.
DV OF AL FRONT CONTACT	22813216.	333457408.	36475872.	7703553.	372635648.
FRONT CONTACT SINTERING	10380199.	6311843.	640527.	295641.	17105456.
CELL CROSSCUT	10405000.	5577291.	587860.	1839468.	17946064.
CELL INTERCONNECTION	20745488.	10807879.	1606638.	2270658.	34505216.
DV SIO2 OPTICAL COVER	132740616.	845030912.	185912672.	169908160.	1256077820.
DV OF SIO2 SUBSTRATE	33740816.	599330304.	127089696.	114727056.	820269824.
PANEL ALIGN & INSERT	21820496.	34692384.	7756555.	10532290.	71610620.
PANEL INTERCONNECTION	10770500.	11150460.	1739638.	5218864.	27910272.
LONGITUDINAL CUT	10405000.	5577291.	587860.	1839468.	17946064.
KAPTON TAPE APPLICATION	20041088.	131546.	40658.	627288.	20827616.
ARRAY SEG. FOLD & PACK	10187750.	375424.	84455.	280417.	10928045.
TELEOPERATOR	187000000.	17400000.	270000.	106920.	204776912.
CRAWLER SYSTEM	127750000.	130083104.	24516000.	6024764.	288373760.
ZONE REFINER	134967488.	83398736.	13220331.	53793072.	285379584.
MASK CLEANUP DEVICE	100294992.	996196.	177500.	1081916.	102550576.
DV OF INTERCONNECTS	22125504.	12876095.	1377199.	5357177.	41735936.
LIQUID AL PIPELINE	20067488.	229000.	45800.	840.	20343104.
IRON PIPELINE	20107488.	37250.	7450.	6.	20152176.
AL ALLOYING FURNACE	58400000.	2520000.	364500.	9235394.	70519888.
IRON ALLOYING FURNACE	58400000.	840000.	121500.	3078464.	62439952.
CONTINUOUS CASTER	23054992.	614000.	178000.	446925.	24293904.
AL SLAB CUTTER	11000000.	200000.	10000.	296911.	11506911.
AL DIE CASTER	105250000.	17524992.	3550000.	676268.	127001248.

$$$'$$$$ NONRECURRING COSTS (CONT.) $$$$$$$$

	R & D	PROCUREMENT	TRANSPORT	POWER	TOTALS
FE DIE CASTER	35524992.	1552500.	315000.	66951.	37459424.
TRANSFORMER CORE CASTER	75250000.	5525000.	1150000.	323433.	82248416.
ROLLING MILL	158050000.	14805000.	18720000.	991824.	192566800.
END TRIM/WELD/ROLL WIND	13410000.	27454160.	168124800.	395422.	209384368.
SHEET TRIMMER	10460000.	78000.	8400.	122022.	10668422.
RIBBON SLICER	45400992.	3545896.	7028000.	645248.	56620128.
RIBBON TRIMMER	10300000.	30000.	3000.	11935.	10344934.
STRIATOR	20000000.	1000000.	2000000.	148500.	23148496.
FORM ROLLER	21830000.	183000.	33900.	100863.	22147728.
KLYSTRON RAD. ASSEMBLY	20480000.	2884840.	445200.	1942292.	25752320.
DC-DC CONV. PRODUCER	30000000.	2000000.	400000.	7351.	32407344.
INSULATION WINDER	12500000.	2000000.	400000.	45600.	14945600.
GLASS FIBER PRODUCER	13222750.	20958736.	1634800.	1580516.	37396784.
DC CONV. RAD. ASSEMBLY	21734992.	372500.	56500.	148485.	22312464.
KLYSTRON PLANT	1624999940.	152500000.	30500000.	95999968.	1903999490.
GLASS FOAMING FACILITY	534249472.	113974992.	22794992.	20485968.	691504896.
FOAMED GLASS CUTTER	38684992.	2868500.	589000.	64840.	42207312.
SHEET CUTTER & SLOTTER	100184992.	224036992.	11238000.	858566.	336318208.
FOAMED GLASS SMOOTHER	101250000.	48374992.	2475000.	231637.	152331616.
WAVEGUIDE DV OF AL	13940125.	2910149.	280800.	792963.	17924016.
WAVEGUIDE PACKAGER	13095000.	1362498.	2505000.	88209.	17050704.
WAVEGUIDE ASSEMBLER	100674992.	386579712.	19428000.	1853276.	508535552.
PERSONNEL DOCKING MECH.	15000000.	2000000.	400000.	11880.	17411872.
PRESSURIZED TUNNEL	60000000.	30000000.	6000000.	15444.	96015440.
CARGO DOCKING MECH.	31000000.	3400000.	440000.	2398.	34842384.
LOAD-UNLOAD MANIPULATOR	190000000.	56000000.	2800000.	124146.	248924144.
MAGNETIC TRANSPORTER	50210000.	6187676.	3406000.	0.	59803664.
TRANSPORTER TRACK	77150000.	18023248.	16640000.	67716.	111880960.
INTERNAL STORAGE DEVICE	11900000.	2360000.	472000.	47045.	14779044.
REPAIR AUTOMATONS	120000000.	84000000.	840000.	504000.	205343984.
TOTALS	5045013540.	4300349440.	944832512.	697467904.	10732580900.

$$$$$$$$ RECURRING COSTS $$$$$$$$

	OPERATING	EXPENDABLES			REPAIR		TOTALS
	LABOR	PROCUREMENT	TRANSPORT	LABOR	PROCUREMENT	TRANSPORT	
THERMAL BELT	0.	232476.	1162379.	100101.	20178368.	9516148.	28844400.
DV OF AL REAR CONTACT	0.	116354.	1163541.	55416.	2033155.	291984.	3385229.
DV OF SI AND P-DOPANT	0.	116471.	1164709.	591557.	24175088.	4601531.	28344896.
PULSE RECRYSTALLIZATION	0.	116471.	1164707.	32032.	576124.	79145.	1820472.
SCAN RECRYSTALLIZATION	0.	116471.	1164707.	32032.	315592.	43236.	1546319.
N-DOPANT IMPLANTATION	0.	466350.	233175.	16016.	617501.	89775.	1315838.
ANNEAL	0.	116471.	1164707.	32032.	315592.	43236.	1546319.
DV OF AL FRONT CONTACT	0.	1164707.	11647082.	151113.	16672924.	2462121.	29684560.
FRONT CONTACT SINTERING	0.	116471.	1164707.	32032.	315592.	43236.	1546319.
CELL CROSSCUT	0.	290595.	1162379.	48049.	278864.	39680.	1682757.
CELL INTERCONNECTION	0.	34837.	232244.	172174.	540394.	108448.	1006285.
DV SIO2 OPTICAL COVER	0.	231780.	2317796.	835164.	42251552.	12549110.	53810560.
DV OF SIO2 SUBSTRATE	0.	231780.	2317796.	583549.	29966560.	8578563.	38544560.
PANEL ALIGN & INSERT	0.	34906.	232709.	1205217.	1734618.	523568.	3450492.
PANEL INTERCONNECTION	0.	34837.	232244.	172174.	557523.	117425.	1030428.
LONGITUDINAL CUT	0.	290595.	1162379.	48049.	278864.	39680.	1682757.
KAPTON TAPE APPLICATION	0.	34976.	233171.	89210.	6577.	2744.	339109.
ARRAY SEG. FOLD & PACK	0	34976.	233176.	95096.	18771.	5701.	387720.
TELEOPERATOR	0.	0.	0.	66225.	1739999.	36450.	1842673.
CRAWLER SYSTEM	0.	1735.	8677.	1791093.	9099153.	2225474.	13126132.
ZONE REFINER	0.	104877.	524383.	651563.	553127.	100582.	1934530.
MASK CLEANUP DEVICE	0.	0.	0.	835351.	15352445.	1184624.	17372416.
DV OF INTERCONNECTS	0.	874.	4370.	37632.	6013995.	2959468.	9016338.
LIQUID AL PIPELINE	0.	0.	0.	373270.	103000.	27810.	504080.
IRON PIPELINE	0.	0.	0.	30102.	28250.	7627.	65980.
AL ALLOYING FURNACE	0.	0.	0.	108369.	915000.	64800.	1088168.
IRON ALLOYING FURNACE	0.	0.	0.	36123.	305000.	21600.	362723.
CONTINUOUS CASTER	0.	0.	0.	66225.	27900.	5670.	99795.
AL SLAB CUTTER	0.	0.	0.	18061.	15200.	1026.	34287.
AL DIE CASTER	73758.	0.	0.	63215.	875000.	236250.	1248223.

$$$$$$$$ RECURRING COSTS (CONT.) $$$$$$$$

	OPERATING LABOR	EXPENDABLES PROCUREMENT	EXPENDABLES TRANSPORT	LABOR	REPAIR PROCUREMENT	TRANSPORT	TOTALS
FE DIE CASTER	73021.	0.	0.	9031.	0.	0.	82052.
TRANSFORMER CORE CASTER	11801.	0.	0.	6020.	275000.	74250.	367072.
ROLLING MILL	0.	1414.	7069.	63215.	402750.	352350.	826797.
END TRIM/WELD/ROLL WIND	0.	0.	0.	36123.	519094.	4059821.	4615038.
SHEET TRIMMER	0.	0.	0.	24082.	7140.	786.	32008.
RIBBON SLICER	0.	0.	0.	322096.	54000.	136080.	512176.
RIBBON TRIMMER	0.	0.	0.	9031.	2880.	397.	12308.
STRIATOR	0.	0.	0.	3010.	50000.	135000.	188010.
FORM ROLLER	0.	0.	0.	12041.	77630.	20579.	110250.
KLYSTRON RAD. ASSEMBLY	0.	0.	0.	2739314.	276414.	48393.	3064121.
DC-DC CONV. PRODUCER	59007.	69419760.	69419760.	6020.	150000.	40500.	139095024.
INSULATION WINDER	0.	0.	0.	120410.	100000.	27000.	247410.
GLASS FIBER PRODUCER	0.	0.	0.	1597548.	936696.	110596.	2644840.
DC CONV. RAD. ASSEMBLY	0.	0.	0.	183625.	29475.	3179.	216279.
KLYSTRON PLANT	0.	87659952.	350639616.	60205.	7649997.	2065499.	448074752.
GLASS FOAMING FACILITY	270651.	133986.	13398550.	261891.	7309494.	1973564.	23348112.
FOAMED GLASS CUTTER	0.	0.	0.	12041.	0.	0.	12041.
SHEET CUTTER & SLOTTER	0.	0.	0.	96328.	4201490.	285120.	4582544.
FOAMED GLASS SMOOTHER	0.	0.	0.	27092.	910500.	63585.	1001177.
WAVEGUIDE DV OF AL	0.	0.	0.	54186.	1522199.	126441.	1702824.
WAVEGUIDE PACKAGER	0.	0.	0.	785755.	11592465.	86064512.	98442720.
WAVEGUIDE ASSEMBLER	0.	0.	0.	469598.	12024000.	816480.	13310076.
PERSONNEL DOCKING MECH.	0.	0.	0.	12041.	100000.	27000.	139041.
PRESSURIZED TUNNEL	0.	0.	0.	36123.	250000.	67500.	353623.
CARGO DOCKING MECH.	0.	0.	0.	24684.	80000.	5400.	110084.
LOAD-UNLOAD MANIPULATOR	1132451.	0.	0.	72246.	2800000.	189000.	4193697.
MAGNETIC TRANSPORTER	0.	0.	0.	1526229.	305837.	229905.	2061970.
TRANSPORTER TRACK	0.	0.	0.	389566.	604163.	321300.	1315029.
INTERNAL STORAGE DEVICE	0.	0.	0.	240819.	118000.	31860.	390679.
REPAIR AUTOMATONS	0.	5891.	29454.	2528604.	0.	0.	2563948.
TOTALS	1620690.	161109984.	462185216.	20097152.	228210608.	143282448.	1000278020.

```
TOTAL DIRECT NON-RECURRING COST =$10732580900.
TOTAL DIRECT RECURRING COST =$ 1000278020.

TOTAL DIRECT PRODUCTION MASS (KG) =  5448325.
TOTAL DIRECT PRODUCTION POWER (KW) =    232489.
TOTAL DIRECT PRODUCTION CREW =   216. PEOPLE

TOTAL SMP CREW =   433.
CREW TRANSPORT MASS =  173151. KG, CONSUMABLE MASS =  131140. KG
CREW TRANSPORT COST=$  77916080. CONSUMABLES COST=  13114043.

CREW TRAINING COSTS =$  21643920.
SUPPORT CREW WAGES =$  65153504.
SUPPORT EXPENDABLES TRANSPORT COST =$        0.

HABITAT MASS (KG) =   1315950.
HABITAT POWER (KW) =       3896.
R&D AND PROCUREMENT COST OF HABITAT ($) =   508594688.
TRANSPORT COST OF HABITAT ($) =   1315 4992.
POWER COST OF HABITAT ($) =    11687717.
NONRECURRING COST OF NONPRODUCTION SMF =$ 50000000.

TOTAL SMF MASS (KG) = 15130126.
TOTAL SMP POWER (KW) =  237385.

SMP SUPPORT TRANSPORT COST =$201000000.
SMP SUPPORT POWER COST =$  2000000.

SETUP COSTS =$ 3086410. FOR    8. PEOPLE


        $$$$$$$$    DIRECT COSTS: NONRECURRING =$10732580900., RECURRING =$ 1000278020.

        $$$$$$$$  INDIRECT COSTS: NONRECURRING =$  907963392., RECURRING =$  177829536.

        $$$$$$$$  SMF LIFE CYCLE COSTS=$  21670486000.

        $$$$$$$$  DISCOUNTED AVERAGE SPS COST=$ 1083524100.
```

A.2: PROGRAM SPSLP

(LINEAR PROGRAMMING OPTIMIZATION

OF SMF BUILDUP SCENARIO)

LISTING

DATA

OUTPUT

```
C***********************************************************************
C*                LP OPTIMIZATION OF SPS PRODUCTION OPTIONS
C*                       M.I.T. SPACE SYSTEMS LAB
C*                            APRIL 11, 1979
C*  PRODUCED UNDER CONTRACT TO THE NASA MARSHALL SPACE FLIGHT CENTER
C*---------------------------------------------------------------------
C*  THIS PROGRAM SETS UP A 64 X 100 SIMPLEX TABLEAU FOR THREE
C*  COMPETING ENERGY OPTIONS:
C*    1) SOLAR POWER SATELLITES PREFABRICATED ON EARTH
C*    2) SOLAR POWER SATELLITES PRODUCED IN SPACE FROM LUNAR MATERIAL
C*    3) GROUND-BASED POWER PRODUCTION IN THE SAME TIME FRAME AS SPS
C*  THE TWO SPS OPTIONS HAVE ASSOCIATED RESEARCH AND DEVELOPMENT COSTS,
C*  WHICH THE GROUND-BASED OPTION DOES NOT HAVE.  THE LP OPTIMIZATION
C*  CHOOSES BUDGETARY ALLOCATIONS FOR A 20-YEAR ENERGY PROGRAM
C*  UNDER THE FOLLOWING ASSUMPTIONS:
C*    1) YEARLY INVESTMENTS ARE LIMITED
C*    2) INVESTMENT CAPITAL IN A GIVEN YEAR MAY BE AUGMENTED FROM
C*       PROFITS OF THE PREVIOUS YEAR
C*    3) THE OBJECTIVE FUNCTION IS TO MAXIMIZE THE NET PRESENT VALUE
C*       OF THE NET PROFITS
C*---------------------------------------------------------------------
C*  VARIABLE DEFINITIONS:
C*    RE        R&D COST OF EARTH-SUPPLY SPS
C*    RL        R&D COST OF LUNAR-SUPPLY S
C*    CE        PRODUCTION COST OF AN EAR -SUPPLY SPS
C*    CL        PRODUCTION COST OF A LUNAR-SUPPLY SPS
C*    CG        PRODUCTION COST FOR 10,000 MW GROUND-BASED POWER STATION
C*    BR        YEARLY MONETARY RETURN FROM ONE SPS OR EQUIVALENT
C*    R         DISCOUNT RATE
C*    SPSMAX    MARKET LIMIT ON POWER STATIONS
C*    Y(I)      BUDGETARY ALLOCATION FOR YEAR I
C*    A         TABLEAU MATRIX
C*    B         CONSTRAINTS
C*    C         COEFFICIENTS OF OBJECTIVE FUNCTION
C*---------------------------------------------------------------------
C*  DAVID I. AKIN                               APRIL 11, 1979
C***********************************************************************
      DIMENSION A(65,100),B(65),C(100),PSOL(100),DSOL(65),RW(4418),
     +IW(193),Y(20)
      READ(5,101)RE,RL,CE,CL,CG,BR,R,SPSMAX,CHECK
      READ(5,102) (Y(I),I=1,10)
      READ(5,102) (Y(I),I=11,20)
      WRITE(6,201)RE,RL
      WRITE(6,202)CE,CL,CG
      WRITE(6,203)BR
C*
C*  INITIALIZE TABLEAU ARRAY
C*
      DO 1 I=1,65
      DO 1 J=1,100
    1 A(I,J)=0.
C*
C*  CONSTRAINT TO PAY R&D ON EARTH-SUPPLY SYSTEM
```

```
C*
      DO 4 I=1,20
      DO 2 J=1,I
 2    A(I,J)=-1./BE
      A(I,I+40)=1.
      IF (I.EQ.1) GO TO 4
      K1=I-1
      DO 3 K=1,K1
 3    A(I,K+40)=-1.
 4    B(I)=0.
C*
C*  CONSTRAINT TO PAY R&D ON LUNAR-SUPPLY SYSTEM
C*
      DO 7 I=1,20
      DO 5 J=1,I
 5    A(I+20,J+20)=-1./BL
      A(I+20,I+60)=1.
      IF (I.EQ.1) GO TO 7
      K1=I-1
      DO 6 K=1,K1
 6    A(I+20,K+60)=-1.
 7    B(I+20)=0.
C*
C*  CONSTRAINT FOR YEARLY BUDGET
C*
      DO 9 I=1,20
      A(I+40,I)=1.
      A(I+40,I+20)=1.
      A(I+40,I+40)=CE
      A(I+40,I+60)=CL
      A(I+40,I+80)=CG
      IF (I.EQ.1) GO TO 9
      K1=I-1
      DO 8 K=1,K1
      A(I+40,K+40)=-BR
      A(I+40,K+60)=-BR
C*  TAKE OUT THE FOLLOWING LINE TO DECOUPLE GROUND-BASED PROFITS
      A(I+40,K+80)=-BR
 8    CONTINUE
 9    B(I+40)=Y(I)
C*
C*  CONSTRAINTS ON NUMBER OF SPS'S AND R&D SPENDING
C*
      DO 10 J=1,20
      A(61,J+40)=1.
      A(61,J+60)=1.
      A(61,J+80)=1.
      A(62,J)=1.
 10   A(63,J+20)=1.
      B(61)=SPSMAX
      B(62)=BE
      B(63)=BL
C*
```

```
C*   SET UP OBJECTIVE FUNCTION
C*
       DO 11 I=1,20
       C(I)=-(1.+B)**(-I)
       C(I+20)=-(1.+B)**(-I)
       C(I+40)=BE*((1.+B)**(-I)-(1.+B)**(-40))/B-CE*(1.+B)**(-I)
       C(I+60)=BR*((1.-B)**(-I)-(1.+B)**(-40))/B-CL*(1.+B)**(-I)
 11    C(I+80)    '((1.+B)**(-I)-(1.+B)**(-40))/B-CG*(1.+B)**(-I)
C*
C*   IF CHECK = 1., PRINT OUT TABLEAU FOR PROGRAM VERIFICATION
C*
       IF (CHECK.NE.1.) GO TO 15
       DO 12 K=1,5
       J1=20*K-19
       J2=20*K
       WRITE(6,301)J1,J2
       DO 12 I=1,63
 12    WRITE(6,302) (A(I,J),J=J1,J2)
       DO 13 K=1,3
       J1=20*K-19
       J2=20*K
       WRITE(6,303)J1,J2
 13    WRITE(6,302) (B(J),J=J1,J2)
       DO 14 K=1,10
       J1=10*K-9
       J2=10*K
       WRITE(6,304)J1,J2
 14    WRITE(6,206) (C(J),J=J1,J2)
C*
C*   SUBROUTINE CALL TO IMSL SUBROUTINE PACKAGE FOR REVISED SIMPLEX
C*   LP OPTIMIZATION ROUTINE
C*
 15    CALL ZX3LP(A,65,B,C,100,63,0,S,PSOL,DSOL,RW,IW,IER)
C*
C*   WRITE OUT LP SUBROUTINE ERROR CODE: STOP IF ABNORMAL
C*
       WRITE(6,208)IER
       IF (IER.NE.0) GO TO 18
C*
C*   WRITE OUT OPTIMUM VALUE OF OBJECTIVE FUNCTION
C*
       WRITE(6,204)S
C*
C*   WRITE OUT PRIMAL SOLUTION
C*
       DO 16 I=1,10
       I1=10*I-9
       I2=10*I
       WRITE(6,205)I1,I2
 16    WRITE(6,206) (PSOL(J),J=I1,I2)
C*
C*   WRITE OUT DUAL SOLUTION
C*
```

```
      DO 17 I=1,6
      I1=10*I-9
      I2=10*I
      WRITE(6,207)I1,I2
   17 WRITE(6,206) (DSOL(J),J=I1,I2)
      I1=61
      I2=63
      WRITE(6,207)I1,I2
      WRITE(6,209) (DSOL(J),J=61,63)
   18 STOP
C*
C* FORMAT STATEMENTS
C*
  101 FORMAT(9F8.3)
  102 FORMAT(10F8.3)
  201 FORMAT(20X,'********* LP OPTIMIZATION OF SPS BUILD-UP ********'/
     *' EARTH SUPPLY R&D COST ($B) = ',F6.1/
     *' LUNAR SUPPLY R&D COST ($B) = ',F6.1)
  202 FORMAT(/' CONSTRUCTION COSTS: $B PER 10,000 MW'/
     *6X,'EARTH SPS OPTION  =  ',F6.1/
     *6X,'LUNAR SPS OPTION  =  ',F6.1/
     *6X,'GROUND-BASED OPTION = ',F5.1)
  203 FORMAT(/' YEARLY RETURN FROM SPS ($B) = ',F8.2)
  204 FORMAT(///' OPTIMIZED NET PROFIT ($B) = ',F8.3///)
  205 FORMAT(/' PRIMAL SOLUTION FOR COLUMNS ',I3,' THROUGH ',I3)
  206 FORMAT(1X,10F12.5)
  207 FORMAT(/'  DUAL SOLUTION FOR ROWS ',I3,' THROUGH ',I3)
  208 FORMAT(///' ERROR CODE FROM LP SUBROUTINE = ',I3)
  209 FORMAT(1[illegible]5)
  301 FORMAT'[illegible]D MATRIX, COLUMNS ',I3,' THROUGH ',I3)
  302 FORMAT(1[illegible]2)
  303 FORMAT(/'[illegible]STRAINT CONSTANTS, ROWS ',I3,' THROUGH ',I3)
  304 FORMAT(/' OBJ[illegible]TIVE FUNCTION, COLUMNS ',I3,' THROUGH ',I3)
      END
```

```
FILE: SPSLP    DATA     A                    CONVERSATIONAL MONITOR SYSTEM

30.     70.     6.      2.      15.     1.752   .1      112.    1.
10.     10.     10.     10.     10.     10.     10.     10.     10.     10.
10.     10.     10.     10.     10.     10.     10.     10.     10.     10.
```

```
******** LP OPTIMIZATION OF SPS BUILD-UP ********
EARTH SUPPLY R&D COST ($B) =   30.0
LUNAR SUPPLY R&D COST ($B) =   70.0

CONSTRUCTION COSTS: $B PER 10,000 MW
     EARTH SPS OPTION  =      6.0
     LUNAR SPS OPTION  =      2.0
     GROUND-BASED OPTION =   15.0

YEARLY RETURN FROM SPS ($B) =      1.75

TABLEAU MATRIX, COLUMNS   1 THROUGH  20
```

-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	0.0
-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLEAU MATRIX, COLUMNS 21 THROUGH 40

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0

-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.0
-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLEAU MATRIX, COLUMNS 41 THROUGH 60

1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	6.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLEAU MATRIX, COLUMNS 61 THROUGH 80

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00	0.0
-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	1.00
2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	2.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLEAU MATRIX, COLUMNS 81 THROUGH 100

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0	0.0
-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	-1.75	15.00	0.0	0.0

```
 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 15.00  0.0
 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 -1.75 15.00
  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

CONSTRAINT CONSTANTS, ROWS   1 THROUGH  20
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

CONSTRAINT CONSTANTS, ROWS  21 THROUGH  40
  0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

CONSTRAINT CONSTANTS, ROWS  41 THROUGH  60
 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00 10.00

OBJECTIVE FUNCTION, COLUMNS   1 THROUGH  10
    -0.90909     -0.82645     -0.75132     -0.68302      -0.62092      -0.56448      -0.51316      -0.46651      -0.42410      -0.38555

OBJECTIVE FUNCTION, COLUMNS  11 THROUGH  20
    -0.35050     -0.31863     -0.28967     -0.26333      -0.23940      -0.21763      -0.19785      -0.17986      -0.16351      -0.14865

OBJECTIVE FUNCTION, COLUMNS  21 THROUGH  30
    -0.90909     -0.82645     -0.75132     -0.68302      -0.62092      -0.56448      -0.51316      -0.46651      -0.42410      -0.38555

OBJECTIVE FUNCTION, COLUMNS  31 THROUGH  40
    -0.35050     -0.31863     -0.28967     -0.26333      -0.23940      -0.21763      -0.19785      -0.17986      -0.16351      -0.14865

OBJECTIVE FUNCTION, COLUMNS  41 THROUGH  50
    10.05561      9.13355      8.26804      7.48122       6.76592       6.11565       5.52450       4.98708       4.49852       4.05438

OBJECTIVE FUNCTION, COLUMNS  51 THROUGH  60
     3.65061      3.28355      2.94985      2.64649       2.37072       2.12000       1.89209       1.68489       1.49652       1.32528

OBJECTIVE FUNCTION, COLUMNS  61 THROUGH  70
    13.72198     12.43934     11.27331     10.21328       9.24962       8.37356       7.57714       6.85312       6.19493       5.59656

OBJECTIVE FUNCTION, COLUMNS  71 THROUGH  80
     5.05260      4.55808      4.10852      3.69983       3.32829       2.99053       2.68347       2.40433       2.15057       1.91987

OBJECTIVE FUNCTION, COLUMNS  81 THROUGH  90
     1.90379      1.69552      1.50619      1.33407       1.17760       1.03536       0.90605       0.78849       0.68161       0.59246

OBJECTIVE FUNCTION, COLUMNS  91 THROUGH 100
     0.49613      0.41584      0.34284      0.27648       0.21616       0.16131       0.11146       0.06613       0.02493      -0.01253


ERROR CODE FROM LP SUBROUTINE =    0


OPTIMIZED NET PROFIT ($B) =  750.526
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PRIMAL SOLUTION FOR COLUMNS   1 THROUGH  10
     0.0          0.0         2.25015     0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  11 THROUGH  20
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  21 THROUGH  30
     9.72222      9.41867     2.39050     0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  31 THROUGH  40
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  41 THROUGH  50
     0.0          0.0         0.07501     0.15001     0.30002     0.60004     1.20008     0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  51 THROUGH  60
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  61 THROUGH  70
     0.13889      0.41233     0.85881     1.71762     3.43524     6.87047    13.74096    27.48187    54.96373     0.0

PRIMAL SOLUTION FOR COLUMNS  71 THROUGH  80
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  81 THROUGH  90
     0.0          0.0         0.0         0.0         0.0         0.0         0.05493     0.0         0.0         0.0

PRIMAL SOLUTION FOR COLUMNS  91 THROUGH 100
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

 DUAL SOLUTION FOR ROWS   1 THROUGH  10
    34.11517     20.53935    12.04770     5.63044     2.45757     0.90365     1.49948     0.0         0.0         0.0

 DUAL SOLUTION FOR ROWS  11 THROUGH  20
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

 DUAL SOLUTION FOR ROWS  21 THROUGH  30
   113.19492     56.84492    28.57626    13.75847     6.39729     2.76060     1.63221     0.10757     0.64124     0.0

 DUAL SOLUTION FOR ROWS  31 THROUGH  40
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

 DUAL SOLUTION FOR ROWS  41 THROUGH  50
     2.27136      0.73692     0.0         0.0         0.0         0.0         0.34655     0.0         0.19505     0.0

 DUAL SOLUTION FOR ROWS  51 THROUGH  60
     0.0          0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0         0.0

 DUAL SOLUTION FOR ROWS  61 THROUGH  63
     6.44606      0.0         0.0
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A.3: PROGRAM SCFCOST

(PROBABILITY ANALYSIS OF SOLAR CELL FACTOR: BREAKDOWN AND REPAIR REQUIREMENTS)

LISTING

DATA

OUTPUT

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C*********************************************************************
C
C                 VARIATION OF PARAMETERS STRATEGY
C         FOR A SOLAR CELL FACTORY AND ITS SUPPORT EQUIPMENT
C               IN A SPACE MANUFACTURING FACILITY
C
C             DEVELOPED UNDER CONTRACT TO THE NASA
C                 MARSHALL SPACE FLIGHT CENTER
C
C             MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C                   SPACE SYSTEMS LABORATORY
C
C---------------------------------------------------------------------
C
C                      CRAIG R. CARIGNAN
C                       AUGUST 14, 1979
C
C*********************************************************************
C*       VARIABLE DEFINITIONS:
C*    ENDPRP  -  NUMBER OF LAST PRODUCTION MACHINE
C*    NOMACH  -  NUMBER OF MACHINES
C*    NCT(I)  -  NUMBER OF COMPONENT TYPES IN MACHINE I
C*    NCCLUS(I)  -  NUMBER OF COMPONENT CLUSTERS IN MACHINE I
C*    DELIT  -  TIME BETWEEN CARGO TRANSPORT DELIVERIES (YRS)
C*    ETT  -  EARTH TRANSIT TIME FOR EMERGENCY COMPONENT (HRS)
C*    TRANT  -  TELEOPERATOR TRANSIT TIME PER REPAIR (HRS)
C*    TRANC  -  CRAWLER TRANSIT TIME PER MISSION (HRS)
C*    DELAY  -  DELAY TIME FOR CRAWLER IN RESPONSE TO PRIORITY
C*               MISSIONS (HRS)  (DOES NOT INCLUDE TRANSIT TIME)
C*    TPER  -  PERSONNEL SHUTTLE TRANSPORT COST ($/KG)
C*    TCARGO  -  CARGO TRANSPORT COSTS ($/KG)
C*    SOBR  -  STOCK ON BOARD RATION (RATIO OF STOCK KEPT TO
C*              EXPECTED NUMBER OF REPAIRS)
C*    ANSTRP  -  APPROXIMATE NUMBER OF STRIPS
C*    UF  -  CRAWLER AND TELEOPERATOR UTILIZATION FACTOR
C*    UFT  -  UTILIZATION FACTOR TOLERANCE
C*    LF  -  FRACTION OF TIME CRAWLER SPENDS LOADING AND UNLOADING STOCK
C*    AH  -  RATIO OF AUTOMATIC TO HUMAN REPAIR TIMES
C*    HABRD  -  HABITAT R&D COST ($)
C*    HABKGP  -  HABITAT MASS/PERSON (KG/PERSON)
C*    HABDKG  -  HABITAT COST ($/KG)
C*    HABKWP  -  HABITAT POWER (KW/PERSON)
C*    SPADKW  -  SOLAR POWER ARRAY COST ($/KW)
C*    SPAGW  -  SOLAR POWER ARRAY MASS (KG/KW)
C*    WAGE  -  PERSONNEL WAGE ($/HR)
C*    TRAIN  -  TRAINING COSTS ($/PERSON)
C*    CONSUM  -  CONSUMABLES (KG/PERSON-HR)
C*    CONCST  -  CONSUMABLES COST ($/KG)
C*    ASTMAS  -  CREW MASS (KG/PERSON)
C*    ROTYR  -  ROTATIONS OF CREW PER YEAR
C*    DAYSUP  -  DAYS REQUIRED TO SET UP THE SCF
C*    SUPROD  -  SET-UP PRODUCTIVITY (KG/PERSON-HR)
C*    SCR  -  SUPPORT CREW RATIO (TOTAL CREW/PRODUCTION CREW)
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C*     SESTAF  -  SUPPORT EQUIPMENT REPAIR STAFF ON DUTY                   SCP00540
C*     FLCT  -  MAXIMUM POWER FLUCTUATION FROM AVERAGE (FRACTION)          SCP00550
C*     LIFE  -  SCP LIFETIME (YRS)                                         SCP00560
C*     DR  -  DISCOUNT RATE                                                SCP00570
C*     STCDKG  -  SCP STRUCTURE R&D AND PROCUREMENT ($/KG)                 SCP00580
C*     STCKGV  -  SCP STRUCTURAL DENSITY (KG/M**3)                         SCP00590
C*     STCVS  -  SCP STRUCTURE (M**3/SECTION)                              SCP00600
C*     STCKWS  -  SCP STRUCTURE (KW/SECTION)                               SCP00610
C*     STCEXP  -  SCP STRUCTURE EXPENDABLES (KG/HR-SECTION)                SCP00620
C*     STCEXC  -  SCP STRUCTURE EXPENDABLES COST ($/KG)                    SCP00630
C*     VOLFM  -  MAXIMUM VOLUMETRIC LOAD FACTOR IN WAREHOUSE               SCP00640
C*     WHDKG  -  WAREHOUSE COST ($/KG)                                     SCP00650
C*     WHKGV  -  WAREHOUSE DENSITY (KG/M**3)                               SCP00660
C*     WHRD  -  W    OUSE R&D ($)                                          SCP00670
C*     WHKWV  -    HOUSE POWER VOLUME (KW/M**3)                            SCP00680
C*     WHEXP  -  WAREHOUSE EXPENDABLES (KG/M**3/HR)                        SCP00690
C*     WHEXC  -  WAREHOUSE EXPENDABLES COST ($/KG)                         SCP00700
C*     CCSMAS  -  CONTROL CENTER STRUCTURAL MASS (KG)                      SCP00710
C*     CCHMAS  -  CONTROL CENTER HARDWARE MASS (KG)                        SCP00720
C*     CCRD  -  CONTROL CENTER R&D (WITH SOFTWARE DEVELOPMENT) ($)         SCP00730
C*     CCHCST  -  CONTROL CENTER HARDWARE COST ($)                         SCP00740
C*     CCSPOW  -  CONTROL CENTER STRUCTURAL POWER (KW)                     SCP00750
C*     CCHPOW  -  CONTROL CENTER HARDWARE POWER (KW)                       SCP00760
C*     CCEXP  -  CONTROL CENTER EXPENDABLES (KG/HR)                        SCP00770
C*     CCEXC  -  CONTROL CENTER EXPENDABLES COST ($/KG)                    SCP00780
C*     CCSTAF  -  CONTROL CENTER STAFF ON DUTY (DOES NOT INCLUDE           SCP00790
C*                TELEOPERATOR STAFF                                       SCP00800
C*     RSSKGP  -  REPAIR SHOP STRUCTURAL MASS (KG/PERSON)                  SCP00810
C*     RSHKGP  -  REPAIR SHOP HARDWARE MASS (KG/PERSON)                    SCP00820
C*     RSHDKG  -  REPAIR SHOP HARDWARE PROCUREMENT COST ($/KG)             SCP00830
C*     RSSKWP  -  REPAIR SHOP STRUCTURAL POWER (KW/PERSON)                 SCP00840
C*     RSHKWP  -  REPAIR SHOP HARDWARE POWER (KW/PERSON)                   SCP00850
C*     RSLD  -  REPAIR SHOP R&D ($)                                        SCP00860
C*     RSEXP  -  REPAIR SHOP EXPENDABLES (KG/PERSON-HR)                    SCP00870
C*     RSEXC  -  REPAIR SHOP EXPENDABLES COST ($/KG)                       SCP00880
C*     MSRD  -  MICROPROCESSORS & SENSORS R&D ($)                          SCP00890
C*     MSCST  -  MICROPROCESSORS & SENSORS PROCUREMENT ($/STRIP)           SCP00900
C*     MSKGST  -  MICROPROCESSORS & SENSORS MASS (KG/STRIP)                SCP00910
C*     MSKWST  -  MICROPROCESSORS & SENSORS POWER (KW/STRIP)               SCP00920
C*     MSEXP  -  MICROPROCESSORS & SENSORS EXPENDABLES (KG/STRIP/HR)       SCP00930
C*     MSEXC  -  MICROPROCESSORS & SENSORS EXP. COST ($/KG)                SCP00940
C*     CRWRD  -  CRAWLER R&D ($)                                           SCP00950
C*     CRWCST  -  CRAWLER PROCUREMENT ($)                                  SCP00960
C*     CRWMAS  -  CRAWLER MASS (KG)                                        SCP00970
C*     CRWPOW  -  CRAWLER POWER (KW)                                       SCP00980
C*     CRWEXP  -  CRAWLER EXPENDABLES MASS (KG/HR)                         SCP00990
C*     CRWEXC  -  CRAWLER EXPENDABLES COST ($/KG)                          SCP01000
C*     TELRD  -  TELEOPERATOR R&D ($)                                      SCP01010
C*     TELCST  -  TELEOPERATOR PROCUREMENT ($)                             SCP01020
C*     TELMAS  -  TELEOPERATOR MASS (KG)                                   SCP01030
C*     TELPOW  -  TELEOPERATOR POWER (KW)                                  SCP01040
C*     TELEXP  -  TELEOPERATOR EXPENDABLES (KG/HR)                         SCP01050
C*     TELEXC  -  TELEOPERATOR EXPENDABLES COST ($/KG)                     SCP01060
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C*      PAKCRW  -  NUMBER OF CRAWLERS NEEDED FOR ARRAY SEGMENT PACKAGING
C*      BOXES  -  COST OF ARRAY SEGMENT STORAGE BOXES/SECTION ($)
C*      OUTPUT  -  NUMBER OF CELLS PRODUCED/YR
C*      NAMEM(I,K)  -  MACHINE NAMES
C*      NAMEC(I,J,K)  -  COMPONENT NAMES
C*      RD(I,J)  -  COMPONENT R&D COST
C*      COST(I,J)  -  COMPONENT PROCUREMENT ($) (WITH 80% LEARNING)
C*      POWER(I,J)  -  COMPONENT POWER (KW)
C*      MASS(I,J)  -  COMPONENT MASS (KG)
C*      VOLUME(I,J)  -  COMPONENT VOLUME (M**3)
C*      NOCCMP(I,J)  -  NUMBER OF COMPONENTS OF THIS TYPE IN A MACHINE IF
C*                      IT IS THE TYPE OF COMPONENT THAT SERVES ONLY ONE
C*                      STRIP; NUMBER OF COMPONENTS OF THIS TYPE IN A
C*                      MACHINE TYPE PER SECTION IF THE COMPONENT SERVICES
C*                      14 STRIPS
C*      SHTDWN(I,J)  -  MINIMUM OPERATION NUMBER OF COMPONENTS/CLUSTER
C*      TYPE(I,J)  -  NUMBER OF STRIPS SERVED BY COMPONENT (1 OR 14)
C*      MAINT(I,J)  -  COMPONENT AVERAGE MAINTENANCE TIME BY CRAWLER/YR
C*      EXPEND(I,J)  -  COMPONENT EXPENDABLES MASS (KG/HR)
C*      EXPCST(I,J)  -  COMPONENTS EXPENDABLES COST ($/KG)
C*      RRCODE(I,J)  -  COMPONENT REPAIR/REPLACE CODE:
C*                    1  -  TELEOPERATOR REPAIR ON LINE
C*                    21  -  CRAWLER REPLACEMENT, AUTOMATED REPAIR
C*                    22  -  CRAWLER REPLACEMENT, HUMAN REPAIR
C*                    3  -  PERIODIC CRAWLER REPLACEMENT (RECYCLE/DISCARD)
C*      NOFAIL(I,J)  -  COMPONENT FAILURES/YR
C*      HUTIME(I,J)  -  HUMAN TIME PER FAILURE (HRS)
C*      TCTIME(I,J)  -  TELEOPERATOR/CRAWLER TIME PER REPAIR/REPLACE
C*      FCR(I,J)  -  FRACTION OF MASS REPLACED PER YEAR
C*                 CODE 3  -  NUMBER OF TIMES COMPONENT IS RECYCLED
C*      CRS(I,J)  -  COST OF REPAIR STOCK ($/KG)
C*      RECTIM(I,J)  -  AVERAGE RECYCLING TIME THROUGH CLEANERS (HR)
C*      AUTRD(I,J)  -  REPAIR AUTOMATON R&D ($)
C*      AUTCST(I,J)  -  REPAIR AUTOMATON PROCUREMENT ($)
C*      AUTMAS(I,J)  -  REPAIR AUTOMATON MASS (KG)
C*      AUTPOW(I,J)  -  REPAIR AUTOMATON POWER (KW)
C*      AUTVOL(I,J)  -  REPAIR AUTOMATON VOLUME (M**3)
C*      AUTEXP(I,J)  -  REPAIR AUTOMATON EXPENDABLES (KG/HR)
C*      AUTEXC(I,J)  -  REPAIR AUTOMATON EXPEND. COST ($/KG)
C*      CLNRD(I,J)  -  CLEANING MACHINE R&D ($)
C*      CLNCST(I,J)  -  CLEANING MACHINE PROCUREMENT ($)
C*      CLNMAS(I,J)  -  CLEANING MACHINE MASS (KG)
C*      CLNPOW(I,J)  -  CLEANING MACHINE POWER (KW)
C*      CLNVOL(I,J)  -  CLEANING MACHINE VOLUME (M**3)
C*      CLNEXP(I,J)  -  CLEANING MACHINE EXPENDABLES (KG/HR)
C*      CLNEXC(I,J)  -  CLEANING MACHINE EXPEND. COST ($/KG)
C*      EARTH(I,J)  -  FRACTION OF COMPONENTS SHIPPED ON EMERGENCY BASIS
C*      TLSERV(I,J)  -  MAX. NUMBER OF STRIPS SERVED BY TELEOPERATOR
C*      TUF(I,J)  -  TELEOPERATOR UTILIZATION FRACTION BY COMPONENT (I,J)
C*      CRSERC(I)  -  MAX. NUMBER OF STRIPS SERVED BY CRAWLER
C*      CUF(I)  -  CRAWLER UTILIZATION FACTOR BY MACHINE (I)
C*      NOSTRP  -  NUMBER OF STRIPS IN SCF (MULTIPLE OF 14)
C*      RRPC  -  RECURRING MACHINE REPLACEMENT PARTS COST ($)
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C*    NERPC  -  NONRECYCLING MACHINE...(ETC.)
C*    REPT  -  RECURRING REPLACEMENT PARTS TRANSPORTATION ($)
C*    NERPT  -  NONRECURRING ...
C*    VOLUM  -  VOLUME OF WAREHOUSE (M**3)
C*    NOTELE  -  TOTAL NUMBER OF TELEOPERATORS
C*    NOCRAW  -  TOTAL NUMBER OF CRAWLERS
C*    NOHUM1  -  CREW ON DUTY SUPERVISING TELEOPERATORS
C*    NOHUM2  -  REPAIR CREW ON DUTY
C*    TCFIDP(I,J)  -  TOTAL COMPONENT FAILURES IN DELIVERY PERIOD FOR
C*                     COMPONENTS OF TYPE (I,J)
C*    NOAUTO(I,J)  -  NUMBER OF REPAIR AUTOMATONS NEEDED FOR (I,J)
C*    NOCLN(I,J)  -  NUMBER OF CLEANING MACHINES NEEDED FOR (I,J)
C*    NOTELE(I,J)  -  NUMBER OF TELEOPERATORS NEEDED FOR (I,J)
C*    NOCRAW(I,J)  -  NUMBER OF CRAWLERS NEEDED FOR (I,J)
C*    NOHUM1(I,J)  -  NUMBER OF HUMANS SUPERVISING TELEOP. FOR (I,J)
C*    NOHUM2(I,J)  -  NUMBER OF HUMANS REPAIRING (I,J)
C*    MACHDC(I)  -  MACHINE DUTY CYCLE
C*    STATDC(I,J)  -  STATION DUTY CYCLE
C*    PSQDC  -  DUTY CYCLE OF PRODUCTION SEQUENCE (ENDS AT MACHINE 14)
C*    ASYDC  -  DUTY CYCLE OF ASSEMBLY SEQUENCE (BEGINS AT MACHINE 15)
C*    SPSCAP  -  NUMBER OF SPS PRODUCED PER YEAR
C* DECLARATIONS
      IMPLICIT REAL (I,M,N)
C* DECLARE IN/OUT LOGICAL DEVICE NUMBERS (NON-IMPLICIT)
      INTEGER OUT
C* DECLARE GENERAL INPUT VARIABLES (NON-IMPLICIT)
      INTEGER ENDPSQ, NOMACH,NCT(20),NCTI
      DIMENSION NOCLOS(20)
C* DIMENSION MACHINE AND COMPONENT NAME ARRAYS
      INTEGER NAMEM(20,10),NAMEC(20,15,6)
C* DECLARE COMPONENT PARAMETERS
      INTEGER RRCODE(20,15)
      DIMENSION NOCOMP(20,15),NOFAIL(20,15),NCSTRP(20,15),RD(20,15),
     +          COST(20,15),POWER(20,15),MASS(20,15),VOLUME(20,15),
     +               SHTDWN(20,15),TYPE(20,15),MAINT(20,15),EXPEND(20,15),
     +               EXPCST(20,15),HUTIME(20,15),TCTIME(20,15),PCR(20,15),
     +               CRS(20,15),RECTIM(20,15)
C* DIMENSION REPAIR AUTOMATION AND CLEANING MACHINE PARAMETERS
      DIMENSION AUTRD(20,15),AUTCST(20,15),AUTMAS(20,15),AUTPOW(20,15),
     +               AUTVOL(20,15),AUTEXP(20,15),AUTEXC(20,15),CLNRD(20,15),
     +               CLNCST(20,15),CLNMAS(20,15),CLNPOW(20,15),
     +               CLNVOL(20,15),CLNEXP(20,15),CLNEXC(20,15)
C* DIMENSION ARRAYS IN COMMON AREA
      DIMENSION EARTH(20,15),TESERV(20,15),CRSERV(20)
      DIMENSION NOAUTO(20,15),NOCLN(20,15),NOTELE(20,15),NOCRAW(20),
     +               NOHUM1(20,15),NOHUM2(20,15),TCFIDP(20,15),
     +               TUF(20,15),CUF(20)
C* DIMENSION DUTY CYCLE ARRAYS
      DIMENSION MACHDC(20),STATDC(20,15),NOSPAR(20,15)
C* GIVE COMMON AREA
      COMMON NOCOMP,TYPE,MAINT,RRCODE,NOFAIL,TCTIME,NCSTRP,NOMACH,
     +          NCT,DELIV,ETT,TRANT,TRANC,DELAY,SOBF,ANSTRP,UP,UPT,LP,
     +          EARTH,TESERV,CRSERV,TUF,CUF,
```

```
     +        COST,MASS,VOLUME,HLTIME,PCR,CRS,RECTIM,TPER,TCARGO,AH,
     +        NOSTBE,RRPC,NRRPC,RRPT,NRRPT,VOLRH,NOTELE,NOCRAW,NOHUM1,
     +        NOHUM2,NOAUTO,NOCLN,NOTELE,NOCRAW,NCHUM1,NCHUM2,TCFIDP
C* PROVIDE IN/OUT LOGICAL DEVICE NUMBERS
      DATA IN,OUT/5,6/
C* READ GENERAL INPUT VARIABLES
      ENCPED=14
      NOMACH=18
C*********************
C*  MODIFICATION 1:
C*    INSERTION OF ADDITIONAL REPAIR PARAMETERS
C*      DCAUTO  -  DUTY CYCLE OF AUTOMATIC REPAIR MACHINERY  (FRACTION)
C*      IREPSW  -  FLAG TO CHANGE ALL CRAWLER REPAIR TO HUMAN REPAIR
C*      IAUTOS  -  FLAG TO CHANGE R&D AND PROCUREMENT OF AUTOMATIC
C*                 REPAIR MACHINERY TO DEFAULT VALUES
C*  25 AUG 79
      READ(IN,9000)DCAUTO,IREPSW,IAUTO
9000  FORMAT(F8.3,I1,7X,I1)
C**********************
      READ(IN,5) (NCT(I),I=1,20),(NOCLUS(I),I=1,20)
5     FORMAT(20I4/20F4.1)
      READ(IN,10) DELIV,ETT,TRANT,TRANC,DELAY,TPER,TCARGO,SOBR,
     +           ANSTEP,UF,UFT,LF,AH,HABRD,HABKGF,HABDKG,HABKWP,
     +           SPACKW,SPAGW,WAGE,TRAIN,CONSUM,CONCST,ASTMAS,ROTYR,
     +           DAYSUP,SUPRCD,SCR,SESTAP,FLCT,LIFE,CR,STCEKG,STCKGV,
     +           STCVS,STCKWS,STCEXP,STCEXC,VOLRM,WHDKG,WHKGV,WHRD,
     +           WHKWV,WHEXP,WHEXC,CCSMAS,CCHMAS,CCRE,CCHCST,CCSPOW,
     +           CCHPOW,CCEXP,CCEXC,CCSTAP,RSSKGP,RSHKGP,RSHDKG,RSSKWP,
     +           RSHKWP,RSRD,RSEXP,RSEXC,RSRE,RSEST,RSKGST,RSKWST,RSEXP,
     +           RSEXC,CRWRD,CRWCST,CRWMAS,CRWPOW,CRWEXP,CRWEXC,TELRD,
     +           TELCST,TELMAS,TELPOW,TELEXP,TELEXC,PARCRW,BOXES,OUTPUT
10    FORMAT(16(5F16.5/),3F20.5)
C* READ MACHINE NAMES
      DO 12 I=1,NOMACH
12    READ(IN,15)(NAMEM(I,K),K=1,10)
15    FORMAT(10A4)
C* READ COMPONENT NAMES
      DO 23 I=1,NOMACH
           NCTI=NCT(I)
           DO 22 J=1,NCTI
                READ(IN,20) (NAMEC(I,J,K),K=1,6)
20              FORMAT(6A4)
22         CONTINUE
23    CONTINUE
C* DECLARE COMPONENT PARAMETERS
C* READ COMPONENT PARAMETERS
      DO 28 I=1,NOMACH
           NCTI=NCT(I)
           DO 27 J=1,NCTI
                READ(IN,25)RE(I,J),COST(I,J),POWER(I,J),MASS(I,J),
     +                    VOLUME(I,J),NOCOMP(I,J),SHTDWN(I,J),
     +                    TYPE(I,J),MAINT(I,J),EXPEND(I,J),
     +                    EXPCST(I,J),RRCODE(I,J),NOFAIL(I,J),
```

```
     +                         NUTIME(I,J),TCTIME(I,J),FCR(I,J),
     +                         CRS(I,J),RECTIM(I,J),NCSTRP(I,J)
25              FORMAT(2(5F16.5/),F16.5,I2,3F16.5/4F16.5)
C********************
C*  MOD 1
      IF (IREPSW.NE.1) GO TO 27
      IF (RRCODE(I,J).EQ.21) RRCODE(I,J)=22
C********************
27          CONTINUE
28      CONTINUE
C* READ REPAIR AUTOMATON PARAMETERS
      DO 38 I=1,NOMACH
          NCTI=NCT(I)
          DO 37 J=1,NCTI
              IF(RRCODE(I,J) .NE. 21) GO TO 37
              READ(IN,35) AUTRD(I,J),AUTCST(I,J),AUTMAS(I,J),
     +                AUTPOW(I,J),AUTVOL(I,J),AUTEXP(I,J),AUTEXC(I,J)
35              FORMAT(5F16.5/2F16.5)
C ********************
C*  MOD 1
      IF (IAUTOS.NE.1) GO TO 37
      AUTRD(I,J)=AUTMAS(I,J)*20000.
      AUTCST(I,J)=AUTMAS(I,J)*1000.
C********************
37          CONTINUE
38      CONTINUE
C* READ CLEANING MACHINE PARAMETERS
      DO 43 I=1,NOMACH
          NCTI=NCT(I)
          DO 42 J=1,NCTI
              IF(RECTIM(I,J) .LT. .0001) GO TO 42
              READ(IN,40) CLNRD(I,J),CLNCST(I,J),CLNMAS(I,J),
     +                CLNPOW(I,J),CLNVOL(I,J),CLNEXP(I,J),CLNEXC(I,J)
40              FORMAT(5F16.5/2F16.5)
42          CONTINUE
43      CONTINUE
C* INITIALIZE NUMBER OF STRIPS SERVED BY CRAWLER AND TELEOPERATOR
C* AND THEIR UTILIZATION FACTORS
      DO 47 I=1,NOMACH
          NCTI=NCT(I)
          CRSERV(I)=0.
          CUF(I)=0.
          DO 46 J=1,NCTI
              TESERV(I,J)=0.
              TUF(I,J)=0.
46          CONTINUE
47      CONTINUE
C* CALL FEMERG TO CALCULATE THE FRACTION OF REPLACEMENTS
C*      COMING ON AN EMERGENCY BASIS FROM EARTH
      CALL FEMERG
C* CALL DCSCF TO FIND STATDC,MACHDC,SCFDC
      CALL DCSCF(NOMACH,ENDPRD,NCT,NOCOMP,SHTDWN,NOCLUS,RRCODE,NOFAIL,
     +          MACHDC,STATDC,PRODC,ASYDC)
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      SCFDC=PBCDC
C* CALL SIZSCF TO FIND THE NO. OF STRIPS NEEDED TO GET SPECIFIED OUTPUT
      CALL SIZSCF(SCFDC,CUTPUT,NOSTRP,SPSCAP)
C* CALL SUBROUTINE WAREHOUSE, REPLACEMENT PARTS, SUPPORT EQUIPMENT
C*    (WHEPSE) TO COMPUTE VARIABLES FROM ERPC CN IN COMMON AREA SUBCST
      CALL WHRPSE(VCIEN,SCFDC,DCAUTO)
C* CALCULATE COMPONENT INTERMEDIATE DATA AND PRINT IT
      DO 58 I=1,NOMACH
            NCTI=NCT(I)
            DO 57 J=1,NCTI
                  IF(NCFAIL(I,J) .LT. .0001) GO TO 56
                  IF(RRCODE(I,J) .EQ. 3) GO TO 53
                  NOSPAR(I,J)=TCFIDP(I,J)*SOBR
                  GO TO 57
   53             IF(RECTIN(I,J) .LT. .0001) GO TO 55
                  NOSPAR(I,J)=(TCFIDP(I,J)*RECTIN(I,J)/
     *                  (365.0*24.0*DELIV))*SOBR
                  GO TO 57
   55             NOSPAR(I,J)=TCFIDP(I,J)
                  GO TO 57
   56             NOSPAR(I,J)=0.
   57       CONTINUE
58    CONTINUE
      WRITE(OUT,70)
   70 FORMAT(11X,'TABLE OF STATION DUTY CYCLE(STATDC), FRACTION OF ',
     &           'REPLACEMENTS OBTAINED BY AN EMERGENCY BASIS(EARTH),'/
     &      11X,'COMPONENT AVERAGE FAILURE REPLACEMENTS IN WAREHOUSE ',
     &           'AT BEGINNING OF DELIVERY PERIOD(NOSPAR), NUMBER OF'/
     &      11X,'CRAWLERS(NOCRAW), CRAWLER UTILIZATION FACTOR(CUF), ',
     &           'NUMBER OF TELEOPERATORS(NOTELE), TELEOPERATOR'/
     &      11X,'UTILIZATION FACTOR(TUF), NUMBER OF REPAIR AUTOMATONS',
     &           '(NCAUTO), NUMBER OF CLEANING MACHINES(NOCLN),'/
     &      11X,'NUMBER OF HUMANS FOR TELEOPERATOR SUPERVISORY CONTROL'
     &           ,'(NCHUM1), AND NUMBER OF HUMANS FOR REPAIR WORK'/
     &      11X,'(NCHUM2), FOR INDIVIDUAL COMPONENTS OF A MACHINE ',
     &           '<TOTALED OVER ALL THE STRIPS> ---------------'////)
      WRITE(CUT,75)
   75 FORMAT(31X,'STATDC',4X,'EARTH',6X,'NOSPAR',4X,'NOCRAW',4X,'CUF',
     &      4X,'NOTELE',4X,'TUF',4X,'NCAUTO',4X,'NOCLN',4X,'NCHUM1',
     &      4X,'NCHUM2'//)
      DO 88 I=1,NOMACH
            WRITE(OUT,80) (NAMEM(I,K),K=1,10),MACHDC(I)
   80       FORMAT(//1X,10A4,15X,'MACHINE DUTY CYCLE [MACHDC] =',F7.5/)
            NCTI=NCT(I)
            DO 87 J=1,NCTI
                  WRITE(OUT,85) (NAMEC(I,J,K),K=1,6),
     &                  STATDC(I,J),EARTH(I,J),NOSPAR(I,J),NOCRAW(I),
     &                  CUF(I),NOTELE(I,J),TUF(I,J),NOAUTO(I,J),NOCLN(I,J),
     &                  NOHUM1(I,J),NCHUM2(I,J)
   85             FORMAT(5X,6A4,1X,F7.5,3X,F6.4,3X,F9.1,4X,F4.0,4X,F5.3,
     &                  4X,F5.3,4X,F5.3,2X,F4.0,6X,F3.0,6X,F6.4,6X,F6.4)
   87       CONTINUE
   88 CONTINUE
```

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C* CALCULATE AND PRINT NON-RECURRING DIRECT COSTS
      MACHIN=0.
      RANDD=0.
      MACMAS=0.
      MACPOW=0.
      DO 93 I=1,NOMACH
         NCTI=NCT(I)
         DO 92 J=1,NCTI
            MACHIN=MACHIN+NOCOMP(I,J)/TYPE(I,J)*COST(I,J)*NOSTRP
            RANDD=RANDD+RD(I,J)
            MACMAS=MACMAS+NOCOMP(I,J)/TYPE(I,J)*MASS(I,J)*NOSTRP
            MACPOW=MACPOW+NOCOMP(I,J)/TYPE(I,J)*POWER(I,J)*NOSTRP
92       CONTINUE
93    CONTINUE
      MACHIN=MACHIN+NPRPC
      MACTRN=MACMAS*ICARGO+NRSPT
      MACPOW=MACPOW*SCFDC*(1.0+PLCT)
      SPA=MACPOW*SPADKW
      NRECD=MACHIN+RANDD+MACTRN+SPA
      WRITE(OUT,95) NRECD,MACHIN,RANDD,MACTRN,SPA
95    FORMAT('1',21X,'SOLAR CELL FACTORY COST BREAKDOWN--------',///
     + 1X,'TOTAL NONRECURRING DIRECT COST IS  $',F13.0/
     + 6X,'MACHINES:    $',F12.0/
     + 6X,'MACHINE RESEARCH AND DEVELOPMENT:     $',F12.0/
     + 6X,'MACHINE TRANSPORTATION:     $',F12.0/
     + 6X,'SOLAR POWER ARRAY (FOR PRODUCTION):     $',F12.0)
C* CALCULATE AND PRINT NON-RECURRING INDIRECT COSTS
      VOLAR=0.
      POWAR=0.
      MASAR=0.
      EXPAR=0.
      EXCAR=0.
      DO 98 I=1,NOMACH
         NCTI=NCT(I)
         DO 97 J=1,NCTI
           VOLAR=VOLAR+NOAUTO(I,J)*AUTVOL(I,J)+NOCLN(I,J)*CLNVOL(I,J)
           POWAR=POWAR+NOAUTO(I,J)*AUTPOW(I,J)+NOCLN(I,J)*CLNPOW(I,J)
           MASAR=MASAR+NOAUTO(I,J)*AUTMAS(I,J)+NOCLN(I,J)*CLNMAS(I,J)
           EXPAR=EXPAR+NOAUTO(I,J)*AUTEXP(I,J)+NOCLN(I,J)*CLNEXP(I,J)
           EXPCAR=EXPCAR+NOAUTO(I,J)*AUTEXP(I,J)*AUTEXC(I,J)+
     +        NOCLN(I,J)*CLNEXP(I,J)*CLNEXC(I,J)
97       CONTINUE
98    CONTINUE
      SSCFC=NCSTRP/14.0*STCVS*STCKGV*STCDKG
      SACC=VOLAR*VCLRM*STCKGV*STCDKG
      SCFSTC=SSCFC+SACC
      WR=VOLWH*WHKGV*WHDKG+WHRD
      CC=CCSMAS*HABDKG+CCHCST+CCRD
      PW=NUMOMZ*(RSSKGP*HABDKG+RSHKGP*RSHDKG)+RSRD
      MS=NOSTRP*MSLST+MSRD
      BOXCST=BOXES*NOSTRP/14.0
      CRAWLR=(NUCRAW+PAKCRW)*CRWCST+CRWRD
      TELEOP=NUTELE*TELCST+TELRD
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      REPAUT=0.
      CLNMAC=0.
      DO 103 I=1,NCMACH
           NCTI=NCT(I)
           DO 102 J=1,NCTI
                IF(NCAUTO(I,J) .LT. .0001) AUTRD(I,J)=0.
                IF(NCCLN(I,J) .LT. .0001) CLNRD(I,J)=0.
                REPAUT=REPAUT+NCAUTO(I,J)*AUTCST(I,J)+AUTRD(I,J)
                CLNMAC=CLNMAC+NCCLN(I,J)*CLNCST(I,J)+CLNRD(I,J)
102        CONTINUE
103   CONTINUE
      SCFCRW=((NUHUM1+CCSTAF)+(NUHUM2+SESTAF))*SCR*3.0
      HABMAS=HABKGP*SCFCRW
      HAB=HAERD+HABMAS*HABCKG
      NPSCFP=(NOSTRP/14.0*STCKWS)+(VOLWH*WHKWV)+(CCSPOW+CCHPOW)
     +     +NUHUM2*(RSSKWP+ESHKWP)+(NOSTRP*MSKWST)+(NUCRAW+PAKCRW)*CRWPOW
     +     +(NUTELE*TELPOW)+PCWAB
      HABPOW=HABKWP*SCFCRW
      NPSPA=(NPSCFP+HABPCW)*SPADKW
      NPSCFM=(SSCFC/STCDKG+SACC/STCDKG)+(VOLWH*WHKGV)+(CCSMAS+CCHMAS)+
     +      NUHUM2*(RSSKGP+RSHKGP)+(NOSTRP*MSKGST)+
     +      (NUCRAW+PAKCRW)*CRWMAS+(NUTELE*TELMAS)+(MASAR)
      NPSCFT=NPSCFM*TCARGO
      HABT=HABMAS*TCARGO
      POWTOT=MACPOW+NPSCFP+HABPOW
      SPAMAS=PCWTCT*SPAGW
      SPAT=SPAMAS*TCARGO
      TOTMAS=MACMAS+NPSCFM+HABMAS+SPAMAS
      PSETUP=TOTMAS/(DAYSUP*24.0*SUPPOD)*3.0
      SETUP=PSETUP*((WAGE*DAYSUP*24.0)+(TRAIN*RCTYR)+(CONSUM*DAYSUP
     6      *24.0*CCNCST)+(CONSUM*DAYSUP*24.0*TCARGO)+(ROTYR*DAYSUP
     6      /365.0*ASTMAS*TPER))
      NPSCF=SCFSTC+WH+CC+RW+MS+BOXCST+CRAWLR+TELEOP+REPAUT+CLNMAC
      NRECIN=NPSCF+HAB+NPSPA+NPSCFT+HABT+SPAT+SETUP
      WRITE(OUT,105)NRECIN,NPSCF,SCFSTC,WH,CC,RW,MS,BOXCST,CRAWLR,
     6      TELEOP,REPAUT,CLNMAC,HAB,NPSPA,NPSCFT,HABT,SPAT,SETUP
105   FORMAT(//1X,'TOTAL NONRECURRING INDIRECT COST IS   $',F12.0/
     + 6X,'NONPRODUCTION SCF EQUIPMENT PROCUREMENT/R&D COST:   $',F12.0/
     + 11X,'SCF STRUCTURE:    $',F12.0/
     + 11X,'WAREHOUSE:    $',F12.0/
     + 11X,'CONTROL CENTER:    $',F12.0/
     + 11X,'REPAIR WORKSHOP:    $',F12.0/
     + 11X,'MICROPROCESSORS/SENSORS:    $',F12.0/
     + 11X,'ARRAY SEGMENT STORAGE BOXES:    $',F12.0/
     + 11X,'CRAWLERS:    $',F12.0/
     + 11X,'TELEOPERATORS:    $',F12.0/
     + 11X,'REPAIR AUTOMATONS:    $',F12.0/
     + 11X,'CLEANING MACHINES:    $',F12.0/
     + 6X,'HABITAT PROCUREMENT COST:    $',F12.0/
     + 6X,'NONPRODUCTION SOLAR POWER ARRAY PROCUREMENT:    $',F12.0/
     + 6X,'NONPRODUCTION SCF TRANSPORTATION:    $',F12.0/
     + 6X,'HABITAT TRANSPORTATION:    $',F12.0/
     + 6X,'SOLAR POWER ARRAY TRANSPORTATION:    $',F12.0/
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     + 6X,'COST TO SET UP SCF:     $',F12.0)
C* CALCULATE AND PRINT ANNUAL RECURRING DIRECT COSTS
      HUMSC=(NUHUM1+CCSTAF)*3.0
      HUMSCL=HUMSC*WAGE*365.0*24.0
      HUMR=(NUHUM2+SESTAF)*3.0
      HUMRL=HUMR*WAGE*365.0*24.0
      SCRW=(SCF-1.0)*(HUMSC+HUMR)
      SCRWL=SCRW*WAGE*365.0*24.0
      MACRPC=RRPC/DELIV
      MACRPT=RRPT/DELIV
      MACEXP=0.
      MACEXT=0.
      DO 108 I=1,NCMACH
           NCTI=NCT(I)
           DO 107 J=1,NCTI
                MACEXP=MACEXP+NOSTRP*(NOCOMP(I,J)/TYPE(I,J)*
     &             EXPEND(I,J)*EXPCST(I,J)*SCFDC*365.0*24.0)
                MACEXT=MACEXT+NOSTRP*(NOCOMP(I,J)/TYPE(I,J)*
     &             EXPEND(I,J)*SCFDC*365.0*24.0*TCARGO)
107        CONTINUE
108   CONTINUE
      RECD=HUMSCL+HUMRL+SCRWL+MACRPC+MACRPT+MACEXP+MACEXT
      WRITE(OUT,110)RECD,HUMSCL,HUMRL,SCRWL,MACRPC,MACRPT,MACEXP,MACEXT
110   FORMAT(//1X,'TOTAL ANNUAL RECURRING DIRECT COST IS   $',F12.0/
     &6X,'HUMAN SUPERVISORY CONTROL LABOR:    $',F12.0/
     &6X,'HUMAN REPAIR LABOR:    $',F12.0/
     &6X,'SUPPORT CREW LABOR:    $',F12.0/
     &6X,'MACHINE REPLACEMENT PARTS:    $',F12.0/
     &6X,'MACHINE REPLACEMENT PARTS TRANSPORTATION:    $',F12.0/
     &6X,'MACHINE EXPENDABLES:    $',F12.0/
     &6X,'MACHINE EXPENDABLES TRANSPORTATION:    $',F12.0)
C* CALCULATE AND PRINT ANNUAL RECURRING INDIRECT COSTS
      CONS=SCFCRW*CONSUM*365.0*24.0*CONCST
      CONTN=SCFCRW*CONSUM*365.0*24.0*TCARGO
      CREWTG=SCFCRW*TRAIN
      CREWTN=SCFCRW*ASTMAS*RCTYS*TPER
      NPSEXP=365.0*24.0*((NOSTRP/14.0*STCEXP*STCEXC)+(VOLWH*WHEXP*WHEXC)
     + +(CCEXP*CCEXC)+(NUHUM2*RSEXP*RSEXC)+(NOSTRP*MSEXP*MSEXC)+
     + (NUCRAW+PAKCRW)*CRWEXP*CRWEXC+(NUTELE*TELEXP*TELEXC)+EXPCAR)
      NPSEXT=TCARGO*365.0*24.0*((NOSTRP/14.0*STCEXP)+(VOLWH*WHEXP)
     +      +(CCEXP)+(NUHUM2*RSEXP)+(NOSTRP*MSEXP)+(NUCRAW+PAKCRW)*CRWEXP
     +      +(NUTELE*TELEXP)+(EXMAR))
      RECIN=CONS+CONTN+CREWTG+CREWTN+NPSEXP+NPSEXT
      WRITE(OUT,115)RECIN,CONS,CONTN,CREWTG,CREWTN,NPSEXP,NPSEXT
115   FORMAT(//1X,'TOTAL ANNUAL RECURRING INDIRECT COST IS  $',F12.0/
     &6X,'CONSUMMABLES:    $',F12.0/
     &6X,'CONSUMMABLES TRANSPORTATION:    $',F12.0/
     &6X,'CREW TRAINING:    $',F12.0/
     &6X,'CREW TRANSPORTATION:    $',F12.0/
     &6X,'NONPRODUCTION SCF EXPENDABLES:    $',F12.0/
     &6X,'NONPRODUCTION SCF EXPENDABLES TRANSPORTATION:    $',F12.0)
C* CALCULATE DISCOUNTED LIFECYCLE COST,YEARLY REFURBISHMENT PARTS MASS
C* (REPLACEMENTS + EXPENDABLES), AND PRINT OTHER RELEVANT PARAMETERS
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      NRBPM=NRBPT/TCARGO
      LIFCST=(NRECD+NRECIN)+(RECD+RECIN)*(1.0-(1.0+DR)**(-LIFE))/DR
     +       -NRBPC*(1.0+DR)**(-LIFE)
      SPSCST=LIFCST/(SPSCAP*LIFE)
      REFURB=0.
      DO 123 I=1,NCMACH
          NCTI=NCT(I)
      WRITE(6,5001) (NAMEM(I,K),K=1,10)
 5001 FORMAT(///1X,10A4/)
          DO 122 J=1,NCTI
                REFURB=REFURB+TCFIDP(I,J)*PCR(I,J)*MASS(I,J)/DELIV
      REPLAC=TCFIDP(I,J)*PCR(I,J)*MASS(I,J)/DELIV
      WRITE(6,2001) (NAMEC(I,J,K),K=1,6),REPLAC
 2001 FORMAT(5X,6A4,5X,F10.0)
122       CONTINUE
123   CONTINUE
      REFURB=REFURB+(MACEXP+NPSEXP)/TCARGO
      WRITE(OUT,125) LIFCST,SPSCST,SPSCAP,SCFDC,ASYDC,NCSTRP,PSETUP,
     +   SETUP,REFURB,TOTMAS,MACMAS,NPSCFM,HABMAS,SPAMAS,POWTOT,MACPOW,
     +   NPSCFP
      WRITE(OUT,130) HABPOW,VOLWH,NRBPM,NRBPC,NUTELE,NUCRAW,SCFCRW,HUMSC,
     +       HUMR,SCRW
125   FORMAT('1',21X,'SOLAR CELL FACTORY MAJOR COST DRIVING FACTORS'///
     + 1X,'LIFECYCLE COST:  $',F12.0/
     + 1X,'COST OF SCF/SMF PER SPS PRODUCED:  $',F12.0/
     + 1X,'NUMBER OF SPS PRODUCED PER YEAR:  ',F4.2//
     + 1X,'SCF DUTY CYCLE:  ',F5.4/
     + 1X,'ASSEMBLY OPERATION DUTY CYCLE:  ',F5.4/
     + 1X,'NUMBER OF PRODUCTION STRIPS  ',F4.0//
     + 1X,'PEOPLE TO SET UP SCF/SMF:  ',F4.0/
     + 1X,'COST TO SET UP SCF/SMF:  $',F9.0//
     + 1X,'YEARLY REFURBISHMENT PARTS (REPLACEMENTS+EXPENDABLES,KG): ',
     + F10.0/
     + 1X,'TOTAL SCF/SMF MASS(KG):  ', F10.0/
     + 6X,'PRODUCTION MACHINERY MASS(KG):  ',F10.0/
     + 6X,'NON PRODUCTION EQUIPMENT MASS(KG):  ',F10.0/
     + 6X,'HABITAT MASS(KG): ',F10.0/
     + 6X,'SOLAR POWER ARRAY MASS(KG):  ', F10.0//
     + 1X,'TOTAL SCF/SMF POWER(KW): ',F10.0/
     + 6X,'PRODUCTION MACHINERY POWER(KW):  ',F10.0/
     + 6X,'NON PRODUCTION EQUIPMENT POWER(KW) ',F10.0)
130   FORMAT(6X,'HABITAT POWER(KW): ',F10.0//
     + 1X,'SCF WAREHOUSE VOLUME (CM): ',F7.0/
     + 1X,'MASS OF BUFFER REPLACEMENT PARTS IN WAREHOUSE(KG ): ',F7.0/
     + 1X,'COST OF BUFFER REPLACEMENT PARTS IN WAREHOUSE  $',F12.0//
     + 1X,'NUMBER OF TELEOPERATORS:  ',F4.0/
     + 1X,'NUMBER OF CRAWLERS:',F4.0/
     + 1X,'TOTAL SCF/SMF CREW:  ',F5.0/
     + 6X,'SUPERVISORY CONTROL CREW:', F5.0/
     + 6X,'REPAIR CREW: ', F5.0/
     + 6X,'SUPPORT CREW: ',F5.0)
      STOP
      END
```

```
C
C
C
C
C
      SUBROUTINE FIEERG
      IMPLICIT REAL (L,M,N)
      INTEGER NCTI,NCMACH,RRCODE(20,15),NCT(20),CNHNDL
      DIMENSION NOCCMP(20,15),TYPE(20,15),MAINT(20,15),NOFAIL(20,15),
     +     TCTIME(20,15),NCSTRP(20,15),EARTH(20,15),TESERV(20,15),
     +     CRSERV(20),COST(20,15),MASS(20,15),VOLUME(20,15),
     +     HUTIME(20,15),FCR(20,15),CRS(20,15),RECTIM(20,15),
     +     NOAUTO(20,15),NOCLN(20,15),NOTELE(20,15),NOCRAW(20),
     +     NOHUM1(20,15),NOHUM2(20,15),TCFIDP(20,15),TUP(20,15),CUP(20)
      COMMON NOCCMP,TYPE,MAINT,RRCODE,NOFAIL,TCTIME,NCSTRP,NCMACH,
     +        NCT,DELIV,ETT,TRANT,TRANC,DELAY,SCBR,ANSTRF,UP,UPT,LF,
     +        EARTH,TESERV,CRSERV,TUP,CUP,
     +        COST,MASS,VOLUME,HUTIME,FCR,CRS,RECTIM,TPER,TCARGO,AM,
     +        NCSTRF,RRPC,NRRPC,RRPT,NRRPT,VOLWH,NUTELE,NOCRAW,NOHUM1,
     +        NOHUM2,NOAUTO,NOCLN,NCTELE,NOCRAW,NCHUM1,NOHUM2,TCFIDP
      AVFAIL=20.
      CNHNDL=SCBR*AVFAIL
      NFEF=0.
      IDUMMY=INT(CNHNDL+1.0)
      DO 2 K=1,IDUMMY
           K=K-1
           Z=FLOAT(K)
           NFEF=NFEF+POISSN(Z,AVFAIL)*(1.0)
           K=K+1
    2 CONTINUE
      DO 3 K=IDUMMY,33
           Z=FLOAT(K)
           NFEF=NFEF+POISSN(Z,AVFAIL)*(CNHNDL/Z)
    3 CONTINUE
      DO 7 I=1,NCMACH
           NCTI=NCT(I)
           DO 6 J=1,NCTI
                IF((RRCODE(I,J).EQ.3).OR.(NOFAIL(I,J).LT..0001))
     +               GO TO 4
                EARTH(I,J)=1.0-NFEF
                GO TO 6
    4           EARTH(I,J)=0.
    6      CONTINUE
    7 CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE DCSCF(NOMACH,ENDPRD,NCT,NOCOMP,SHTDWN,NOCLUS,ERCODE,
     +                 NOFAIL,MACHDC,STATDC,PRODC,ASYDC)
      IMPLICIT REAL (L,M,N)
      INTEGER ENDPRD,NOMACH,NCT(20),ERCODE(20,15)
      DIMENSION MACHDC(20),STATDC(20,15),NOCOMP(20,15),SHTDWN(20,15),
     +     NOCLUS(20),NOFAIL(20,15)
      PRODC=1.0
      DO 8 I=1,ENDPRD
           CALL DCMACH(I,MACHDC(I),STATDC,NCT,NOCOMP,SHTDWN,NOCLUS,
     +          ERCODE,NOFAIL)
           PRODC=PRODC*MACHDC(I)
    8 CONTINUE
      ASYDC=MACHDC(ENDPRD)
      IDUMMY=ENDPRD+1
      DO 11 I=IDUMMY,NOMACH
           CALL DCMACH(I,MACHDC(I),STATDC,NCT,NOCOMP,SHTDWN,NOCLUS,
     +          ERCODE,NOFAIL)
           ASYDC=ASYDC*MACHDC(I)
   11 CONTINUE
      RETURN
      END
```

```
C
      SUBROUTINE DCMACH(I,MACHDC,STATDC,NCT,NOCOMP,SHTDWN,NOCLUS,
     +     ERCODE,NOFAIL)
      IMPLICIT REAL (L,M,N)
      INTEGER NCTI,NCT(20),NINC,SHUT,ERCODE(20,15)
      DIMENSION NOFAIL(20,15),STATDC(20,15),NOCOMP(20,15),NOCLUS(20),
     +     SHTDWN(20,15)
      MACHDC=1.0
      NCTI=NCT(I)
      DO 8 J=1,NCTI
           IF(NOFAIL(I,J) .LT. .0001) GO TO 7
           CALL DCSTAT(I,J,STATDC(I,J),ERCODE(I,J),NOFAIL(I,J))
           IF(INT(STATDC(I,J)) .EQ. 1) GO TO 8
           IF(INT(NOCOMP(I,J)) .EQ. 1) GO TO 6
           IF(ABS(NOCOMP(I,J)/NOCLUS(I)-SHTDWN(I,J)) .LT. .001) GO TO 4
           CLUSDC=0.
           SHUT=INT(SHTDWN(I,J))
           NINC=INT(NOCOMP(I,J)/NOCLUS(I))
           DO 2 K=SHUT, NINC
                CLUSDC=CLUSDC+BINDIS(K,NINC,STATDC(I,J))
    2      CONTINUE
           GO TO 5
    4      CLUSDC=STATDC(I,J)**(NOCOMP(I,J)/NOCLUS(I))
    5      MACHDC=MACHDC*CLUSDC**(NOCLUS(I))
           GO TO 8
    6      MACHDC=MACHDC*STATDC(I,J)
           GO TO 8
    7      STATDC(I,J)=1.0
    8 CONTINUE
      RETURN
      END
```

```
C                                                                       SCF06830
      SUBROUTINE DCSTAT(I,J,STATDC,RRCODE,NOFAIL)                       SCF06840
      IMPLICIT REAL (L,M,N)                                             SCF06850
      INTEGER RRCODE                                                    SCF06860
      IF(RRCODE .EQ. 3) GO TO 3                                         SCF06870
      IF((RRCODE .EQ. 21) .OR. (RRCODE .EQ. 22)) GO TO 5                SCF06880
      CALL RRC1(I,J,ROLTIM)                                             SCF06890
      STATDC=1.0-NOFAIL*ROLTIM/(365.0*24.0)                             SCF06900
      RETURN                                                            SCF06910
    3 STATDC=1.0                                                        SCF06920
      RETURN                                                            SCF06930
    5 CALL RRC2(I,J,RANTIM)                                             SCF06940
      STATDC=1.0-NOFAIL*RANTIM/(365.0*24.0)                             SCF06950
      RETURN                                                            SCF06960
      END                                                               SCF06970
```

```
C                                                                       SCF06980
      SUBROUTINE RRC1(I,J,RCLTIM)                                       SCF06990
      IMPLICIT REAL (L,M,N)                                             SCF07000
      INTEGER RRCODE(20,15),NCT(20),NOMACH                              SCF07010
      DIMENSION NOCOMP(20,15),TYPE(20,15),MAINT(20,15),NOFAIL(20,15),   SCF07020
     +    TCTIME(20,15),NCSTRP(20,15),EARTH(20,15),TESERV(20,15),       SCF07030
     +     CRSERV(20),COST(20,15),MASS(20,15),VOLUME(20,15),            SCF07040
     +     HUTIME(20,15),FCR(20,15),CRS(20,15),RECTIM(20,15),           SCF07050
     +     NOAUTO(20,15),NOCLN(20,15),NOTELE(20,15),NOCRAW(20),         SCF07060
     +     NOHUM1(20,15),NOHUM2(20,15),TCFIDP(20,15),TUF(20,15),CUF(20) SCF07070
      COMMON NOCOMP,TYPE,MAINT,RRCODE,NOFAIL,TCTIME,NCSTRP,NOMACH,      SCF07080
     +        NCT,DELIV,ETT,TRANT,TRANC,DELAY,SCDR,ANSTRP,UF,UFT,LF,    SCF07090
     +        EARTH,TESERV,CRSERV,TUF,CUF,                              SCF07100
     +        COST,MASS,VOLUME,HUTIME,FCR,CRS,RECTIM,TPER,TCARGO,AH,    SCF07110
     +        NOSTRP,NRPC,NRRPC,RRPT,NRRPT,VOLWH,NUTELE,NUCRAW,NUHUM1,  SCF07120
     +        NUHUM2,NOAUTO,NOCLN,NOTELE,NOCRAW,NOHUM1,NOHUM2,TCFIDP    SCF07130
      TIME14=NOFAIL(I,J)*(NOCOMP(I,J)/TYPE(I,J))*14.0*                  SCF07140
     +      (TCTIME(I,J)+TRANT)                                         SCF07150
      TELE14=TIME14/(365.0*24.0*UF)                                     SCF07160
      TESERV(I,J)=RNDOFF(14.0/TELE14,.5)                                SCF07170
      IF(TESERV(I,J) .GT. ANSTRP) TESERV(I,J)=ANSTRP                    SCF07180
      TUF(I,J)=(TESERV(I,J)/14.0)*TIME14/(365.0*24.0)                   SCF07190
      AVERT=TCTIME(I,J)+TRANT                                           SCF07200
      LAMBDA=UF/AVERT                                                   SCF07210
      RCLTIM=QUEUE(AVERT,LAMBDA)+ETT*EARTH(I,J)                         SCF07220
      RETURN                                                            SCF07230
      END                                                               SCF07240
```

```
C
      SUBROUTINE FRC2(I,J,RANTIM)
      IMPLICIT REAL (L,M,N)
      INTEGER NOMACH,RRCODE(20,15),NCT(20),NCTI
      DIMENSION NOCOMP(20,15),TYPE(20,15),MAINT(20,15),NOFAIL(20,15),
     +     TCTIME(20,15),NCSTRP(20,15),EARTH(20,15),TESERV(20,15),
     +     CRSERV(20),COST(20,15),MASS(20,15),VOLUME(20,15),
     +     HUTIME(20,15),FCR(20,15),CRS(20,15),RECTIM(20,15),
     +     NOAUTO(20,15),NOCLN(20,15),NOTELE(20,15),NOCRAW(20),
     +     NOHUM1(20,15),NOHUM2(20,15),TCPIDP(20,15),TUF(20,15),CUF(20)
      COMMON NOCOMP,TYPE,MAINT,RRCODE,NOFAIL,TCTIME,NCSTRP,NOMACH,
     +       NCT,DELIV,ETT,TRANT,TRANC,DELAY,SCBR,ANSTRP,UF,UFT,LP,
     +       EARTH,TESERV,CRSERV,TUF,CUF,
     +       COST,MASS,VOLUME,HUTIME,FCR,CRS,RECTIM,TPER,TCARGO,AH,
     +       NCSTRP,LBPC,NBFFC,RRPT,NRRPT,VOLUM,NUTELE,NUCRAW,NUHUM1,
     +       NUHUM2,NOAUTO,NOCLN,NOTELE,NOCRAW,NCHUM1,NCHUM2,TCPIDP
      TIME14= .0
      TPFAIL= .0
      PRITIM= .0
      NCTI=NCT(I)
      DO 5 K=1,NCTI
         IF(RRCODE(I,K) .EQ. 1) GO TO 3
         TIME14=TIME14+NOFAIL(I,K)*NOCOMP(I,K)/TYPE(I,K)*14.0*
     +          (TCTIME(I,K)+TRANC)+NOCOMP(I,K)/TYPE(I,K)*14.0*
     +          MAINT(I,K)
         IF(RRCODE(I,K) .EQ. 3) GO TO 5
         TPFAIL=TPFAIL+NOFAIL(I,K)*NOCOMP(I,K)/TYPE(I,K)*14.0
         GO TO 5
 3       TIME 14=TIME14+NOCOMP(I,K)/TYPE(I,K)*14.0*MAINT(I,K)
 5    CONTINUE
      CRAW14=TIME14/(365.0*24.0*UF)
      CRSERV(I)=RNDOFF(14.0/CRAW14,.5
      IF(CRSERV(I) .GT. ANSTRP) CRSERV(I)=ANSTRP
      CUF(I)=(CRSERV(I)/14.0)*TIME14/(365.0*24.0)
      AVERT=TCTIME(I,J)+TRANC
      LAMBDA=TPFAIL*(CRSERV(I)/14.0)/(365.0*24.0)
      RANTIM=QUEUE(AVERT,LAMBDA)+(CUF(I)-LAMBDA*AVERT+LP)*DELAY+
     +     ETT*EARTH(I,J)
      RETURN
      END
```

```
C
      SUBROUTINE SIZSCF(SCFDC,OUTPUT,NOSTRP,SPSCAP)
      IMPLICIT REAL (L,M,N)
      NOSTRP=FLOAT(INT(OUTPUT/(365.0*24.0*51.0*252.0/1.17*SCFDC)))
      IF(NOSTRP/14.0-FLOAT(INT(NOSTRP/14.0)) .GE. .5) GO TO 6
      NOSTRP=FLOAT(INT(NOSTRP/14.0))*14.0
      GO TO 8
 6    NOSTRP=FLOAT(INT(NOSTRP/14.0)+1)*14.0
 8    SPSCAP=(NOSTRP*SCFDC*365.0*24.0*51.0*252.0/1.17)/OUTPUT
      RETURN
      END
```

```
C
      SUBROUTINE WHFFSE(VOLBM,SCFDC,DCAUTO)
      IMPLICIT REAL (L,M,N)
      INTEGER NCTI,NCT(20),RRCODE(20,15),NOMACH
      DIMENSION COST(20,15),MASS(20,15),VOLUME(20,15),NOCOMP(20,15),
     +      TYPE(20,15),NOFAIL(20,15),HUTIME(20,15),TCTIME(20,15),
     +      FCR(20,15),CRS(20,15),RECTIM(20,15),EARTH(20,15),
     +      TESERV(20,15),CRSERV(20),NOAUTO(20,15),NOCLN(20,15),
     +      NOTELE(20,15),NOCRAW(20),NOHUM1(20,15),NOHUM2(20,15),
     +      TCFIDP(20,15),MAINT(20,15),NCSTRP(20,15),TUF(20,15),CUF(20),
     +      CODE1(20,15),CODE2A(20,15),CODE2H(20,15),CODE3(20,15)
      COMMON NOCOMP,TYPE,MAINT,RRCODE,NOFAIL,TCTIME,NCSTRP,NOMACH,
     +        NCT,DELIV,ETT,TRANT,TRANC,DELAY,SOBR,ANSTRP,UP,UPT,LP,
     +        EARTH,TESERV,CRSERV,TUF,CUF,
     +        COST,MASS,VOLUME,HUTIME,FCR,CRS,RECTIM,TPRR,TCARGO,AH,
     +        NCSTRF,RRPC,NRRPC,RRPT,NRRPT,VOLWH,NUTELE,NUCRAW,NUHUM1,
     +        NUHUM2,NCAUTO,NOCLN,NOTELE,NOCRAW,NOHUM1,NOHUM2,TCFIDP
      DO 2 I=1,NOMACH
           NCTI=NCT(I)
           DO 1 J=1,NCTI
                CODE1(I,J)=0.
                CODE2A(I,J)=0.
                CODE2H(I,J)=0.
                CODE3(I,J)=0.
                IF(RRCODE(I,J) .EQ. 1) CODE1(I,J)=1.0
                IF(RRCODE(I,J) .EQ. 21) CODE2A(I,J)=1.0
                IF(RRCODE(I,J) .EQ. 22) CODE2H(I,J)=1.0
                IF(RRCODE(I,J) .EQ. 3) CODE3(I,J)=1.0
                NOTELE(I,J)=0.
                NOCRAW(I)=0.
                NOHUM1(I,J)=0.
1          CONTINUE
2     CONTINUE
      RRPC=0.
      NRRPC=0.
      RRPT=0.
      NRRPT=0.
      VOLWH=0.
      NUHUM1=0.
      NUHUM2=0.
      NUTELE=0.
      NUCRAW=0.
      DO 15 I=1,NOMACH
           NCTI=NCT(I)
           DO 14 J=1,NCTI
                TCFIDP(I,J)=DELIV*NOFAIL(I,J)*NOCOMP(I,J)/TYPE(I,J)*
     +                       NOSTRP*SCFDC
                VOLWH=VOLWH+(CODE1(I,J)+CODE2A(I,J)+CODE2H(I,J))*
     +                SOBR*(FCR(I,J)*VOLUME(I,J)*TCFIDP(I,J))
     +                +CODE3(I,J)*((TCFIDP(I,J)*RECTIM(I,J)/
     +                (365.0*24.0*DELIV)*VOLUME(I,J)*SOBR)
     +                +(FCR(I,J)*VOLUME(I,J)*TCFIDP(I,J)))
                RRPC=RRPC+TCFIDP(I,J)*FCR(I,J)*MASS(I,J)*CRS(I,J)
```

```
            NRRPC=NRRPC+(CODE1(I,J)+CODE2A(I,J)+CODE2B(I,J))*
     +           (SOBR-1.C)*(TCFIDP(I,J)*FCB(I,J)*MASS(I,J)*
     +           CRS(I,J)) + CODE3(I,J)*(TCFIDP(I,J)*RECTIN(I,J)/
     +           (365.0*24.0*DELIV)*COST(I,J)*SCBR)
            RRPT=RRPT+(CODE1(I,J)+CODE2A(I,J)+CODE2B(I,J))*
     +           (TCFIDP(I,J)*FCB(I,J)*MASS(I,J))*(EARTH(I,J)*TPER
     +           +(1.0-EARTH(I,J))*TCARGO)
     +           +CODE3(I,J)*TCFIDP(I,J)*FCB(I,J)*MASS(I,J)*TCARGO
            NRRPT=NRRPT+(CODE1(I,J)+CODE2A(I,J)+CODE2B(I,J))*
     +           (SOBR-1.0)*(TCFIDP(I,J)*FCB(I,J)*MASS(I,J))*TCARGO
     +           +CODE3(I,J)*(TCFIDP(I,J)*RECTIN(I,J)/
     +           (365.0*24.0*DELIV)*SOBR*MASS(I,J))*TCARGO
C********************
C*  NOB 1
            NOAUTO(I,J)=CODE2A(I,J)*TCFIDP(I,J)*HUTIME(I,J)*
     +                        AH/(365.0*24.0*DELIV*DCAUTO)
C********************
            IF(RRCODE(I,J) .NE. 21) GO TO 4
            IF(NCAUTO(I,J) .LT. 1.0) GO TO 3
            NOAUTO(I,J)=RNDOFF(NOAUTO(I,J),.01)
            GO TO 4
    3       NOAUTO(I,J)=1.0
    4       NOHUB2(I,J)=CODE2B(I,J)*TCFIDP(I,J)*HUTIME(I,J)/
     +                        (365.0*24.0*DELIV)
            NUHUB2=NUHUB2+NOHUB2(I,J)
            IF(TESERV(I,J) .GT. .0001) GO TO 5
            GO TO 6
    5       IF(ABS(TESERV(I,J)-ANSTRP) .LT. .0001) GO TO 55
            NOTELE(I,J)=RNDOFF(NOSTRP/TESERV(I,J),UPT)
            GO TO 555
   55       NOTELE(I,J)=TUP(I,J)/UP
  555       NUTELE=NUTELE+NOTELE(I,J)
            IF((RRCODE(I,J).EQ.1).AND.(HUTIME(I,J).GT..0001))
     +          NOHUB1(I,J)=HUTIME(I,J)/TCTIME(I,J)*NOTELE(I,J)
            NUHUB1=NUHUB1+NOHUB1(I,J)
    6       IF((CRSERV(I) .GT. .0001) .AND. (J .EQ. 1)) GO TO 7
            GO TO 8
    7       IF(NOSTRP/CRSERV(I) .LT. UPT) GO TO 75
            NOCRAW(I)=RNDOFF(NOSTRP/CRSERV(I),UPT)
            GO TO 76
   75       NOCRAW(I)=1.0
   76       NUCRAW=NUCRAW+NOCRAW(I)
    8       NOCLN(I,J)=CODE3(I,J)*TCFIDP(I,J)*RECTIN(I,J)/
     +                        (365.0*24.0*DELIV)
            IF(NOCLN(I,J) .LT. .001) GO TO 14
            IF(NOCLN(I,J) .LT. 1.0) GO TO 10
            NOCLN(I,J)=RNDOFF(NOCLN(I,J),.01)
            GO TO 14
   10       NOCLN(I,J)=1.0
   14     CONTINUE
   15 CONTINUE
      NUHUB1=RNDOFF(NUHUB1,.01)
      NUHUB2=RNDOFF(NUHUB2,.01)
      VCLWN=VCLWN*VCLSN
      RETURN
      END
```

```
C
C
C
C
      REAL FUNCTION QUEUE(MU,LAMBDA)
      REAL MU, LAMBDA
      QUEUE=1.0/(1.0/MU-LAMBDA)
      RETURN
      END


C
      REAL FUNCTION POISSN(X,Y)
      REAL E,Y,X
      DATA E/2.71828/
      POISSN=(Y**X)*(E**(-Y))/FACT(X)
      RETURN
      END

C
      REAL FUNCTION FACT(Z)
      INTEGER I,K
      REAL Z
      FACT=1.0
      IF((Z-1.0) .LT. .0001) RETURN
      K=INT(Z)
      DO 10 I=2,K
           FACT=FACT*FLOAT(I)
   10 CONTINUE
      RETURN
      END

C
      REAL FUNCTION BINDIS(K,N,P)
      INTEGER N,K
      REAL P
      BINDIS=FACT(FLOAT(N))/(FACT(FLOAT(N-K))*FACT(FLOAT(K)))*
     +      (P**K)*((1.0-P)**(N-K))
      RETURN
      END


C
      REAL FUNCTION RNDOFF(N,MAX)
      REAL N, MAX
      IF (N-FLOAT(INT(N)).GE.MAX) GO TO 4
      RNDOFF=FLOAT(INT(N))
      RETURN
    4 RNDOFF=FLOAT(INT(N)+1)
      RETURN
      END
```

```
1.0      0       0
   4   7   8   3   3   1   3   9   3   4   7  13  13   7   7   4   7   5
  1.  1.  4.  1.  1.  1.  1.  2.  1.  1.  1.  6.  4.  1.  1.  1.  1.  1.
.5             72.            .17            .05            .02
300.           100.           1.4            280.           .7
.15            .05            .5             0.             3040.
100.           9.             2000.          10.            35.
100.           .035           10.            100.           4.
365.           300.           1.5            0.             .1
20.            .10            1100.          2.5            25000.
10.            0.             0.             2.             100.
2.5            0.             .001           0.             0.
0.             3000.          60000000.      2400000.       0.
20.            0.             0.             10.            1040.
2500.          100.           9.             2.             10000000.
.1             20.            5000000.       7500.          15.
1.             0.             0.             7000000.       150000.
2000.          25.            .001           20.            15000000.
400000.        750.           1.             0.             0.
1.                 1100.              24000000000.
THERMAL BELT
DV OF AL REAR CONTACT
DV OF SI WAFER AND P-DOPANT IMPLANTATION
PULSE RECRYSTALLIZATION
SCAN RECRYSTALLIZATION
N-DOPANT IMPLANTATION
ANNEAL
DV OF AL FRONT CONTACT
FRONT CONTACT SINTERING
CELL CROSSCUT
CELL INTERCONNECTION
DV OF SILICA OPTICAL COVER
DV OF SILICA SUBSTRATE
PANEL ALIGNMENT & SPARE PANEL INSERTION
PANEL INTERCONNECTION
LONGITUDINAL CUT
KAPTON TAPE APPLICATION
ARRAY SEGMENT FOLDING AND PACKAGING
BELT
MOTOR/DRIVE
END ROLLERS
THERMAL CONTROL
EB GUN
FILAMENT MAGAZINE
SLAB FEEDER
PANEL BAFFLE
SIDE BAFFLE
SIDE BAFFLE GUIDES
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
SLAB FEEDER
PANEL BAFFLE
SIDE BAFFLE
SIDE BAFFLE GUIDE
```

BORON ION IMPLANTER
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
COOLING SYSTEM
PHOSPHORUS ION IMPLANTER
EB GUN
FILAMENT MAGAZINE
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
SLAB FEEDER
MASK
MASK GUIDE AND ROLLUP
PANEL BAFFLE
SIDE BAFFLE
SIDE BAFFLE GUIDE
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
COOLING SYSTEM
LASER
KRYPTON LAMP MAGAZINE
GUIDE ROLLERS
SHIELD
ELECTROSTATIC WELDER
INTERCONNECT FEEDER
INTERCONNECT ROLL
SENSORS
VARIABLE SPEED ROLLERS
MOTOR
GUIDE ROLLERS
EB GUN
FILAMENT MAGAZINE
SLAB FEEDER
MASKING DEVICE
T-STRIP MASK PACKAGE
OXYGEN DISPENSER
PANEL BAFFLE
SIDE BAFFLE
SIDE BAFFLE GUIDE
SOFT SURFACE BELT
MOTOR/DRIVE
END ROLLER
COOLING SYSTEM
EB GUN
FILAMENT MAGAZINE
SLAB FEEDER
MASKING DEVICE
T-STRIP MASK PACKAGE
OXYGEN DISPENSER
PANEL BAFFLE

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SIDE BAFFLE
SIDE BAFFLE GUIDE
SOFT SURFACE BELT
MOTOR/DRIVE
END ROLLER
COOLING SYSTEM
ACCELERATOR BELT
VARIABLE SPEED ROLLERS
PANEL REMOVER
PANEL INSERTER
PANEL HOPPER
SENSORS
GUIDE ROLLERS
ELECTROSTATIC WELDER
INTERCONNECT FEEDER
INTERCONNECT ROLL
SENSORS
VARIABLE SPEED ROLLERS
MOTOR
GUIDE ROLLERS
LASER
KRYPTON LAMP MAGAZINE
GUIDE ROLLERS
SHIELD
STATIONARY TAPER
STATIONARY TAPE REFILL
CROSS TAPER
CROSS TAPE REFILL
SOFT ROLLER
GUIDE ROLLERS
CROSS TAPE MOTOR
GUIDE ROLLERS
VERTICAL DEFLECTORS
BOX ALIGNMENT
BOX LABELING
TRAILING EDGE GUIDE
1000000.     25000.     0.       4000.     2.
1.           1.         1.       5.        .0001
10.           00.        0.       0.
0.           0.         0.       1.
500000.      10000.     20.      1000.     5.
1.           1.         1.       5.        .001
10.           1 1.       .5       2.
.025         20.        0.       1.
25000.       500.       5.       50.       20.
2.           2.         1.       2.        .001
10.           11.        .25      1.
.05          15.        0.       6.
5000000.     25000.     20.      200.      5.
1.           1.         1.       5.        .001
50.           12.        .3       1.
.01          200.       0.       1.
1000000.      720.      3.1      20.       .1
2.           1.         1.       1.         0.
0.           215.        0.5      .05
```

.005	50.	0.	2.	
5000.	10.	0.	.04	.003
2.	0.	1.	0.	0.
0.	311.	0.	.02	
1.	250.	0.	0.	
500000.	500.	.01	50.	.5
2.	1.	1.	.5	0.
0.	212.	.25	.05	
.01	10.	0.	6.	
25000.	.05	0.	.05	.00005
1.	0.	1.	0.	0.
0.	373.6	0.	.03	
1.	1.5	0.	3.	
25000.	15.5	0.	10.	.025
2.	0.	14.	0.	0.
0.	336.8	0.	.02	
1.	1.5	0.	20.	
250000.	50.	.01	25.	1.
2.	2.	14.	4.	.0001
5.	11.	.01	.1	
.02	5.	0.	20.	
5000000.	89.	.007	22.	.2
1.	1.	1.	5.	.0005
10.	215.	1.	.05	
.02	15.	0.	2.	
0.	920.	7.3	25.	.1
20.	4.	1.	1.	0.
0.	215.	.5	.05	
.005	50.	0.	70.	
0.	10.	0.	.04	.003
20.	0.	1.	0.	0.
0.	311.	0.	.02	
1.	250.	0.	0.	
0.	600.	.01	60.	.5
20.	4.	1.	.6	0.
0.	212.	.25	.05	
.01	10.	0.	20.	
0.	.35	0.	.25	.00035
4.	0.	1.	0.	0.
0.	3319.6	0.	.03	
1.	1.5	0.	14.	
0.	15.5	0.	10.	.025
4.	0.	14.	0.	0.
0.	3159.8	0.	.02	
1.	1.5	0.	20.	
0.	50.	.01	25.	1.
4.	1.	14.	4.	.0001
5.	11.	.01	.1	
.02	5.	0.	20.	
1000000.	2500.	1.75	25.	.5
20.	4.	1.	2.	.00002
200.	215.	.25	.05	
.01	100.	0.	20.	
0.	1330.	.152	360.	2.
1.	1.	1.	20.	.002

```
10.                   2110.                  2.                    .05
.01                   15.                       0.                   2.
0.                    430.                  1.8                   10.                   .05
2.                    1.                    1.                    1.                        0.
0.                    215.                      .5                  .05
.005                  50.                      0.                 6.
0.                     '0.                  0.                    .04                   .003
2.                    0.                    1.                    0.                    0.
0.                     35.                     0.                   .02
1.                    250.                   0.                   0.
0.                    95.                    .008                 24.                     .2
1.                    1.                    1.                    5.                     .0005
10.                   215.                    1.                    .05          .
.02                    15.                  0.                    2.
0.                    270.                  .6                    5.                      .05
2.                    1.                    1.                    1.                    0.
0.                    215.                    .5                          .05
.C05                  50.                   0.                    6.
0.                    10.                   C.                    .04                   .003
2.                    0.                    1.                    0.                    0.
0.                     33.                     0.                   .02
1.                    250.                  0.                     0.
0.                    62.                   .003                  14.                   .1
1.                    1.                    1.                    5.                    .0005
10.                   ?15.                    1.                     .05
.02                    15.                  0.                    3.
2C00000.              25C0.                 1.75                  25.                   .5
2.                     2.                    1.                   2.                    .00003
200.                  215.                    .25                   .05
.01                   100.                  0.                    20.
0.                    240.                  .4                    5.                    .05
2.                    1.                    1.                     1.                     0.
0.                    215.                    .5                    .05
.005                      50.                      0.             6.
0.                    1C.                   0.                    .04                   .003
2.                    0.                    1.                    0.                     0.
0.                     33.                     0.                   .02
1.                    250.                  0.                    0.
0.                    62.                   .001                  14.                   .1
1.                    1.                    1.          .         5.                     .0005
10.                   215.                    1.                    .05
.02                   15.                   0.                    3.
0.                    410.                  1.6                   10.                    .05
4.                    1.                    1.                    1.                     0.
0.                    215.                        .5                       .05
.005                  50.                   0.                     6.
0.                    1C.                   0.                    .04                   .003
4.                    0.                    1.                    0.                    0.
0.                     34.                     0.                   .02
1.                     250.                 0.                    0.
0.                    5C0.                  .01                    50.                  .5
4.                    1.                    1.                    .2                    0.
0.                    212.                    .25                   .05
.01                   10.                   0.                    6.
100000.               12000.                0.                     300.                  1.
```

2.	0.	1.	0.	0.
0.	3353.	0.	.1	
.01	20.	1.	2.	
250000.	2500.	2.	250.	3.
2.	1.	1.	5.	.001
10.	15.	.05	.25	
.05	10.	0.	2.	
0.	.05	0.	.05	.00005
2.	0.	1.	0.	0.
0.	336.8	0.	.03	
1.	1.5	0.	3.	
0.	15.5	0.	10.	.025
4.	0.	14.	0.	0.
0.	318.4	0.	.02	
1.	1.5	0.	20.	
0.	50.	.01	25.	1.
4.	2.	14.	4.	.0001
5.	11.	.01	.1	
.02	5.	0.	20.	
0.	190.	.006	30.	-.2
1.	1.	1.	10.	.0001
10.	2110.	1.	.05	
.01	15.	0.	1.	
0.	220.	0.2	5.	.05
2.	1.	1.	1.	0.
0.	21 5.	.5	.05	
.005	50.	0.	6.	
0.	10.	0.	.04	.003
2.	0.	1.	0.	0.
0.	3 3.	0.	.02	
1.	250.	0.	0.	
0.	62.	.001	14.	.1
1.	1.	1.	5.	.0005
10.	21 5.	1.	.05	
.02	15.	0.	3.	
750000.	3250.	2.5	20.	.25
1.	1.	1.	5.	.001
25.	21 10.	1.	.05	
.05	25.	0.	2.	
1000.	100.	0.	.1	.005
1.	0.	1.	0.	0.
0.	3 2.	0.	.03	
1.	1000.	0.	2.	
1000.	10.	0.	.5	.003
2.	0.	1.	0.	0.
0.	3 .05	0.	.05	
1.	20.	0.	0.	
500.	20.	0.	1.	.01
1.	0.	1.	.1	0.
0.	0 0.	0.	0.	
0.	0.	0.	0.	
80000.	140.	0.5	10.	.1
1.	1.	1.	.01	.00001
15.	21 8.	.25	.03	
.04	35.	0.	2.	

400000.	500.	1.0	20.	.1
1.	1.	1.	.01	.00001
15.	21 4.	.25	.03	
.1	130.	0.	2.	
20000.	120.	0.	15.	.05
1.	1.	1.	0.	0.
0.	3 70.2	0.	.03	
0.	0.	0.	0.	
20000.	500.	.1	.1	.005
2.	2.	1.	0.	0.
0.	22 .7	1.	.03	
.2	5000.	0.	4.	
5000.	50.	.1	.8	.007
4.	2.	1.	0.	0.
0.	21 .2	.75	.03	
.06	75.	0.	40.	
300000.	150.	1.	10.	.025
1.	1.	1.	.01	.00004
15.	21 1.	2.5	.03	
.04	135.	0.	2.	
0.	10.	0.	.5	.003
4.	0.	1.	0.	0.
0.	3 .05	0.	.05	
1.	20.	0.	0.	
0.	870.	7.0	25.	.1
30.	4.	1.	1.	0.
0.	215.	.5	.05	
.005	50.	0.	70.	
0.	10.	0.	.04	.003
30.	0.	1.	0.	0.
0.	311.	0.	.02	
1.	250.	0.	0.	
0.	600.	.01	60.	0.5
30.	4.	1.	.3	0.
0.	212.	.25	.05	
.01	10.	0.	50.	
100000.	500.	1.	50.	1.
1.	1.	1.	10.	.0005
15.	215.	.25	.05	
.01	20.	0.	2.	
25000.	100.	0.	5.	.002
1.	0.	1.	15.	0.
0.	371.	0.	.03	
.001	20.	.75	2.	
5000.	25.	.0005	5.	.5
6.	1.	1.	5.	0.
0.	11.	0.	.03	
.01	10.	0.	5.	
0.	.35	.0	.25	.00035
6.	0.	1.	0.	0.
0.	3319.6	0.	.03	
7.0	1.5	.0	14.	
0.	15.5	.0	10.	.025
6.	0.	14.	0.	0.
0.	3159.8	0.	.02	

1.0	1.5	.0	20.	
0.	50.	.01	25.	1.
6.	1.	14.	4.	.0001
5.	11.	.01	.1	
.02	5.	0.	20.	
1000000.	20000.	0.	3000.	2.
1.	1.	1.	5.	.001
10.	00.	0.	0.	
0.	0.	0.	1.	
0.	7000.	15.	700.	4.
1.	1.	1.	5.	.0001
10.	11.	.5	2.	
.025	20.		1.	
0.	1000.	5.	100.	80.
1.	1.	1.	2.	.001
10.	12.	.25	1.	
.05	15.	0.	6.	
0.	1577.	.219	531.	3.
1.	1.	1.	30.	.003
10.	2115.	2.	.05	
.0033	15.	0.	1.	
0.	870.	7.0	25.	.1
20.	4.	1.	1.	0.
0.	215.	.5	.05	
.005	50.	0.	70.	
0.	10.	0.	.04	.003
20.	0.	1.	0.	0.
0.	311.	0.	.02	
1.	250.	0.	0.	
0.	600.	.01	60.	.5
20.	4.	1.	.3	0.
0.	212.	.25	.05	
.01	10.	0.	50.	
0.	500.	1.	50.	1.
1.	1.	1.	10.	.0005
15.	215.	.25	.05	
.01	20.	0.	2.	
0.	100.	0.	5.	.005
1.0	0.	1.	15.	0.
0.	347.	0.	.03	
.001	20.	.75	2.	
0.	25.	.0005	5.	.5
4.	1.	1.	5.	0.
0.	11.	0.	0.	
.01	10.	0.	5.	
0.	.35	0.	.25	.00035
4.	0.	1.	0.	0.
0.	3319.6	0.	.03	
1.	1.5	0.	14.	
0.	15.5	.0	10.	.025
4.	0.	14.	.0	.0
.0	3159.8	0.	.02	
1.0	1.5	.0	20.	
0.	50.	.01	25.	1.
4.	1.	14.	4.	.0001

```
5.          11.         .01         .1
.02         5.          0.          20.
0.          15000.      0.          2000.       2.
1.          1.          1.          5.          .0001
10.          00.         0.          0.
0.          0.          0.          1.
0.          5000.       10.         500.        3.
1.          1.          1.          5.          .001
10.          11.         .5          2.
.025        20.         0.          1.
0.          1000.       5.           100.        40.
1.          1.          1.          2.          .001
10.          12.         .25         1.
.05         15.         0.          6.
0.          1318.       .146        354.        2.
1.          1.          1.          20.         .002
10.         2110.        2.          .05
.005        15.         0.          2.
100000.       400.      5.           70.          .15
1.           1.         1.           .2          .0001
15.         1    1.        .4          1.
.1          15.         0.           1.
0.            50.          .1          .8          .010
32.           25.        1.          0.          0.
0.          21    .2       .75          .03
.06           75.        0.          40.
450000.       250.       .7          22.5          .3
2.          2.          1.           .1          .00001
15.         21     4.       .35          .03
.1            25.        0.          2.
450000.       250.      .7           22.5          .3
1.            1.         1.           .1           .00001
15.         21     4.      .35          .03
.1          25.          0.          1.
600000.       100.      1.           30.          1.
3.            3.        1.           0.          0.
0.          0    0.       0.          0.
0.          0.           0.          3.
0.            250.      .1           .1          .005
10.         7.          1.           0.           0.
0.          22    .7       1.            .03
.2            5000.     0.           10.
0.            10.       0.           .5            .003
60.         0.           1.           0.          0.
0.           3    .05      0.          .05
1.            20.       0.           0.
0.          140.        .5           10.         .1
1.          1.          1.           .01         .00001
15.         21    8.      .25            .03
.04         35.         0.           2.
0.          500.        1.           20.         .1
1.          1.          1.           .01         .00001
15.         21     4.       .25          .03
.1          130.        0.           2.
0.          120.        0.           15.         .05
```

```
1.        1.        1.        0.        0.
0,        3    4.1      0.       .03
0.        0.        0.        0.
0.        500.      .1        .1        .005
2.        2.        1.        0.        0.
0.        22  .7      1.        .03
.2        5000.     0.        4.
0.        50.       .1        .8        .007
4.        2.        1.        0.        0.
0.        21   .2      .75       .03
.06       75.       0.        40.
0.        250.      5.        15.       .024
1.        1.        1.        .01       .00004
15.       21    1.      2.5      .03
.04       135.      0.        2.
0.        10.       0.        .5        .003
4.        0.        1.        0.        0.
0.        3   .05      0.        .05
1.        20.       0.        0.
0.        3500.     2.5       20.       .25
1.        1.        1.        5.        .001
25.       215.      1.        .05
.05       25.       0.        2.
0.        100.      0.        .1        .005
1.        0.        1.        0.        0.
0.        32.            0.        .03
1.        1000.     0.        2.
0.        10.       0.        .5        .003
2.        0.        1.        0.        0.
0.        3.05      0.        .05
1.        20.       0.        0.
0.        20.       0.        1.        .01
1.        0.        1.        .1        0.
0.        00.       0.        0.
0.        0.        0.        2.
25000.    50.       .5        5.        .25
13.       13.       14.       .1        .00001
15.       211.      .4        .03
.05       10.       0.        13.
0.        60.       0.        .6        .015
13.       0.        14.       0.        0.
0.        3705.     0.        .02
1.        100.      0.        0.
75000.    500.      .5        25.       1.
1.        1.        14.       .1        .00001
15.       212.      .3        .03
.05       20.       0.        1.
0.        60.       0.        .6        .015
1.        0.        14.       0.        0.
0.        3705.     0.        .02
1.        100.      0.        0.
25000.    10.       0.        .5        .005
22.       0.        14.       0.        0.
0.        60.       0.        0.
0.        0.        0.        0.
```

0.	10.	0.	.5	.003
112.	0.	14.	0.	0.
0.	3.05	0.	.05	
1.	20.	0.	0.	
5000.	1000.	5.	50.	.5
1.	1.	14.	1.	.0001
15.	211.	2.5	.03	
.05	40.	0.	1.	
0.	10.	0.	.5	.003
154.	0.	14.	0.	0.
0.	3.05	0.	.05	
1.	20.	0.	0.	
5000.	1500.	1.	20.	.005
1.	1.	14.	.1	.00001
15.	15.	.05	.2	
.05	20.	0.	1.	
10000.	1000.	4.	300.	2.
1.	1.	14.	.1	.00005
15.	11.	0.	.25	
.05	0.	0.	1.	
1000.	[illegible]00.	.01		.002
1.	1.	14.		0.
0.	22.1	1.	[illegible]3	
.05	50.	0.	[illegible]	
5000.	2000.	.01	[illegible]	2.5
1.	1.	14.	[illegible]	.00001
15.	1.5	.01	[illegible]	
.1	150.	0.	[illegible]	
3000000.	75000.	75.	[illegible]	2.
.001	20.			
500000.	50000.	500.	2.	5.
.001	20.			
2000000.	100000.	100.	2.	[illegible]
.001	2[illegible]			
0.	100000.	100.	2.	2.
.001	20.			
0.	60000.	600.	2.	5.
.001	20.			
5000000.	250000.	250.	2.	5.
.001	20.			
0.	500000.	500.	2.	5.
.001	20.			
0.	50000.	50.	2.	2.
.001	20.			
0.	100000.	100.	2.	2.
.001	20.			
0.	25000.	25.	2.	2.
.001	20.			
0.	50000.	50.	2.	2.
.001	20.			
0.	250000.	250.	2.	5.
.001	20.			
0.	25000.	25.	2.	1.
.001	20.			
[illegible]	50000.	50.	2.	2.

.001	20.			
0.	50000.	50.	2.	2.
.001	20.			
0.	50000.	500.	2.	5.
.001	20.			
0.	50000.	50.	2.	2.
.001	20.			
0.	25000.	25.	2.	1.
.001	20.			
0.	50000.	50.	2.	2.
.001	20.			
2400000.	120000.	120.	2.	2.
.001	20.			
2000000.	100000.	100.	2.	2.
.001	20.			
2000000.	200000.	200.	2.	2.
.001	20.			
160000.	8000.	8.	1.	1.
.001	20.			
3000000.	150000.	150.	2.	1.
.001	20.			
0.	100000.	100.	2.	2.
.001	20.			
0.	60000.	600.	2.	5.
.001	20.			
500000.	50000.	500.	2.	5.
.001	20.			
0.	500000.	500.	2.	5.
.001	20.			
0.	100000.	100.	2.	2.
.001	20.			
0.	60000.	600.	2.	5.
.001	20.			
0.	50000.	500.	2.	5.
.001	20.			
0.	500000.	500.	2.	5.
.001	20.			
0.	8000.	8.	1.	1.
.001	20.			
225000.	22500.	225.	2.	2.
.001	20.			
0.	22500.	225.	2.	2.
.001	20.			
0.	100000.	100.	2.	2.
.001	20.			
0.	200000.	200.	2.	2.
.001	20.			
0.	8000.	8.	1.	1.
.001	20.			
0.	150000.	150.	2.	1.
.001	20.			
0.	120000.	120.	2.	2.
.001	20.			
50000.	5000.	50.	2.	2.
.001	20.			

250000.	25000.	250.	2.	5.
.001	20.			
500000.	50000.	500.	2.	5.
.001	20.			
216000.	4000.	200.	16.	48.
.001	20.			
100000.	2000.	100.	5.	3.
.001	20.			
0.				
0.				
0.				
0.				
0.				
0.				
0.				
0.				

TABLE OF STATION DUTY CYCLE(STATDC), FRACTION OF REPLACEMENTS OBTAINED ON AN EMERGENCY BASIS(EARTH), COMPONENT AVERAGE FAILURE REPLACEMENTS IN WAREHOUSE AT BEGINNING OF DELIVERY PERIOD(NOSPAR), NUMBER OF CRAWLERS(NOCRAW), CRAWLER UTILIZATION FACTOR(CUF), NUMBER OF TELEOPERATORS(NOTELE), TELEOPERATOR UTILIZATION FACTOR(TUF), NUMBER OF REPAIR AUTOMATONS(NOAUTO), NUMBER OF CLEANING MACHINES(NOCLN), NUMBER OF HUMANS FOR TELEOPERATOR SUPERVISORY CONTROL(NOHUM1), AND NUMBER OF HUMANS FOR REPAIR WORK (NOHUM2), FOR INDIVIDUAL COMPONENTS OF A MACHINE <TOTALED OVER ALL THE STRIPS> --------------

	STATDC	EARTH	NOSPAR	NOCRAW	CUF	NOTELE	TUF	NOAUTO	NOCLN	NOHUM1	NOHUM2
THERMAL BELT			MACHINE DUTY CYCLE [MACHDC] =0.99712								
BELT	1.00000	0.0	0.0	0.	0.0	0.0	0.0	0.	0.	0.0	0.0
MOTOR/DRIVE	0.99912	0.0066	172.5	0.	0.0	0.099	0.069	0.	0.	0.0248	0.0
END ROLLERS	0.99950	0.0066	345.1	0.	0.0	0.107	0.075	0.	0.	0.0267	0.0
THERMAL CONTROL	0.99900	0.0066	345.1	0.	0.0	0.107	0.075	0.	0.	0.0321	0.0
DV OF AL REAR CONTACT			MACHINE DUTY CYCLE [MACHDC] =0.99935								
EB GUN	0.99966	0.0066	1725.3	1.	0.584	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	2711.2	1.	0.584	0.0	0.0	0.	0.	0.0	0.0
SLAB FEEDER	0.99986	0.0066	690.1	1.	0.584	0.0	0.0	1.	0.	0.0	0.0
PANEL BAFFLE	1.00000	0.0	9070.3	1.	0.584	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE	1.00000	0.0	647.9	1.	0.584	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE GUIDE	0.99984	0.0066	24.6	1.	0.584	0.002	0.001	0.	0.	0.0002	0.0
COOLING SYSTEM	0.99966	0.0066	862.7	1.	0.584	0.0	0.0	1.	0.	0.0	0.0
DV OF SI WAFER AND P-DOPANT IMPLANTATION			MACHINE DUTY CYCLE [MACHDC] =0.99868								
EB GUN	0.99966	0.0066	17253.3	10.	0.709	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	27112.3	10.	0.709	0.0	0.0	0.	0.	0.0	0.0
SLAB FEEDER	0.99986	0.0066	6901.3	10.	0.709	0.0	0.0	1.	0.	0.0	0.0
PANEL BAFFLE	1.00000	0.0	157547.3	10.	0.709	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE	1.00000	0.0	5626.7	10.	0.709	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE GUIDE	[illegible]	0.0066	49.3	10.	0.709	0.004	0.002	0.	0.	0.0004	0.0
BORON ION IMPLANTER	0.99966	0.0066	17253.3	10.	0.709	0.0	0.0	1.	0.	0.0	0.0
COOLING SYSTEM	0.99932	0.0066	1725.3	10.	0.709	0.0	0.0	1.	0.	0.0	0.0
PULSE RECRYSTALLIZATION			MACHINE DUTY CYCLE [MACHDC] =0.99966								
EB GUN	0.99966	0.0066	1725.3	1.	0.294	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	1232.4	1.	0.294	0.0	0.0	0.	0.	0.0	0.0
COOLING SYSTEM	0.99966	0.0066	862.7	1.	0.294	0.0	0.0	1.	0.	0.0	0.0

SCAN RECRYSTALLIZATION			MACHINE DUTY CYCLE (MACHDC) =0.99966								
EB GUN	0.99966	0.0066	1725.3	1.	0.285	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	739.4	1.	0.285	0.0	0.0	0.	0.	0.0	0.0
COOLING SYSTEM	0.99966	0.0066	862.7	1.	0.285	0.0	0.0	1.	0.	0.0	0.0
N-DOPANT IMPLANTATION			MACHINE DUTY CYCLE (MACHDC) =0.99933								
PHOSPHORUS ION IMPLANTER	0.99967	0.0066	1725.3	1.	0.160	0.0	0.0	1.	0.	0.0	0.0
ANNEAL			MACHINE DUTY CYCLE (MACHDC) =0.99966								
EB GUN	0.99966	0.0066	1725.3	1.	0.285	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	739.4	1.	0.285	0.0	0.0	0.	0.	0.0	0.0
COOLING SYSTEM	0.99966	0.0066	862.7	1.	0.285	0.0	0.0	1.	0.	0.0	0.0
DV OF AL FRONT CONTACT			MACHINE DUTY CYCLE (MACHDC) =0.99656								
EB GUN	0.99966	0.0066	3450.7	6.	0.702	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	1971.8	6.	0.702	0.0	0.0	0.	0.	0.0	0.0
SLAB FEEDER	0.99986	0.0066	1300.3	6.	0.702	0.0	0.0	1.	0.	0.0	0.0
MASK	1.00000	0.0	27.0	6.	0.702	0.0	0.0	0.	20.	0.0	0.0
MASK GUIDE AND ROLLUP	0.99093	0.0066	1725.3	6.	0.702	0.192	0.134	0.	0.	0.0384	0.0
PANEL BAFFLE	1.00000	0.0	9070.3	6.	0.702	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE	1.00000	0.0	647.9	6.	0.702	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE GUIDE	0.99984	0.0066	49.3	6.	0.702	0.004	0.002	0.	0.	0.0004	0.0
COOLING SYSTEM	0.99932	0.0066	1725.3	6.	0.702	0.0	0.0	1.	0.	0.0	0.0
FRONT CONTACT SINTERING			MACHINE DUTY CYCLE (MACHDC) =0.99966								
EB GUN	0.99966	0.0066	1725.3	1.	0.285	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	739.4	1.	0.285	0.0	0.0	0.	0.	0.0	0.0
COOLING SYSTEM	0.99966	0.0066	862.7	1.	0.28	0.0	0.0	1.	0.	0.0	0.0
CELL CROSSCUT			MACHINE DUTY CYCLE (MACHDC) =0.99933								
LASER	0.99933	0.0066	1725.3	1.	0.200	0.0	0.0	1.	0.	0.0	0.0
KRYPTON LAMP MAGAZINE	1.00000	0.0	246.5	1.	0.200	0.0	0.0	0.	0.	0.0	0.0
GUIDE ROLLERS	1.00000	0.0	12.3	1.	0.200	0.0	0.0	0.	0.	0.0	0.0
SHIELD	1.00000	0.0	0.0	1.	0.200	0.0	0.0	0.	0.	0.0	0.0

CELL INTERCONNECTION				MACHINE DUTY CYCLE (MACHDC) =0.99907							
ELECTROSTATIC WELDER	0.99948	0.0066	1380.3	1.	0.220	0.0	0.0	1.	0.	0.0	0.0
INTERCONNECT FEEDER	0.99974	0.0066	690.1	1.	0.220	0.0	0.0	1.	0.	0.0	0.0
INTERCONNECT ROLL	1.00000	0.0	8651.3	1.	0.220	0.0	0.0	0.	0.	0.0	0.0
SENSORS	0.99995	0.0066	241.5	1.	0.220	0.0	0.0	0.	0.	0.0	0.0394
VARIABLE SPEED ROLLERS	0.99999	0.0066	130.0	1.	0.220	0.0	0.0	1.	0.	0.0	0.0
MOTOR	0.99994	0.0066	172.5	1.	0.220	0.0	0.0	1.	0.	0.0	0.0
GUIDE ROLLERS	1.00000	0.0	24.6	1.	0.220	0.0	0.0	0.	0.	0.0	0.0
DV OF SILICA OPTICAL COVER				MACHINE DUTY CYCLE (MACHDC) =0.99504							
EB GUN	0.99966	0.0066	25879.9	14.	0.714	0.0	0.0	2.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	40668.5	14.	0.714	0.0	0.0	0.	0.	0.0	0.0
SLAB FEEDER	0.99986	0.0066	10352.0	14.	0.714	0.0	0.0	1.	0.	0.0	0.0
MASKING DEVICE	0.99966	0.0066	862.7	14.	0.714	0.0	0.0	1.	0.	0.0	0.0
T-STRIP MASK PACKAGE	1.00000	0.0	2.1	14.	0.714	0.0	0.0	0.	2.	0.0	0.0
OXYGEN DISPENSER	0.99987	0.0066	1035.2	14.	0.714	0.055	0.038	0.	0.	0.0	0.0
PANEL BAFFLE	1.00000	0.0	236320.9	14.	0.714	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE	1.00000	0.0	8440.0	14.	0.714	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE GUIDE	0.99984	0.0066	73.9	14.	0.714	0.005	0.004	0.	0.	0.0005	0.0
SCPT SURFACE BELT	1.00000	0.0	0.0	14.	0.714	0.0	0.0	0.	0.	0.0	0.0
MOTOR/DRIVE	0.99912	0.0066	172.5	14.	0.714	0.099	0.069	0.	0.	0.0248	0.0
END ROLLER	0.99900	0.0066	345.1	14.	0.714	0.107	0.075	0.	0.	0.0267	0.0
COOLING SYSTEM	0.99898	0.0066	2588.0	14.	0.714	0.0	0.0	1.	0.	0.0	0.0
DV OF SILICA SUBSTRATE				MACHINE DUTY CYCLE (MACHDC) =0.99600							
EB GUN	0.99966	0.0066	17253.3	10.	0.697	0.0	0.0	1.	0.	0.0	0.0
FILAMENT MAGAZINE	1.00000	0.0	27112.3	10.	0.697	0.0	0.0	0.	0.	0.0	0.0
SLAB FEEDER	0.99986	0.0066	6901.3	10.	0.697	0.0	0.0	1.	0.	0.0	0.0
MASKING DEVICE	0.99966	0.0066	862.7	10.	0.697	0.0	0.0	1.	0.	0.0	0.0
T-STRIP MASK PACKAGE	1.00000	0.0	1.4	10.	0.697	0.0	0.0	0.	1.	0.0	0.0
OXYGEN DISPENSER	0.99988	0.0066	690.1	10.	0.697	0.031	0.022	0.	0.	0.0	0.0
PANEL BAFFLE	1.00000	0.0	157547.3	10.	0.697	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE	1.00000	0.0	5626.7	10.	0.697	0.0	0.0	0.	0.	0.0	0.0
SIDE BAFFLE GUIDE	0.99984	0.0066	49.3	10.	0.697	0.004	0.002	0.	0.	0.0004	0.0
SCPT SURFACE BELT	1.00000	0.0	0.0	10.	0.697	0.0	0.0	0.	0.	0.0	0.0
MOTOR/DRIVE	0.99912	0.0066	172.5	10.	0.697	0.099	0.069	0.	0.	0.0248	0.0
END ROLLER	0.99900	0.0066	345.1	10.	0.697	0.107	0.075	0.	0.	0.0267	0.0
COOLING SYSTEM	0.99932	0.0066	1725.3	10.	0.697	0.0	0.0	1.	0.	0.0	0.0
PANEL ALIGNMENT & SPARE PANEL INSERTION				MACHINE DUTY CYCLE (MACHDC) =0.99873							
ACCELERATOR BELT	0.99950	0.0066	172.5	1.	0.091	0.053	0.037	0.	0.	0.0214	0.0
VARIABLE SPEED ROLLERS	0.99999	0.0066	1104.2	1.	0.091	0.0	0.0	1.	0.	0.0	0.0
PANEL REMOVER	0.99974	0.0066	1380.3	1.	0.091	0.0	0.0	1.	0.	0.0	0.0
PANEL INSERTER	0.99974	0.0066	690.1	1.	0.091	0.0	0.0	1.	0.	0.0	0.0
PANEL HOPPER	1.00000	0.0	0.0	1.	0.091	0.0	0.0	0.	0.	0.0	0.0
SENSORS	0.99995	0.0066	1207.7	1.	0.091	0.0	0.0	0.	0.	0.0	0.1970
GUIDE ROLLERS	1.00000	0.0	369.7	1.	0.091	0.0	0.0	0.	0.	0.0	0.0

PANEL INTERCONNECTION MACHINE DUTY CYCLE [MACHDC] =0.99908

ELECTROSTATIC WELDER	0.99949	0.0066	1300.3	1.	0.051	0.0	0.0	1.	0.	0.0	0.0
INTERCONNECT FEEDER	0.99974	0.0066	690.1	1.	0.051	0.0	0.0	1.	0.	0.0	0.0
INTERCONNECT ROLL	1.00000	0.0	505.3	1.	0.051	0.0	0.0	0.	0.	0.0	0.0
SENSORS	0.99996	0.0066	241.5	1.	0.051	0.0	0.0	0.	0.	0.0	0.0394
VARIABLE SPEED ROLLERS	0.99999	0.0066	130.0	1.	0.051	0.0	0.0	1.	0.	0.0	0.0
MOTOR	0.99994	0.0066	172.5	1.	0.051	0.0	0.0	1.	0.	0.0	0.0
GUIDE ROLLERS	1.00000	0.0	24.6	1.	0.051	0.0	0.0	0.	0.	0.0	0.0

LONGITUDINAL CUT MACHINE DUTY CYCLE [MACHDC] =0.99967

LASER	0.99967	0.0066	862.7	1.	0.184	0.0	0.0	1.	0.	0.0	0.0
KRYPTON LAMP MAGAZINE	1.00000	0.0	246.5	1.	0.184	0.0	0.0	0.	0.	0.0	0.0
GUIDE ROLLERS	1.00000	0.0	12.3	1.	0.184	0.0	0.0	0.	0.	0.0	0.0
SHIELD	1.00000	0.0	0.0	1.	0.184	0.0	0.0	0.	0.	0.0	0.0

KAPTON TAPE APPLICATION MACHINE DUTY CYCLE [MACHDC] =0.99896

STATIONARY TAPER	0.99993	0.0066	160.2	2.	0.697	0.0	0.0	1.	0.	0.0	0.0
STATIONARY TAPE REFILL	1.00000	0.0	80676.7	2.	0.697	0.0	0.0	0.	0.	0.0	0.0
CROSS TAPER	0.99987	0.0066	24.6	2.	0.697	0.0	0.0	1.	0.	0.0	0.0
CROSS TAPE REFILL	1.00000	0.0	6205.9	2.	0.697	0.0	0.0	0.	0.	0.0	0.0
SOFT ROLLER	1.00000	0.0	0.0	2.	0.697	0.0	0.0	0.	0.	0.0	0.0
GUIDE ROLLERS	1.00000	0.0	49.3	2.	0.697	0.0	0.0	0.	0.	0.0	0.0
CROSS TAPE MOTOR	0.99993	0.0066	12.3	2.	0.697	0.0	0.0	1.	0.	0.0	0.0

ARRAY SEGMENT FOLDING AND PACKAGING MACHINE DUTY CYCLE [MACHDC] =0.99873

GUIDE ROLLERS	1.00000	0.0	67.8	1.	0.002	0.0	0.0	0.	0.	0.0	0.0
VERTICAL DEFLECTORS	0.99902	0.0066	61.6	1.	0.002	0.006	0.004	0.	0.	0.0015	0.0
BOX ALIGNMENT	0.99979	0.0066	12.3	1.	0.002	0.001	0.001	0.	0.	0.0	0.0
BOX LABELING	0.99999	0.0066	1.2	1.	0.002	0.0	0.0	0.	0.	0.0	0.0002
TRAILING EDGE GUIDE	0.99993	0.0066	6.2	1.	0.002	0.000	0.000	0.	0.	0.0001	0.0

SOLAR CELL FACTORY COST BREAKDOWN-------

TOTAL NONRECURRING DIRECT COST IS $ 1025776640.
    MACHINES: $ 84922256.
    MACHINE RESEARCH AND DEVELOPMENT: $ 21138400.
    MACHINE TRANSPORTATION: $ 553165024.
    SOLAR POWER ARRAY (FOR PRODUCTION): $ 366631168.

TOTAL NONRECURRING INDIRECT COST IS $ 1741493250.
    NONPRODUCTION SCF EQUIPMENT PROCUREMENT/R&D COST: $ 1383049730.
        SCF STRUCTURE: $ 1243500290.
        WAREHOUSE: $ 2900253.
        CONTROL CENTER: $ 62000000.
        REPAIR WORKSHOP: $ 10354000.
        MICROPROCESSORS/SENSORS: $ 6890000.
        ARRAY SEGMENT STORAGE BOXES: $ 15800.
        CRAWLERS: $ 15250000.
        TELEOPERATORS: $ 15432431.
        REPAIR ACTUATORS: $ 26303968.
        CLEANING MACHINES: $ 400000.
    HABITAT PROCUREMENT COST: $ 16416000.
    NONPRODUCTION SOLAR POWER ARRAY PROCUREMENT: $ 5503363.
    NONPRODUCTION SCF TRANSPORTATION: $ 129400592.
    HABITAT TRANSPORTATION. $ 16416000.
    SOLAR POWER ARRAY TRANSPORTATION: $ 186067200.
    COST TO SET UP SCF: $ 4636405.

TOTAL ANNUAL RECURRING DIRECT COST IS $ 197416912.
    HUMAN SUPERVISORY CONTROL LABOR: $ 10117800.
    HUMAN REPAIR LABOR: $ 915600.
    SUPPORT CREW LABOR: $ 5518800.
    MACHINE REPLACEMENT PARTS: $ 27945600.
    MACHINE REPLACEMENT PARTS TRANSPORTATION: $ 146916256.
    MACHINE EXPENDABLES: $ 665369.
    MACHINE EXPENDABLES TRANSPORTATION: $ 5133307.

TOTAL ANNUAL RECURRING INDIRECT COST IS $ 8538916.
    CONSUMMABLES: $ 165564.
    CONSUMMABLES TRANSPORTATION: $ 1655639.
    CREW TRAINING: $ 5400.
    CREW TRANSPORTATION: $ 6480000.
    NONPRODUCTION SCF EXPENDABLES: $ 38719.
    NONPRODUCTION SCF EXPENDABLES TRANSPORTATION: $ 193596.

THERMAL BELT

BELT	0.
MOTOR/DRIVE	6162.
END ROLLERS	1232.
THERMAL CONTROL	586.

DV OF AL REAR CONTACT

EB GUN	246.
FILAMENT MAGAZINE	217.
SLAB FEEDER	453.
PANEL BAFFLE	507.
SIDE BAFFLE	12558.
SIDE BAFFLE GUIDE	18.
COOLING SYSTEM	542.

DV OF SI WAFER AND P-DOPANT IMPLANTATION

EB GUN	3081.
FILAMENT MAGAZINE	2169.
SLAB FEEDER	5515.
PANEL BAFFLE	76774.
SIDE BAFFLE	112534.
SIDE BAFFLE GUIDE	35.
BORON ION IMPLANTER	6162.
COOLING SYSTEM	6673.

PULSE RECRYSTALLIZATION

EB GUN	123.
FILAMENT MAGAZINE	99.
COOLING SYSTEM	592.

SCAN RECRYSTALLIZATION

EB GUN	62.
FILAMENT MAGAZINE	59.
COOLING SYSTEM	345.

N-DOPANT IMPLANTATION

PHOSPHORUS ION IMPLANTER	616.

ANNEAL

EB GUN	62.
FILAMENT MAGAZINE	59.
COOLING SYSTEM	345.

DV OF AL FRONT CONTACT

EB GUN	246.
FILAMENT MAGAZINE	158.
SLAB FEEDER	586.
MASK	522035.
MASK GUIDE AND ROLLUP	30809.
PANEL BAFFLE	907.
SIDE BAFFLE	12558.
SIDE BAFFLE GUIDE	35.
COOLING SYSTEM	739.

FRONT CONTACT SINTERING

EB GUN	62.
FILAME AGAZINE	59.
COOL YSTEM	345.

CELL CROSSCUT

LASER	2465.
KRYPTON LAMP MAGAZINE	45.
GUIDE ROLLERS	12.
SHIELD	0.

CELL INTERCONNECTION

ELECTROSTATIC WELDER	789.
INTERCONNECT FEEDER	1972.
INTERCONNECT ROLL	0.
SENSORS	7.
VARIABLE SPEED ROLLERS	9.
MOTOR	59.
GUIDE ROLLERS	25.

EV OF SILICA OPTICAL COVER

EB GUN	4621.
FILAMENT MAGAZINE	3253.
SLAB FEEDER	6673.
MASKING DEVICE	616.
T-STRIP MASK PACKAGE	87.
OXYGEN DISPENSER	74.
PANEL BAFFLE	116160.
SIDE BAFFLE	168801.
SIDE BAFFLE GUIDE	53.
SOFT SURFACE BELT	0.
MOTOR/DRIVE	4313.
END ROLLER	2465.
COOLING SYSTEM	6478.

LT OF SILICA SUBSTRATE

EB GUN	3081.
FILAMENT MAGAZINE	2169.
SLAB FEEDER	5915.
MASKING DEVICE	616.
T-STRIP MASK PACKAGE	58.
OXYGEN DISPENSER	49.
PANEL BAFFLE	76774.
SIDE BAFFLE	112534.
SIDE BAFFLE GUIDE	35.
SOFT SURFACE BELT	0.
MOTOR/DRIVE	3081.
END ROLLER	2465.
COOLING SYSTEM	4363.

PANEL ALIGNMENT & SPARE PANEL INSERTION

ACCELERATOR BELT	1725.
VARIABLE SPEED ROLLERS	76.
PANEL REMOVER	4037.
PANEL INSERTER	2218.
PANEL HOPPER	0.
SENSORS	35.
GUIDE ROLLERS	370.

PANEL INTERCONNECTION

ELECTROSTATIC WELDER	789.
INTERCONNECT FEEDER	1972.
INTERCONNECT ROLL	0.
SENSORS	7.
VARIABLE SPEED ROLLERS	9.
MOTOR	148.
GUIDE ROLLERS	25.

LONGITUDINAL CUT

LASER	1232.
KAPTON TAPE MAGAZINE	49.
GUIDE ROLLERS	12.
SHIELD	0.

KAPTON TAPE APPLICATION

STATIONARY TAPER	57.
STATIONARY TAPE REFILL	56812.
CROSS TAPER	44.
CROSS TAPE REFILL	7447.
SOFT ROLLER	0.
GUIDE ROLLERS	49.
CROSS TAPE NOTCH	44.

ARRAY SEGMENT FOLDING AND PACKAGING

GUIDE ROLLERS	68.
VERTICAL DEFLECTORS	88.
BOX ALIGNMENT	264.
BOX LABELING	0.
TRAILING EDGE GUIDE	44.

SOLAR CELL FACTORY MAJOR COST DRIVING FACTORS

LIFECYCLE COST: $ 4520513540.
COST OF SCF/SMF PER SPS PRODUCED: $ 228721184.
NUMBER OF SPS PRODUCED PER YEAR: 0.99

SCF DUTY CYCLE: .5781
ASSEMBLY OPERATION DUTY CYCLE: .9952
NUMBER OF PRODUCTION STRIPS 252.

PEOPLE TO SET UP SCF/SMF: 10.
COST TO SET UP SCF/SMF: $ 4636409.

YEARLY REFURBISHMENT PARTS (REPLACEMENTS+EXPENDABLES,KG): 1476406.
TOTAL SCF/SMF MASS(KG): 8815426.
PRODUCTION MACHINERY MASS(KG): 5496544.
NON PRODUCTION EQUIPMENT MASS(KG): 1294050.
HABITAT MASS(KG): 164160.
SOLAR POWER ARRAY MASS(KG): 1860672.

TOTAL SCF/SMF POWER(KW): 186067.
PRODUCTION MACHINERY POWER(KW): 183316.
NON PRODUCTION EQUIPMENT POWER(KW) 2266.
HABITAT POWER(KW): 486.

SCF WAREHOUSE VOLUME (CM): 11601.
MASS OF BUFFER REPLACEMENT PARTS IN WAREHOUSE(KG): 35309.
COST OF BUFFER REPLACEMENT PARTS IN WAREHOUSE $ 1106034.

NUMBER OF TELEOPERATORS: 1.
NUMBER OF CRAWLERS: 54.
TOTAL SCF/SMF CREW: 54.
SUPERVISORY CONTROL CREW: 33.
REPAIR CREW: 3.
SUPPORT CREW: 18.

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