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PHASE I OF THE AUTOMATED ARRAY ASSEMBLY TASK OF THE
LOW COST SILICON SOLAR ARRAY PROJECT

Technical Quarterly Report No. 6

MASTER

By
L. A. Grenon
M. G. Coleman

October 1977

Work Performed Under Contract No. NAS-7-100-954363

Motorola Incorporated
Semiconductor Group
Phoenix, Arizona

U.S. Department of Energy

Solar Energy

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PHASE I OF THE AUTOMATED ARRAY ASSEMBLY TASK
OF THE LOW COST SILICON SOLAR ARRAY PROJECT

Motorola Report No. 2258/7

Technical Quarterly Report No. 6

October 1977

JPL CONTRACT NO. 954363

PREPARED BY

L. A. Grenon and M. G. Coleman

MOTOROLA INC. SEMICONDUCTOR GROUP
5005 East McDowell Road
Phoenix, Arizona 85005

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Project NO. 2258

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1.0 SUMMARY

This report constitutes a detailed cost evaluation for solar cell module manufacturing. Emphasis in this analysis is applied to a critical appraisal of near term technology for application to the intermediate (1982) goal of \$2.00/watt.

The approach used in this cost analysis is to pursue a systematic examination of each of its many parts, and then to apply these parts to a final cost projection. In this approach, significant detail is generated; this is done in order to permit determination of the sensitivity to cost as a function of variations in the constituent parts of the analysis.

The first step of this approach is to define process sequences which can be used effectively to manufacture solar cell modules, starting with crystal growth and finishing with shipping of the completed module. The lowest common denominator of the approach is the single piece of equipment used in a particular process step. Input to the analysis from these many equipment items are: maximum capacity of the machine (wafers/hour) assuming 100% utilization; capital cost of the machine; labor required for each machine; area required for each machine including the access area around the machine; facility (electrical, exhaust, DH_2O) requirements for each machine, assuming a 100% duty cycle for each facility used; consumables used per machine (per year); and the efficiency of each machine, i.e., effective time the machine will operate compared to the total demand time (assuming demand is 100% of the available work hours). Additionally, each process step contains: a yield factor, i.e., the number of expected wafers out of the process step divided by the number of wafers put into the process step; a dollar per 1000 wafers, where appropriate, for expense and material items; a maintenance

requirement for equipment used in the process step. Using step yield figures, a cumulative yield for each process step of the process is determined. By inputting the desired annual production goal, the number of wafers that must be handled in each process step to achieve that goal can be calculated. From this initial calculation, the number of machines required for each step, the cost of those machines, direct labor requirements, and manufacturing area requirements can be determined. It is important to note that when selecting high capacity, state-of-the-art equipment, this equipment (and concomitant labor) may not be fully utilized when manufacturing volume is low. The sensitivity of cost as a function of volume is examined in this analysis.

After establishing the process used, factory support functions (overhead) must be evaluated. In this analysis, each category of overhead is examined with respect to the number of people required, their aggregate incomes (including fringe benefits), and the expenses, depreciation, materials and commissions incurred by these categories. Each category is determined to be either constant or variable as a function of time throughout the life of the factory, and manufacturing volume. Each area of the analysis is shown in detail to illustrate cost intensive items. In the sensitivity portion of the analysis, variables examined are annual production volume, cell efficiency, cell size, process type, polycrystalline silicon cost, interest rate, electrical power rate, and duration of each of the four phases in the life of the factory.

2.0 INTRODUCTION

Phase I of the Automated Array Assembly Task, LSSA Project, is concerned with a comprehensive assessment of the improvements in existing technology that may be needed to develop, within a period of no more than 10 years, an industrial capability of low cost, mass production of very durable silicon solar photovoltaic modules (and arrays).

This portion of the Phase I study involves the analysis of present technology as applied to the interim (1982) Project objective of \$2.00/peak watt.

3.0 TECHNICAL DISCUSSION

This report presents the results of a detailed cost analysis of a factory which manufactures flat plate silicon solar photovoltaic modules. The goal of this study is to evaluate the feasibility of establishing a factory which is capable of manufacturing solar cell modules to be sold profitably at \$2.00 per peak watt in 1982 (or earlier). Accordingly, the major emphasis of this study is placed on the utilization of near term technology.

3.1 ANALYSIS APPROACH

There are numerous approaches which could be chosen in the cost analysis of an as-yet unbuilt factory. Motorola, in this study, has chosen the option that the factory, equipment, direct labor, and overhead structures can be optimized for the specific function of manufacturing solar cell modules and need not be patterned after any existing factory. In addition, a very strong and basic assumption is made that the factory will manufacture only one standardized product, allowing complete redundancy for all processing equipment performing the same function.

3.1.1 TECHNOLOGY READINESS

The present study assumes that the desired factory will be manufacturing at full capacity in 1982 with a chosen technology. Due to 1) factory construction, 2) equipment purchase, construction, and installation, and 3) factory start-up (including personnel training) a significant lead time is necessary to achieve full capacity operation. The emphasis of the present

study, thus, is to include primarily manufacturing technology and equipment which is available in 1977, with any exceptions being technology now under development, but which will be secure no later than the end of 1978.

The technology readiness assumption has several significant areas of impact on costs. The most important result of this assumption is that the factory will have a limited useful life, ultimately being entirely replaced by an advanced technology which is capable of producing solar cells at a greatly reduced cost. Specifically, a factory which utilizes 1977 - 78 technology may be capable of \$2.00/peak watt in 1982, but will probably not be capable of \$1.00/watt in 1984 or \$.50/watt by 1986. Beyond fundamental technology constrictions, other impacts are seen. Utilization of near term technology (and limited factory life) implies only moderate automation. This, in turn, leads to higher labor costs than would be seen with more complete automation.

A further impact of 1977 - 1978 technology is related to module reliability considerations. With the goal of a minimum 20 year useful life, present technology dictates stringent encapsulation requirements to protect the solar cells, leading to appreciable encapsulation costs. While this may not change significantly with advanced technology developments, the possibility exists that solar cell structures, more reliable under harsh environments, or more effective cheap encapsulants, will evolve to result in lower costs.

In addition to identifying costs for 1982 manufacturing, a near term technology study provides an additional very important result: identification of areas in which technology advancement will be most fruitful for cost reduction in the next generation production plant. Technologies which have little or no possibility of meeting 1986 (and beyond) goals may be eliminated from further consideration.

3.1.2 MARKET AND FACTORY SIZE

This analysis first assumes that the factory under study will manufacture 25 megawatts in 1982 and that the entire factory is dedicated to a single product. This assumption, in turn, assumes that the market size is a minimum of 25 megawatts and that everything manufactured can be sold. The factory size assumption is made in order to assure that economies of scale, which optimize both equipment and labor, are utilized. (This assumption is later refined to allow variations in factory size in order to identify the cost dependence on factory size.)

A total market size in 1982 of 25 megawatts is a major increase over today's market. At \$2.00/watt, this market size means total sales of \$50 million. While this is large compared to current solar photovoltaic module sales, it is a small portion of today's total semiconductor market. The technologies utilized in solar cell manufacturing are closely related to those employed in the semiconductor industry. The technology driving force for the 1982 time frame, thus, is primarily the semiconductor industry. For later times, both larger markets and present (and future) government funded programs will contribute to larger technology advances for solar cell modules independent of the semiconductor industry.

3.2 SCOPE OF PRESENT STUDY

The present study is to determine whether or not \$2.00/peak watt is a reasonable goal for 1982 (or earlier). Included in this study are identification of specific equipment, proposed factory layouts, and specific process sequences.

Motorola, during this study, has performed multiple cost analyses from which broader conclusions may be drawn. First, three different process sequences have been analyzed, two processes utilizing today's technology and a third with an advanced, longer range technology yet to be completely developed. Today's technology process sequences are a diffusion based sequence and an ion implantation sequence incorporating machines presently available. The advanced process sequence looks at the effects of a much higher beam current ion implanter than is available today.

The cost analysis in each process sequence includes all steps following polycrystalline silicon formation. This analysis includes, thus, single crystal growth, crystal slicing, wafer preparation, cell processing, cell testing, module assembly and module testing. For the process sequences investigated in this study, effects of cell size are evaluated for the entire sequence. The individual process sequences studied involve variations in only the cell processing portion of an overall sequence, leaving both the substrate formation and encapsulation portions unchanged. The two basic cell processing sequences are listed in Tables 1 and 2. These process sequences have been discussed extensively in previous reports.

Three separate solar cell size options have been evaluated. Constraints imposed on these size options are that a single solar cell module, including borders, must fit within a 120 cm (~45") square and that the module must contain an integral number of series strings of solar cells having a minimum of 33 cells per string (to guarantee a 12V battery charging capability under worst case conditions). Each cell is assumed to have an encapsulated efficiency of 14%, representing a 15% base cell efficiency. This value is also treated as a variable, ranging from 5% to 20%, to measure cost sensitivity to this factor. The actual cell and module dimensions chosen are:

TABLE 1

SOLAR CELL DIFFUSION PROCESS SEQUENCE OUTLINE

1. Blanket P⁺ Diffusion, Oxide Growth
2. Front Strip and Texture Etch
3. N⁺ Diffusion
4. Mesa Etch
5. AR Coat
6. Front Pattern, Back Strip
7. Metal

TABLE 2

SOLAR CELL ION IMPLANTATION PROCESS SEQUENCE OUTLINE

1. Back Resist, Texture Etch
2. AR Coat
3. Front Pattern, Back Strip
4. Back I² - P⁺
5. Front I² (Masked) - N⁺
6. Activation Anneal
7. Metal

<u>CELL DIAMETER</u>	<u>MODULE</u>
7.6 cm	118 cm x 116 cm
12 cm	119 cm x 120 cm
12 cm, halved	110 cm x 113 cm

All of these sizes have been evaluated for each of the three process sequences.

Cost analyses are performed from single crystal growth through encapsulation. As a result of the 1977 - 1978 technology restriction, ingot crystal growth is assumed -- in particular, Czochralski crystal growth. This report first incorporates, as defined, a polycrystalline silicon cost of \$25.00/Kg, but varies this cost later in the study to observe total sensitivity to the cost of polycrystalline silicon.

Other parameters which affect costs have been varied in this analysis to identify their cost sensitivities. In addition to the annual production volume of the factory and the cost of polycrystalline silicon, interest rate, electrical power rate, production life of the factory, and the encapsulated solar cell efficiency have each been treated as variables to determine their influence on costs.

As stated earlier, no factory now exists which can be identified with this analysis. In order to achieve such a factory, it must be built, equipped, and staffed before full production capacity can be achieved. Accordingly, this analysis incorporates these start-up costs and treats each of the sequential phases as a cost item of variable duration.

3.3 ASSUMPTIONS

It is necessary to fix certain cost inputs and assumptions in order to perform a cost analysis. These input assumptions must be carefully scrutinized when comparing separate cost analysis studies or when making

absolute judgements concerning the validity of a particular cost analysis. This section presents the assumptions and cost inputs utilized by Motorola in this analysis.

3.3.1 DEFINITION OF COST CATEGORIES

In order to account for all of the costs associated with the factory, individual cost items are allocated to specific cost categories. Separate assumptions are made for each individual cost category, allowing ready examination of the costing basis of any item. The cost categories are listed and discussed in the following paragraphs. Specific assumptions for each category are then detailed in subsequent sections.

3.3.1.1 MATERIAL ITEMS

Items which appear in the final product and can be readily identified.

3.3.1.2 EXPENSE ITEMS

Items which are expended in the manufacture of product but do not appear in that product. Additional expense items not directly related to the manufacturing processes have been included in the Overhead category.

3.3.1.3 LABOR

Direct labor personnel salaries including burden and fringe benefits.

3.3.1.4 OVERHEAD ITEMS

This category contains all indirect labor, including such items as management, data processing, cafeteria, legal, training, etc. In addition, building services, indirect expense items, and all maintenance functions are included in this cost category.

3.3.1.5 INTEREST

Interest paid on all borrowed money.

3.3.1.6 DEPRECIATION

Depreciation on both buildings and capital equipment. Capital equipment is separated into that used directly for manufacturing, and that used for support functions.

3.3.2 CREATION AND LIFE OF THE FACTORY

This cost analysis assumes that the desired factory does not currently exist and must be started from the drawing-board. Four distinct phases of factory life have been identified: the building phase, equipment phase, labor training and build-up phase, and production phase.

3.3.2.1 PHASE I: BUILDING PHASE

In the building phase, a minimum staff is required to supervise the design and construction of the facility. These personnel and their several expenses are included in the first phase overhead section. Operating capital must be borrowed to pay these overhead expenses, construct the factory, and pay interest on this money during the first phase. Equipment is identified and ordered during this phase but no equipment capital is expended.

3.3.2.2 PHASE II: EQUIPMENT PHASE

In the equipment phase, all capital equipment is purchased and installed. The debt incurred in Phase I is carried into this phase. Additionally, that debt must be increased to include capital equipment expenditures as well as Phase II expense, overhead, and interest costs.

3.3.2.3 PHASE III: LABOR PHASE

During this period, the labor force is built-up and trained such that, at its conclusion, the factory is capable of running at full capacity. As in Phase II, all debts previously incurred must be included in this, the Labor Phase. Phase III material, expense, labor, overhead, and interest costs must be added to the overall debt. Although some revenue is realized from product manufactured in this phase, it is assumed that it will occur at the end of the phase and not significantly effect the magnitude of the debt.

3.3.2.4 PHASE IV: PRODUCTION PHASE

The factory is defined as running at full manufacturing capacity during this phase. At the end of this phase, there is no tapering down of the operation -- production is assumed to cease abruptly.

During this phase, income from the sale of product will be realized. It is assumed that the sum of all debts incurred in the first three phases and the debt incurred in this phase will be paid on a straight line basis over the duration of Phase IV. As a result, for the purposes of calculating interest, it is assumed that on the average half the total debt is owed over the entire duration of this phase.

3.3.2.5 FACTORY LIFE SUMMARY

The cost and income categories utilized during the four factory phases described in the previous sections are represented schematically in Figure 1. In the detailed cost analysis, each phase is treated separately. Further, the duration of each phase is treated as a variable, allowing sensitivity to each phase for the cost of the final solar cell modules to be studied.

FIGURE 1: A SCHEMATIC REPRESENTATION OF COSTS AND INCOME DURING EACH PHASE OF THE FACTORY LIFE.

3.3.3 GENERAL INPUTS AND ASSUMPTIONS

In addition to specific assumptions which can be identified with each cost category, listed in later sections, certain general assumptions and inputs must be made to form a basis for the factory. These general assumptions are listed below:

1. The factory produces only one product and supplies less than ten customers.
2. Annual production level: Treated as a variable, but 25 megawatts unless otherwise stated.
3. Solar cell efficiency: Treated as a variable, but 14% encapsulated (15% bare) unless otherwise stated.
4. Solar cell efficiency is independent of cell area.
5. Insolation assumed at 1 kilowatt/M² (peak).
6. Silicon wafer thickness, as sawn, is 0.008 inch.
7. Wafer diameters; 7.6 cm, 12.0 cm, and halved 12.0 cm.
8. Only one module type fabricated in the factory, chosen from three options dependent upon the cell size.
9. Total work days/year = 240, (260 - 20, vacation, holidays, etc.)

3.3.4 MATERIALS AND EXPENSE ASSUMPTIONS

The costs and sizes of specific items utilized in this analysis are listed below:

MATERIALS

Polycrystalline silicon

Treated as a variable, but
\$25.00/Kg unless otherwise
stated.

Cold Rolled Steel	-	\$0.225/lb (0.020 inch thick), \$0.204/lb (0.030 inch thick), based on 99% yield and density of 7.83 g/cm ³ .
Nylon Coating	-	0.003 inch powder coating at \$0.0225/mil/ft ² .
Glass	-	3/16 inch clear tempered glass at \$10.91/4 ft. x 4 ft. sheet, 99% yield.
Silicone	-	0.009 inch thick, \$3.75/lb (in 800 lb. drums) at 8 lbs/ gallon.
Polysulfide gasket	-	\$0.60 (based on \$6/gallon).
Interconnect	-	\$0.60/ft ² , 99% yield.
Feedthroughs	-	\$0.60, (2 at \$0.30 each).
<u>D.I. WATER</u>		
Volume Rate	-	\$0.0031/gal.
<u>ELECTRICITY</u>		
Power rate	-	Treated as a variable, but \$0.025/kilowatt-hour unless otherwise stated.
<u>ACIDS</u>		
Hydrofluoric	-	\$ 2.90/Gal.
Acetic	-	\$ 3.95/Gal.
Nitric	-	\$ 2.45/Gal.
Hydrochloric	-	\$ 2.97/Gal.

Sulfuric	-	\$ 2.45/Gal.
Buffered Hydrofluoric	-	\$ 2.95/Gal.
Waste Treatment	-	\$ 0.0020/Gal. X DIH ₂ O consumptic

SOLVENTS

isopropyl Alcohol	-	\$ 1.05/Gal.
Acetone	-	\$ 1.15/Gal.
Butyl Acetate	-	\$ 2.60/Gal.
VMP	-	\$ 0.75/Gal.
Photoresist (44 cps)	-	\$55.19/Gal.
Deionized Water (DIH ₂ O)	-	\$ 0.0031/Gal.
J100	-	\$ 7.25/Gal.

GASES

Nitrogen	-	\$ 0.0033/CF
Argon	-	\$ 0.1172/CF
Oxygen	-	\$ 0.002/CF
BCl ₃	-	\$10.6061/CF
PH ₃	-	\$28.0702/CF
Hydrogen	-	\$ 0.044/CF
H ₂ SiCl ₂	-	\$ 0.6331/CF
NH ₃	-	\$ 1.0619/CF

SOLUTIONS

Nickel Plating	-	\$ 0.48/liter
Palladium Plating	-	\$ 2.137/liter
Texture Etching	-	\$ 2.38/Gal.

IMPLANT SOURCES

Enriched Boron	-	\$200/lb.
Phosphorous	-	\$ 2.76/gram

3.3.5 DIRECT LABOR ASSUMPTIONS

A number of assumptions are made for direct labor, many of which are also utilized for indirect labor. As discussed in the overhead assumptions, Section 3.3.8, however, each labor category has its own salary assumption.

1. One work day = 3 shifts = 22.5 work hours; (24-1.5 lunch)
2. First shift, second shift, third shift - 8, 8, 6.5 hrs. respectively
3. Second and third shift premium = 10%
4. First shift salary rate = \$4.00/hour
(Rate with burden and fringes = \$5.96/hour)
5. Absentee/turnover time loss factor = 5%
6. Miscellaneous laboratory supplies (paper towels, record forms, pencils, etc.), protective clothing, and safety equipment are assumed to be \$325/year for each direct labor employee.

Examples of burden and fringe accounts are given below:

TABLE 3
BURDEN ACCOUNTS
(EXAMPLES)

1. Utility Operators
2. Employee Instruction time
3. Set-up time
4. Clean-up time
5. Coffee breaks and rest room time
6. Material handling and transfer
7. Data compilation and transfer

TABLE 4

EMPLOYEE FRINGES
(EXAMPLES)

1. Vacation
2. Holiday
3. Retirement Fund
4. Insurances
5. Cafeteria
6. F.I.C.A.
7. Unemployment Taxes
8. Credit Union
9. Employee Sales
10. Recreation Activities

3.3.6 BUILDING, DEPRECIATION, AND INTEREST ASSUMPTIONS

Assumptions utilized in determining building, depreciation, and interest costs are listed below:

1. Construction cost for production space is \$80/sq. ft.
2. Construction cost for support space is \$30/sq. ft.
3. Depreciation on building: Straight line for 40 years.
4. Depreciation on manufacturing equipment: Straight line over life of factory, starting after equipment is installed (at the end of Phase 2).
5. Depreciation on support equipment: Straight line for eight years.
6. Interest rate: Treated as a variable but 7% unless otherwise stated.

7. Building and support equipment sold at end of production phase to exactly offset closedown costs.

3.3.7 PROCESS STEP AND EQUIPMENT SPECIFICATIONS AND ASSUMPTIONS

This section defines the equipment specifications and assumptions for each process step utilized in all of the process sequences. Since the number of individual process steps is large, a common format is utilized for consistency. Each step is numbered for identity in the final costing data. The format utilized is as follows:

CAPITAL EQUIPMENT ASSUMPTIONS

- Type of equipment (Manufacturers model where possible)*
- Cost of equipment
- Maximum capacity of equipment (showing calculations)
- Floor space requirements (equipment and aisle and work area)
- Labor requirement

EXPENSE ITEMS

- Equipment facility requirements (electrical, exhaust, water, gases, etc.)
- Chemical and material consumption (showing calculations)
- Parts used on equipment requiring periodic replacement
- Non capitalized items necessary to perform the process (e.g., furnace tubes, beakers, etc.)

MATERIAL ITEMS

- Items appearing in finished product, (e.g., silicon, metal, module parts).

*

The specification of a given manufacturer does not necessarily mean that Motorola would prefer that manufacturer or equipment item over a competitive product. In most cases, competitive equipment exists and may be comparable or superior. Identification in this report, however, allows substantiation of information and allows direct comparison with other possible choices to determine suitability of the cost assumptions with those of other cost analysis studies.

3.3.7.1 STEP 1, CRYSTAL GROWTH

Capital Equipment Assumptions

For these calculations, a Hamco CG 2000 Czochralski crystal puller costing \$125K is used. The maximum capacity of this equipment is a 60 inch pull length and 20 Kg charge. Pulling rates are assumed to be 1 Kg/hour for 7.6 cm diameter crystals and 1.5 Kg/hour for 12 cm diameter crystals. Floor space is 40 ft². One operator can run three crystal pullers. In order to determine the usable crystal from this equipment, the following assumptions are made.

- 7.6 cm diameter cells are cut from a crystal which is grown to a diameter = $7.6 \text{ cm} \pm \frac{.6350 \text{ cm}}{.0000}$ (7.9175 cm diameter average)
- 12 cm diameter cells are cut from a crystal which is grown to a diameter = $12 \text{ cm} \pm \frac{.6350 \text{ cm}}{.0000}$ (12.3175 cm diameter average)
- the cropping from the tapered upper portion of the crystal will have a length of d (equal to the diameter) and an approximate volume of $\pi d^3/8$.
- the cropping from the tapered bottom portion of the crystal will have a length of d and an additional cropping from the cylindrical portion, also of length d, will result in a total cropped length of 2d and an approximate volume of $3\pi d^3/8$.
- only the portion cropped from the top of the crystal will be reclaimed.

Crystal Growth Calculations

Definition of Symbols:

$$\rho_{\text{Si}} = \text{Density of silicon} = 2.33 \text{ g/cm}^3$$

$$M = \text{Mass of crucible charge (maximum of 20 Kg)}$$

$$V_1 = \text{Volume of cropped upper end} = \frac{\pi d^3}{8}$$

$$V_2 = \text{Volume of useful portion of crystal} = \frac{\pi d^2 L}{4}$$

$$V_3 = \text{Volume of cropper lower end} = \frac{3\pi d^3}{8}$$

L = Length of useful portion of crystal

d = Diameter (average) of as-grown crystal

Calculations

$$(\rho_{Si}) \left(\frac{V_1 + V_2 + V_3}{M} \right) = 1$$

$$(\rho_{Si}) \left(\frac{\frac{\pi d^3}{8} + \frac{\pi d^2 L}{4} + \frac{3\pi d^3}{8}}{M} \right) = 1$$

$$L = \frac{1 - (\rho_{Si}) \left(\frac{\pi d^3}{2M} \right)}{(\rho_{Si}) \left(\frac{\pi d^2}{4M} \right)}$$

or

$$M = (\rho_{Si})(V_1 + V_2 + V_3) = \left(\rho_{Si} \right) \left(\frac{\pi d^3}{2} + \frac{\pi d^2 L}{4} \right)$$

For the 7.6 cm diameter cell,

d = 7.9175 cm (average), giving

L = 158.5 cm = 62.4 inches (for M = 20 Kg).

Since the maximum pull length of the crystal growth machine is 60 inches, this limits the actual growth of the crystal. Accordingly, the maximum actual useful crystal length is the equipment limitation minus the cropped end lengths.

$$L = 60 \text{ inches} - 3d$$

$$L = 50.65 \text{ inches} = 128.65 \text{ cm}$$

Solving for the useful melt size,

$$M = 16.57 \text{ Kg}$$

Following growth, the crystal is cropped and ground to a diameter of 7.6 cm.

The resultant volume is the usable crystal for subsequent sawing. That volume has a mass of 13.6 Kg, representing 82% of the original polycrystalline silicon melt material.

For the 12 cm diameter cell,

$d = 12.3175 \text{ cm}$ (average), giving

$L = 47.40 \text{ cm} = 18.7 \text{ inches}$ (for $M = 20 \text{ Kg}$).

This length, utilizing a 20 Kg melt, is much shorter than the capacity of the crystal puller and hence is crucible limited. This will eventually lead to larger crucibles or multiple pull techniques. For this analysis, however, the conservative assumption will utilize single pulls and 20 Kg melts. Following growth, cropping and grinding, the amount of usable silicon crystal prior to sawing is 12.49 Kg, representing 62.5% of the original melt.

The crystal growth cycle is specified below:

	7.6 cm Diameter (Minutes)	12 cm Diameter (Minutes)
Charge, pump down	90	90
Melt down	120	120
Stabilize	30	30
Pull time		
neck	30	30
shoulder	60	60
straight	885 (1 Kg/hr)	526 (1.5 Kg/hr)
end	90	90
Cool down	120	120
Crystal removal - clean up	90	90
	<hr/>	<hr/>
SUB TOTAL	1515	1156
X 1.05 for maintenance and repair =	1591 minutes	1215 minutes
=	<u>26.5 hours</u>	<u>20.25 hours</u>

Using the growth rates calculated in this section and the sawing parameters of step 4 (Section 3.3.7.4), the crystal growth capacity is shown below in wafer equivalent form.

$$7.6 \text{ cm: } \frac{1 \text{ wafer}}{.0155''} \times \frac{50.65''}{\text{crystal}} \times \frac{1 \text{ crystal}}{26.50 \text{ hrs.}} = 123.25 \text{ wafers/hour}$$

$$12 \text{ cm: } \frac{1 \text{ wafer}}{.0155''} \times \frac{28.7''}{\text{crystal}} \times \frac{1 \text{ crystal}}{20.25 \text{ hrs.}} = 59.50 \text{ wafers/hour}$$

Expense Items

Facility requirements are:

Electrical	55 KW
Exhaust	40 CFM
Argon	35 SCFH
Chilled H ₂ O	30 GPM

Additional expense items include:

Crucible (12")	\$47 for each crystal
----------------	-----------------------

3.3.7.2 STEP 2: CRYSTAL GRIND

Capital Equipment Assumptions

Grinding of the crystal to 7.6 cm or 12 cm diameter is necessary both for subsequent processing and for module informity. Grinding equipment costing \$50K is capable of handling lengths of 40 inches/hour for 7.6 cm diameter crystals and 25 inches/hour for 12 cm diameter crystals. This equipment requires 97 ft² and one operator can control four grinders. The maximum length capacity for a single crystal is 23".

Expense Items

Facility Requirements

Electrical	1.5 KW
Exhaust	40 CMF

Additional expense items include:

Grinder coolant @ \$3/m² of crystal surface

Silicon lost during the grinding operation is considered an

expense item - in this step, it is assumed that the crystal

is grown to an average diameter of 7.9175 cm or 12.3175 cm and ground to a final diameter of 7.6 cm or 12 cm respectively. The length of the crystal is either 128.65 cm or 47.40 cm respectively. From these numbers, the volume of wasted silicon from the grinding operation can be calculated. The volume of silicon ground off is the volume of the useful as-grown crystal minus the volume of the crystal ground to size.

Definition of Terms

V_G	=	Volume lost during grinding
M_G	=	Mass of ground crystal
d_I	=	As-grown diameter
d_F	=	Final crystal diameter
L	=	Length of useful portion of silicon
t	=	Thickness of as-sawn wafer <u>plus</u> thickness of sawing kerf
N_G	=	Number of wafers/crystal
ρ_{Si}	=	Density of silicon ($2.33 \text{ g (cm}^3\text{)}$)
P_p	=	Price of polycrystalline silicon (\$/Kg)
C_G	=	Cost of ground-off crystal surface-material/1000 wafers

Calculations

$$V_G = \frac{\pi L}{4} (d_I^2 - d_F^2)$$

$$M_G = V_G \rho_{Si}$$

$$N_G = \frac{L}{t}$$

$$C_G = \left(\frac{M_G}{N_G} \right) (P_p)(1000)$$

For the 7.6 cm diameter cell

$$V_G = \frac{\pi (128.65 \text{ cm}) [(7.9175 \text{ cm})^2 - (7.6 \text{ cm})^2]}{4}$$

$$V_G = 497.8 \text{ cm}^3$$

$$M_G = (497.8 \text{ cm}^3)(2.33 \text{ g/cm}^3) = 1.16 \text{ Kg}$$

$$N_G = \frac{(128.65 \text{ cm})}{(0.0394 \text{ cm/wafer})} = 3267 \text{ wafers}$$

$$C_G = \left(\frac{1.16 \text{ Kg}}{3267 \text{ wafers}} \right) (P_p)(1000) = \$0.355 P_p \text{ per 1000 wafers}$$

For the 12 cm diameter cell

$$V_G = \frac{\pi (47.40 \text{ cm}) [(12.3175 \text{ cm})^2 - (12.0 \text{ cm})^2]}{4}$$

$$V_G = 287.4 \text{ cm}^3$$

$$M_G = (287.4 \text{ cm}^3)(2.33 \text{ g/cm}^3) = 0.670 \text{ Kg}$$

$$N_G = \frac{(47.4 \text{ cm})}{(0.0394 \text{ cm/wafer})} = 1204 \text{ wafers}$$

$$C_G = \left(\frac{0.670 \text{ Kg}}{1204 \text{ wafers}} \right) (P_p)(1000) = \$0.556 P_p \text{ per 1000 wafers}$$

3.3.7.3 STEP 3: CRYSTAL CROPPING

Capital Equipment Assumptions

Crystals to be sawed into wafers must first be cropped and sawed into appropriate length pieces to fit into the wafer sawing apparatus. The equipment used to perform this operation is an O.D. diamond saw costing approximately \$8000 including the necessary fixtures. Floor space is expected to be 40 ft². Cutting time is based on 3"/minute plus 30 seconds/cut set-up time.

Expense Items

Facility requirements include:

Electrical = 6 KW

Exhaust = 100 CFM

Additionally, blades must be replaced after 10,000 cuts. Assuming 14 cuts for 7.6 cm diameter crystals and 6 cuts for 12 cm diameter crystals which result in 3267 wafers and 1204 wafers respectively then 2333571 and 2006667 wafer equivalents can be expected for each \$425 blade resulting in a blade expense of \$0.1821 per thousand wafers for 7.6 cm diameter crystals and \$0.2118 per thousand wafers for 12 cm diameter crystals.

In this step, the upper and lower portions of the crystal are removed, each having volumes of $\pi d^3/8$ and $3\pi d^3/8$ respectively, with $d = 7.9175$ or 12.3175 cm. If the upper portion of the crystal is reclaimed for remelt, the resultant loss of silicon from the lower end is then $3\pi d^3/8$.

Definition of Terms

V_3	=	Volume of lower cropped end
M_3	=	Mass of cropped lower crystal end
ρ_{si}	=	Density of silicon
N_G	=	Number of wafers/crystal
t	=	Thickness of as-sawn wafer plus thickness of sawing kerf
L	=	Length of useful portion of silicon crystal
d_i	=	As-grown diameter of crystal
P_p	=	Price of polycrystalline silicon (\$/Kg)
C_3	=	Cost of cropped lower end of crystal/1000 wafers

Calculations

$$V_3 = \frac{3\pi d_i^3}{8}$$

$$M_3 = V_3 \rho_{si}$$

$$N_G = \frac{L}{t}$$

$$C_3 = \left(\frac{M_3}{N_G} \right) (P_p) (1000)$$

For the 7.6 cm diameter solar cell,

$$V_3 = \frac{3\pi (7.9175 \text{ cm})^3}{8} = 584.7 \text{ cm}^3$$

$$M_3 = (584.7 \text{ cm}^3)(2.33 \text{ g/cm}^3) = 1.362 \text{ Kg}$$

$$N_G = 3267 \text{ wafers (from process step \#2 calculations)}$$

$$C_3 = \left(\frac{1.362 \text{ Kg}}{3267 \text{ wafers}} \right) (P_p)(1000)$$
$$= \$0.417 P_p \text{ per 1000 wafers}$$

For the 12 cm diameter solar cell,

$$V_3 = \frac{3\pi (12.3175 \text{ cm})^3}{8} = 2202 \text{ cm}^3$$

$$M_3 = (2202 \text{ cm}^3)(2.33 \text{ g/cm}^3) = 5.13 \text{ Kg}$$

$$N_G = 1204 \text{ wafers (from process step 2 calculations)}$$

$$C_3 = \left(\frac{5.13 \text{ Kg}}{1204 \text{ wafers}} \right) (P_p)(1000)$$
$$= \$4.26 P_p \text{ per 1000 wafers}$$

3.3.7.4 STEP 4: CRYSTAL SAWING

Capital Equipment Assumptions

The sawing operation will require a wire saw which costs \$30K for cutting 7.6 cm diameter crystals and \$35K for cutting 12 cm diameter crystals. It will need a 40 ft² floor space and 0.1 and 0.05 operators per saw respectively. 7.6 cm wafers will be cut at the rate of 86 wafers/hour. 12 cm wafers will be cut at the rate of 34.4 wafers/hour. As-cut wafer thickness is 9.02032 cm (8 mils).

Expense Items

Facility requirements:

Electrical	1 KW
Raw Water	1 gpm

Kerf loss for a saw cut is assumed to be 0.01905 cm (7.5 mil) for all crystal diameters). The number of cuts to produce 1000 wafers will be 999.

Definition of Terms

V_K	=	Volume of kerf/1000 wafers
N_K	=	Number of cuts/1000 wafers
d_F	=	Diameter of final crystal
P_p	=	Price of polycrystalline silicon (\$/Kg)
ρ_{si}	=	Density of silicon = 2.33 g/cm ³
t_K	=	Thickness of kerf per cut
C_K	=	Cost of kerf silicon/1000 wafers

Calculations

$$V_K = \frac{N_K t_K \pi d_F^2}{4}$$

$$C_K = V_K \rho_{si} P_p$$

For the 7.6 cm diameter solar cell,

$$V_K = (999 \text{ cuts}) \left(\frac{0.01905 \text{ cm}}{\text{cut}} \right) \left(\frac{\pi}{4} \right) (7.6 \text{ cm})^2$$

$$V_K = 863.3 \text{ cm}^3$$

$$C_K = (863.3 \text{ cm}^3) (2.33 \text{ g/cm}^3) (1 \text{ Kg}/1000 \text{ g}) P_p$$

$$C_K = \$2.01 P_p \text{ per 1000 wafers}$$

For the 12 cm diameter solar cell,

$$V_K = (999 \text{ cuts}) \left(\frac{0.01905 \text{ cm}}{\text{cut}} \right) \left(\frac{\pi}{4} \right) (12 \text{ cm})^2$$

$$V_K = 2152 \text{ cm}^3$$

$$C_K = (2152 \text{ cm}^3) (2.33 \text{ g/cm}^3) (1 \text{ Kg}/1000 \text{ g}) P_p$$

$$C_K = \$5.01 P_p \text{ per 1000 wafers}$$

Additional major expense items are the cost of supplies used during the sawing operation which include slurry, wire, wire guides, and miscellaneous supplies. These expenses total \$13.79 per square meter of silicon wafers.

3.3.7.5 STEP 5: CLEAN ETCH

Capital Equipment Assumptions

This process step is intended to remove from the silicon wafers damage induced during the sawing operation. An in-line ultrasonic tank containing a caustic etch will be used. This equipment costs \$75K, requires one operator and 360 ft^2 ; 228 wafers can be cleaned and etched in 10 minutes resulting in a process rate of 1368 wafers/hour.

Expense Items

Facility requirements are:

Electrical	10 KW
Exhaust	600 CFM
DIH ₂ O	5 gpm

In this process step, 0.5 mil will be etched from both sides of each wafer resulting in a 1 mil (.00254 cm) silicon loss per wafer.

An additional expense item is the caustic etch. 15% NaOH:H₂O will be used in a 22 gal. tank, changed daily and costing \$0.05/gal. = \$5000/year.

Definition of Terms

t_W	=	Thickness of final wafer
t_E	=	Thickness of silicon etched from sawed wafer
d_F	=	Final Diameter of wafer
ρ_{si}	=	Density of silicon
V_E	=	Volume of etched silicon/1000 wafers
P_p	=	Price of polycrystalline silicon (\$/Kg)
C_E	=	Cost of etched-away silicon/1000 wafers

V_W = Volume of wafers after etching/1000 wafers

C_W = Cost of silicon in final wafers/1000 wafers

Calculations

$$V_E = (t_E) \left(\frac{\pi d_F^2}{4} \right) (1000)$$

$$C_E = V_E \rho_{si} P_p$$

$$V_W = (t_W) \left(\frac{\pi d_F^2}{4} \right) (1000)$$

$$C_W = V_W \rho_{si} P_p$$

For the 7.6 cm diameter solar cell,

$$V_E = (2.54 \text{ cm}) \left(\frac{\pi}{4} \right) (7.6 \text{ cm})^2$$

$$V_E = 115.23 \text{ cm}^3$$

$$C_E = (115.23 \text{ cm}^3)(2.33 \text{ g/cm}^3) P_p (1 \text{ Kg}/1000 \text{ g})$$

$$C_E = \$0.268 P_p \text{ per 1000 wafers}$$

For the 12 cm diameter solar cell,

$$V_E = (2.54 \text{ cm}) \left(\frac{\pi}{4} \right) (12 \text{ cm})^2$$

$$V_E = 287.3 \text{ cm}^3$$

$$C_E = (287.3 \text{ cm}^3)(2.33 \text{ g/cm}^3) P_p (1 \text{ Kg}/1000 \text{ g})$$

$$C_E = \$0.669 P_p \text{ per 1000 wafers}$$

Material Items

Silicon wafers are treated in this step, for the first and only time, as a material item. Wafer thickness is assumed to be 7 mil (0.0178 cm).

For the 7.6 cm diameter wafer,

$$V_W = (17.8 \text{ cm}) \left(\frac{\pi}{4} \right) (7.6 \text{ cm})^2$$

$$\begin{aligned}
 V_W &= 807.5 \text{ cm}^3 \\
 C_W &= (807.5 \text{ cm}^3)(2.33 \text{ g/cm}^3) P_p (1 \text{ Kg}/1000 \text{ g}) \\
 C_W &= \$1.88 P_p \text{ per 1000 wafers}
 \end{aligned}$$

For the 12 cm diameter wafer,

$$\begin{aligned}
 V_W &= (17.8 \text{ cm}) \left(\frac{\pi}{4}\right) (12 \text{ cm})^2 \\
 V_W &= 2013 \text{ cm}^3 \\
 C_W &= (2013 \text{ cm}^3)(2.33 \text{ g/cm}^3) P_p (1 \text{ Kg}/1000 \text{ g}) \\
 C_W &= \$4.69 P_p \text{ per 1000 wafers}
 \end{aligned}$$

3.3.7.6 STEP 6: CENTRIFUGE

Capital Equipment Assumptions

Cost estimates are based on the use of a Fluoroware K-100 rinser-dryer with a #1150 frame and a #1231 cradle, all of which are intended to process 7.6 cm diameter wafers. This apparatus will hold six 25 wafer cassettes and cost \$2500. Use of a different cradle will allow the processing of four 25 wafer (12 cm diameter) cassettes for the same price. For both wafer diameters, a 15 minute cycle time (including load and unload) will be assumed, resulting in throughput of:

For 7.6 cm diameter wafers,

$$\frac{25 \text{ wafers}}{\text{cassette}} \times \frac{6 \text{ cassettes}}{\text{machine}} \times \frac{4 \text{ runs}}{\text{hour}} = \frac{600 \text{ wafers}}{\text{machine-hour}}$$

For 12 cm diameter wafers,

$$\frac{25 \text{ wafers}}{\text{cassette}} \times \frac{4 \text{ cassettes}}{\text{machine}} \times \frac{4 \text{ runs}}{\text{hour}} = \frac{400 \text{ wafers}}{\text{machine-hour}}$$

Floor space required for this equipment is estimated to be 30 ft².
One operator will run four units.

Expense Items

Facility requirements include:

Electrical	1 KW (115 VAC - 8.5 A)
DH ₂ O	1.6 GPM @ 40 psi
N ₂	13.2 l/min @ 40 psi

Assume two wafer carriers for each slot in the cradle, one in use and one being loaded or unloaded.

7.6 cm: 12 carriers x \$19.20/carrier = \$230.40/machine

12 cm: 8 carriers x \$32.00/carrier = \$256.00/machine

3.3.7.7 STEP 7: TEXTURE ETCH

Capital Equipment Assumptions

Equipment used in the texture etch process includes a six foot laminar flow exhaust hood (IAS LV6 - 30X) containing six etch tanks (7" wide x 6" deep x 20" long) and a chemical recirculating system (Fluorocarbon Model 5000) which is used to maintain the etch integrity. The cost of the hood is \$4500 and the recirculating system costs \$7500 resulting in a total system cost of \$12K. Assuming a one hour process time:

$$7.6 \text{ cm cell: } \frac{50 \text{ wafers}}{\text{carrier}} \times \frac{4 \text{ carriers}}{\text{sink}} \times \frac{6 \text{ sinks}}{\text{hood}} = \frac{1200 \text{ wafers}}{\text{hour}}$$

$$12 \text{ cm cell: } \frac{50 \text{ wafers}}{\text{carrier}} \times \frac{3 \text{ carriers}}{\text{sink}} \times \frac{6 \text{ sinks}}{\text{hood}} = \frac{900 \text{ wafers}}{\text{hour}}$$

Floor space is 45 ft² and one operator is necessary for two such hoods.

Expense Items

Facility requirements include:

Electrical 1.6 KW

Exhaust 500 CFM

Assumptions used in the cost analysis for chemicals are as follows:

7.6 cm: Displacement of carrier and 50 wafers is 300 cm^3 .

Assuming a liquid level of 4" when four loaded carriers are placed in the tank, then:

$$\left(\frac{9177 \text{ cm}^3}{\text{tank}} - \frac{300 \text{ cm}^3}{\text{carrier}} \right) \times \left(\frac{4 \text{ carriers}}{\text{tank}} \right) \times \frac{6 \text{ tanks}}{\text{hood}} \times \frac{2.64 \times 10^{-4} \text{ gal}}{\text{cm}^3} = \frac{12.6356 \text{ gal}}{\text{hood}}$$

Utilizing a recirculating system to maintain etch solution integrity, it is assumed that, on the average, the entire solution will be replaced every four days, which results in 60 annual chemical replacements. Therefore:

$$\frac{12.6356 \text{ gal}}{\text{hood}} \times \frac{\$2.38}{\text{gal.}} \times \frac{60}{\text{year}} = \frac{\$1803}{\text{year}} \text{ (chemical cost) per hood}$$

= \$0.28/1000 wafer if the equipment is fully utilized.

12 cm: Displacement of carrier and 50 wafers is 515 cm^3 .

Assuming a liquid level of 6" when three loaded carriers are placed in the tank, then:

$$\left(\frac{13765 \text{ cm}^3}{\text{tank}} - \frac{515 \text{ cm}^3}{\text{carrier}} \right) \times \left(\frac{3 \text{ carriers}}{\text{tank}} \right) \times \frac{6 \text{ tanks}}{\text{hood}} \times \frac{2.64 \times 10^{-4} \text{ gal}}{\text{cm}^3} = \frac{19.3567 \text{ gal.}}{\text{hood}}$$

Using the same assumptions as for 7.6 cm wafers,

$$\frac{19.3567 \text{ gal}}{\text{hood}} \times \frac{\$2.3783}{\text{gal.}} \times \frac{60}{\text{year}} = \frac{\$2762}{\text{year}} \text{ (chemical costs) per hood}$$

= $\frac{\$0.57}{1000 \text{ wafers}}$ if the equipment is fully utilized.

Additional expense items include:

Carriers:

$$7.6 \text{ cm: } 2 \times \frac{4 \text{ carriers}}{\text{sink}} \times \frac{6 \text{ sink}}{\text{hood}} \times \frac{\$19.20}{\text{carrier}} = \$921.60/\text{year per hood}$$
$$= \$0.14/1000 \text{ wafers if fully utilized.}$$

$$12 \text{ cm: } 2 \times \frac{3 \text{ carriers}}{\text{sink}} \times \frac{6 \text{ sink}}{\text{hood}} \times \frac{\$32.00}{\text{carrier}} = \$1152.00/\text{year per hood}$$
$$= \$0.24/1000 \text{ wafers if fully utilized.}$$

Quartzware: Assume $\$1/\text{in}^2$ for quartz liners which results in

$$\frac{464 \text{ in}^2}{\text{liner}} \times \frac{6 \text{ liners}}{\text{hood}} \times \frac{\$1}{\text{in}^2} = \$2784/\text{hood}$$

These liners should have a two year life resulting in \$1392/year cost. The liner cost is thus \$0.21/1000 wafers (7.6 cm) and \$0.27/1000 wafers (12 cm) assuming 100% equipment utilization.

3.3.7.8 STEP 8: COAT, BAKE, AND STEP 11: ETCH STOP APPLY

Capital Equipment Assumptions

Equipment specified for this process is a Macronetics coater-oven unit capable of containing four separate tracks, each costing \$13,365. Additional costs for this unit are a cabinet costing \$3,000 and a hood (IAS LV10-30) costing \$2,500. Assuming a complete, four track unit, total capital cost of \$58,960. Each track is capable of processing 250 wafers/hour and a unit will require 80 ft². One operator can control two four track systems.

Expense Items

Facility requirements are:

Electrical	1.1 KW + 2.5 KW/track
Exhaust	120 CFM/track

Additional expense items include the cost of photoresist. For this analysis, it is assumed that an excess of resist is used while coating and that both 7.6 cm and 12 cm diameter wafers can be coated at 9470 wafers/gallon. Cost of the photoresist is \$55.19/gallon resulting in an expense of \$5.83/1000 wafers.

All assumptions apply to both process steps (8 and 11).

3.3.7.9 STEP 9: ALIGN, EXPOSE

Capital Equipment Assumptions

A Kasper 2001P aligner with automatic loading, costing \$30,000, has been specified for this operation. A hood costing \$1250 will be used for this equipment, and total capacity is assumed to be 200 wafers/hour. Floor space is 40 ft² and one operator is required for each aligner.

Expense Items

Facility requirements are:

Electrical	1.5 KW
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Exposure lamps which have an average life of 1500 operating hours and cost \$42 add \$151.20/year to the operating expenses - \$0.14/1000 wafers.

3.3.7.10 STEP 10: DEVELOP, BAKE

Capital Equipment Assumptions

This process step utilizes a Macronetics developer-oven unit capable of containing four separate tracks, each costing \$13,100. Additional costs for this unit are a cabinet costing \$3,000 and a hood (IAS LV10-30) costing \$2,500. Assuming a complete, four track unit, total capital cost is \$57,900.

Each track is capable of processing 250 wafers/hour and a unit will require 80 ft². One operator can control eight individual tracks (or two systems).

Expense Items

Facility requirements are:

Electrical	1.1 KW + 2.5 KW/track
Exhaust	120 CFM/track

Additional expense items include the cost of developer at \$1.675/gallon. This developer can process 240 wafers (7.6 cm or 12 cm diameter) resulting in a \$6.98/1000 wafer expense.

3.3.7.11 STEP 12: BORON DIFFUSION

Capital Equipment Assumptions

This process step assumes a Thermco eight-tube diffusion module, Type 4000S72 per Spec 19000 with load station, source cabinets and appropriate options at \$49,271. Process controllers are estimated to be \$2,000/tube, resulting in a total system cost of \$65,271.

One operator will run the system, assuming a one hour average process time. Using 25 wafer dump transfer type boats, 125 wafers/tube or 1000 wafers/hour can be processed. Floor space required for this diffusion system is 275 ft².

Expense Items

Facility requirements are:

Electrical	140 KW
Exhaust	125 CFM

Doping and carrier gases:

$$\text{BCl}_3 @ \frac{0.4138 \text{ cc}}{\text{wafer}} \times \frac{\$0.3745}{1000 \text{ cc}} = \$0.1546/1000 \text{ wafers}$$

$$\text{N}_2 @ \frac{3 \text{ ft}^3}{\text{hour}} \times \frac{\$0.0033}{\text{ft}^3} \times \frac{1 \text{ hour}}{\text{run}} \times \frac{1 \text{ run}}{125 \text{ wafers}} = \$0.0792/1000 \text{ wafers}$$

Quartzware: (assumes tubes and boats replaced annually) = \$769/year per tube
= \$1.14/1000 wafers, assuming 100% utilization of the equipment.

3.3.7.12 STEP 13: PHOSPHORUS DIFFUSION

Capital Equipment Assumptions

This process step assumes a Thermco eight-tube diffusion module, Type 4000S72 per Spec 19000 with load station, source cabinets and appropriate options at \$49,271. Process controllers are estimated to be \$2,000/tube, resulting in a total system cost of \$65,271.

One operator will run the system assuming a one hour average process time. Using the 25 wafer dump transfer type boat, 125 wafers/tube or 1000 wafers/hour can be processed. Floor space required for this diffusion system is 275 ft².

Expense Items

Facility requirements are:

Electrical	140 KW
Exhaust	125 CFM

Doping and carrier gases:

$$\text{PH}_3 @ \frac{0.1164 \text{ ft}^3}{1000 \text{ wafers}} \times \frac{\$28.07}{\text{ft}^3} = \frac{\$3.27}{1000 \text{ wafers}}$$

$$\text{Argon} @ \frac{14.8 \text{ ft}^3}{1000 \text{ wafers}} \times \frac{\$0.1172}{\text{ft}^3} = \frac{\$1.73}{1000 \text{ wafers}}$$

Quartzware: (assume tubes and boats replaced annually = \$769/year per tube
 = \$1.14/1000 wafers,
 assuming 100% utilization of the equipment.

3.3.7.13 STEP 14: DRIVE-IN DIFFUSION

Capital Equipment Assumptions

This process step assumes a Thermco eight-tube diffusion module Type 4000S72 per Spec 19000 with load station, source cabinets and appropriate options at \$49,271. Process controllers are estimated to be \$2,000/tube resulting in a total system cost of \$64,271.

One operator will run the system, assuming a one hour average process time. Using the close pack (50 wafer) dump transfer type boat, 250 wafers/tube or 2000 wafers/hour can be processed. Floor space required for this diffusion system is 275 ft².

Expense Items

Facility requirements are:

Electrical	140 KW per module
Exhaust	125 CFM per module
N ₂	3 l/min. per tube

$$\frac{3 \text{ l}}{\text{min.}} \times \frac{60 \text{ min.}}{\text{Hr.}} \times \frac{.0353 \text{ CF}}{\text{l}} \times \frac{5400 \text{ hr.}}{\text{year}} \times \frac{\$.0033}{\text{CF}} = \$115.25/\text{year per tube}$$

Quartzware: (assume tubes and boats replaced annually = \$769/year per tube
 = N₂ and Quartzware, thus, represent \$0.084 and \$0.57,
 respectively, per 1000 wafers assuming 100% utilization
 of the equipment.

3.3.7.14 STEPS 15 AND 38: ION IMPLANTATION

Capital Equipment Assumptions

Today's available implantation technology has been used to estimate the cost of an ion implantation process. The equipment specified is an Extrion 200-1000 implanter which costs approximately \$300,000. Maximum throughput for 7.6 cm diameter wafers is 80/hour. By modifying the wafer holder, it is anticipated that 12 cm diameter wafers can be processed at the rate of 40/hour. Floor space requirement is 400 ft² and one operator can control 2 implanters.

Expense Items

Facility requirements include:

Electrical	20 KW
Exhaust	200 CFM
DIH ₂ O	5 GPM

Additional expense items are:

$$\text{LN}_2: \frac{5 \text{ } \ell}{\text{shift}} \times \frac{3 \text{ shift}}{\text{day}} \times \frac{240 \text{ day}}{\text{year}} \times \frac{28.32 \text{ CF}}{\ell} \times \frac{\$.0026}{\text{CF}} = \frac{\$265}{\text{year}}$$

Assuming 100% utilization of the equipment, the cost of LN₂ is:

7.6 cm: \$0.61/1000 wafers

12 cm: \$1.22/1000 wafers

Wafer holders are assumed to be included in the original capital cost.

Assuming a 10% source efficiency for phosphorus implants, then:

$$\frac{6.0225 \times 10^{23} \text{ atoms}}{30.9738 \text{ g (Phos)}} = \frac{1.944 \times 10^{22} \text{ atoms}}{\text{gram}}$$

at 10% efficiency, available source = 1.944×10^{21} atoms/gram.

Selecting an implant of 2×10^{15} atoms/cm², then:

7.6 cm diameter cells

$$\frac{2 \times 10^{15} \text{ atoms}}{\text{cm}^2} \times \frac{45.36 \text{ cm}^2}{\text{wafer}} \times \frac{\$2.76}{\text{gram}} \times \frac{1 \text{ gram}}{1.944 \times 10^{21} \text{ atoms}} = \frac{\$0.1288}{1000 \text{ wafers}}$$

12 cm diameter cells

$$\frac{2 \times 10^{15} \text{ atoms}}{\text{cm}^2} \times \frac{113.097 \text{ cm}^2}{\text{wafer}} \times \frac{\$2.76}{\text{gram}} \times \frac{1 \text{ gram}}{1.944 \times 10^{21} \text{ atoms}} = \frac{\$0.3211}{1000 \text{ wafers}}$$

Assuming a 2% source efficiency for boron implants, then:

$$\frac{6.0225 \times 10^{23} \text{ atoms}}{10.811 \text{ g (Boron)}} = 5.5707 \times 10^{22} \text{ atoms/gram}$$

$$\text{at 2\% efficiency, available source} = 1.1141 \times 10^{21} \text{ atoms/gram}$$

Selecting an implant of 1×10^{15} atoms/cm², then:

7.6 cm diameter cells

$$\frac{1 \times 10^{15} \text{ atoms}}{\text{cm}^2} \times \frac{45.36 \text{ cm}^2}{\text{wafer}} \times \frac{\$0.4409}{\text{gram}} \times \frac{1 \text{ gram}}{1.1141 \times 10^{21} \text{ atoms}} = \frac{\$0.018}{1000 \text{ wafers}}$$

12 cm diameter cells

$$\frac{1 \times 10^{15} \text{ atoms}}{\text{cm}^2} \times \frac{113.097 \text{ cm}^2}{\text{wafer}} \times \frac{\$0.4409}{\text{gram}} \times \frac{1 \text{ gram}}{1.1141 \times 10^{21} \text{ atoms}} = \frac{\$0.0448}{1000 \text{ wafers}}$$

Vacuum pump oil is expected to be changed on a bi-monthly basis.

At \$17.42/bottle, total annual cost is expected to be \$413.

Pump oil is:

7.6 cm: \$0.97/1000 wafers

12 cm: \$1.94/1000 wafers

3.3.7.15 STEPS 16 AND 37: ADVANCED ION IMPLANTATION

This system will use an unanalyzed ion beam system. Current cost and capacity estimates anticipate that a 100 mA phosphorus system and a 10 mA boron system can be purchased for \$85K. Utilizing a belt transport system through a differentially pumped vacuum chamber, implant times will probably

be mechanically limited to 0.5 sec/wafer. The chart below shows estimated implant times and throughputs.

7.6 cm Cell

	Calculated time (sec)	Machine time (sec)	Throughput (WPH)
Phosphorous (2×10^{15} @ 100 mA)	.2686	.5	7200
Boron (1×10^{15} @ 10 mA)	1.3429	1.5	2400
Boron (8×10^{14} @ 10 mA)	1.0743	1.25	2889

12 cm Cell

	Calculated time (sec)	Machine time (sec)	Throughput (WPH)
Phosphorous (2×10^{15} @ 100 mA)	.6696	.75	4800
Boron (1×10^{15} @ 10 mA)	3.348	3.5	1030
Boron (8×10^{14} @ 10 mA)	2.6784	2.75	1310

Floor space is assumed to be 400 ft^2 and one operator is required for each implanter.

Expense Items

Electrical	50 KW
Exhaust	40 CFM
DIH ₂ O	10 GPM

Expense items for LN₂, vacuum pump oil, and ion sources listed in Section 3.3.7.14.

3.3.7.16 STEP 17: SILICON NITRIDE

Capital Equipment Assumptions

This process step assumes a Thermco eight-tube diffusion module, Type 4000S72 per Spec 19000 with load station, source cabinets and appropriate

options at \$49,271. Process controllers estimated to be \$2,000/tube result in a total system cost of \$65,271.

One operator will run the system, assuming a one hour average process time. Using the close pack (50 wafer) dump transfer type boat, 250 wafers/tube, or 2000 wafers/hour, can be processed. Floor space required for this system is 275 ft².

Expense Items

Facility requirements are:

Electrical	140 KW
Exhaust	125 CFM

Gases used in the formation of this dielectric anti-reflection layer are shown below:

$$\text{H}_2\text{SiCl}_2: \frac{10 \text{ cm}^3}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{5400 \text{ hr}}{\text{year}} \times \frac{3.53 \times 10^{-5} \text{ CF}}{\text{cm}^3} \times \frac{\$8.6331}{\text{CF}} = \frac{\$987.50}{\text{year}}$$

$$\text{NH}_3: \frac{15 \text{ cm}^3}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{5400 \text{ hr}}{\text{year}} \times \frac{3.53 \times 10^{-5} \text{ CF}}{\text{cm}^3} \times \frac{\$1.0619}{\text{CF}} = \frac{\$181.25}{\text{year}}$$

Assuming that this equipment is 100% utilized, H₂SiCl₂ and NH₃ represent costs of \$0.73/1000 wafers and \$0.13/1000 wafers, respectively.

Quartzware: (assume tubes and boats replaced annually) = \$769/year per tube
 = \$0.57/1000 wafers, assuming 100% utilization of the equipment.

3.3.7.17 STEP 18: HIGH PRESSURE SCRUBBER

Capital Equipment Assumptions

This process step uses a Macronetics HPC-1000. To normalize floor space, a four track unit is suggested. Cost items are as follows:

Scrubber @ \$12,925/track	= \$51,700
Four track cabinet	= 3,000
Laminar flow hood	= <u>1,795</u>
TOTAL	\$56,495

It is anticipated that a four track unit can process 1000 wafers/hour and will require one operator. Floor space is estimated to be 45 ft².

Expense Items

Electrical	1.1 KW + 0.25 KW/track
Exhaust	80 CFM/track
DIH ₂ O	0.8 GPM/track

3.3.7.18 STEP 19: PLASMA CLEAN

Capital Equipment Assumptions

It is anticipated that a two chamber unit, each capable of containing two 50 wafer carriers, will be used. A complete cycle will be 15 minutes including pump down, ash, and vent. Since only one chamber can be operated with rf power at a time, the other will be vented, unloaded, loaded, and pumped down and waiting for the 10 minute ashing cycle. Thus, six runs/hour X 100 wafers/run result in a throughput of 600 wafers/hour. It is expected that a plasma asher of this type can be bought for \$15K. Floor space is 30 ft² and one operator can run two units.

Expense Items

Electrical	1.5 KW
Exhaust	40 CFM
Vacuum pump oil @ $\frac{\$17.42}{\text{bottle}}$	$\times \frac{24 \text{ bottles}}{\text{year}} = \frac{\$418.08}{\text{year}} = \frac{\$0.13}{1000 \text{ wafers}}$

assuming 100% utilization of the equipment.

3.3.7.19 STEPS 20, 21, 22: MESA ETCH 1 and 2, RINSE, DRY

Capital Equipment Assumptions

The sequence used for these process operations is:

1. 30 sec silicon etch in a 5:1:4 HNO_3 :Acetic:HF mixture
2. 5 min DIH_2O rinse
3. 3 min rinse-dry
4. 15 min plasma clean
5. 15 sec in a 4:1 NH_4 :HF solution
6. 5 min DIH_2O rinse

Operations 1 and 2 will be performed in a six foot laminar flow exhaust hood (IAS LV6-30X) containing six etch tanks (7 inches wide X 6 inches deep X 20 inches long) and a wafer carrier transport system. Three of the tanks will contain the etch solution and three will be utilized for the DIH_2O rinse operation. Each wafer carrier will contain 50 wafers. Cost of this hood is \$4.5K. Floor space is 45 ft^2 and one operator is required. These two operations will require 6 minutes (10/hr) and result in the following hood capacity:

$$\begin{aligned} 7.6 \text{ cm cell: } & \frac{200 \text{ wafers}}{\text{tank}} \times \frac{3 \text{ sinks}}{\text{hood}} \times \frac{10 \text{ runs}}{\text{hour}} = \frac{6000 \text{ wafers}}{\text{hour}} \\ 12 \text{ cm cell: } & \frac{150 \text{ wafers}}{\text{tank}} \times \frac{3 \text{ sinks}}{\text{hood}} \times \frac{10 \text{ runs}}{\text{hour}} = \frac{4500 \text{ wafers}}{\text{hour}} \end{aligned}$$

The third operation of this process is that of a rinse and dry procedure as is described in Section 3.3.7.6. The shorter time will result in capacities of 1800 wafers/hour and 1200 wafers/hour for 7.6 cm and 12 cm diameter wafers respectively.

Next, photoresist is removed by plasma technology as is described in Section 3.3.7.18.

Oxide is then removed (operations 5 and 6) utilizing a hood as described in operations 1 and 2 of this process. All physical assumptions and calculations for operations 5 and 6 are the same as those used in operations 1 and 2.

Expense Items

Cost of 5:1:4 HNO_3 :Acetic:HF - assume chemicals changed daily

$$= \frac{5 [\text{\$2.45/gal } (\text{HNO}_3)] + \$3.95/\text{gal (Acetic)} + 4 [\text{\$2.90/gal (HF)}]}{10} = \frac{\text{\$2.78}}{\text{gal}}$$

$$\underline{7.6 \text{ cm}}, 3 \text{ tanks: } \frac{6.318 \text{ gal}}{\text{hood}} \times \frac{\text{\$2.78}}{\text{gal}} \times \frac{240 \text{ days}}{\text{year}} = \frac{\text{\$4215}}{\text{year}} = \frac{\text{\$0.13}}{1000 \text{ wafers}}$$

$$\underline{12 \text{ cm}}, 3 \text{ tanks: } \frac{9.6784 \text{ gal}}{\text{hood}} \times \frac{\text{\$2.78}}{\text{gal}} \times \frac{240 \text{ days}}{\text{year}} = \frac{\text{\$6457}}{\text{year}} = \frac{\text{\$0.27}}{1000 \text{ wafers}}$$

Annual cost of 4:1 NH_4F :HF @ \\$2.97/gallon using the same calculations as above is:

$$\underline{7.6 \text{ cm}}: \$4503/\text{year} = \$0.14/1000 \text{ wafers}$$

$$\underline{12 \text{ cm}}: \$6899/\text{year} = \$0.28/1000 \text{ wafers}$$

Additional expense items include carriers and quartzware which were previously described in Section 3.3.3.7. The costs, assuming 100% equipment utilization, are:

$$\underline{7.6 \text{ cm}} \quad \$922/\text{year} - \text{carriers} = \$0.028/1000 \text{ wafers}$$

$$\quad \$1392/\text{year} - \text{quartz} = \$0.043/1000 \text{ wafers}$$

$$\underline{12 \text{ cm}} \quad \$1152/\text{year} - \text{carriers} = \$0.047/1000 \text{ wafers}$$

$$\quad \$1392/\text{year} - \text{quartz} = \$0.057/1000 \text{ wafers}$$

Facility requirements are:

Electrical	1.1 KW hood (operations 1-2 & 5-6)
	1 KW Rinse-dry
Exhaust	450 CFM Hood (operations 1-2 & 5-6)
DIH ₂ O	1.6 GPM - Rinse-Dry
	3 GPM - Hood (operations 1-2 & 5-6)

3.3.7.20 STEP 23: DIELECTRIC ETCH (WET)

Capital Equipment Assumptions

Wet chemistry etching of dielectrics utilizes the same hoods described in Section 3.3.7.19. As was stated in that discussion, three tanks will contain etch and three will be used for a short DIH₂O rinse. Cost of this hood is expected to be \$4500, it requires 45 ft² and one operator. Assume 10 minutes/batch (load + 1.5 min. etch + unload + 5 min DIH₂O rinse), thus, 6 batches/hour.

$$\underline{7.6 \text{ cm cell:}} \quad \frac{6 \text{ batches}}{\text{hour}} \times \frac{200 \text{ wafers}}{\text{sink}} \times \frac{3 \text{ tanks}}{\text{batch}} = \frac{3600 \text{ wafers}}{\text{hour}}$$

$$\underline{12 \text{ cm cell:}} \quad \frac{6 \text{ batches}}{\text{hour}} \times \frac{150 \text{ wafers}}{\text{sink}} \times \frac{3 \text{ tanks}}{\text{batch}} = \frac{2700 \text{ wafers}}{\text{hour}}$$

Expense Items (assume chemicals changed daily)

$$\underline{7.6 \text{ cm cell:}} \quad \frac{6.3178 \text{ gal}}{\text{day/hood}} \times \frac{240 \text{ day}}{\text{year}} \times \frac{\$2.97}{\text{gal}} = \frac{\$4503}{\text{year/hood}} = \frac{\$0.23}{1000 \text{ wafers}}$$

$$\underline{12 \text{ cm cell:}} \quad \frac{9.6784 \text{ gal}}{\text{day/hood}} \times \frac{240 \text{ day}}{\text{year}} \times \frac{\$2.97}{\text{gal}} = \frac{\$6899}{\text{year/hood}} = \frac{\$0.47}{1000 \text{ wafers}}$$

Other expenses which are explained in step 7 include:

$$\underline{7.6 \text{ cm}} \quad \$922/\text{year} - \text{carriers} = \$0.047/1000 \text{ wafers}$$

$$\quad \$1392/\text{year} - \text{quartz} = \$0.072/1000 \text{ wafers}$$

$$\underline{12 \text{ cm}} \quad \$1152/\text{year} - \text{carriers} = \$0.079/1000 \text{ wafers}$$

$$\quad \$1392/\text{year} - \text{quartz} = \$0.095/1000 \text{ wafers}$$

Facility requirements are:

$$\text{Electrical} \quad 1.1 \text{ KW}$$

$$\text{Exhaust} \quad 450 \text{ CFM}$$

$$\text{DIH}_2\text{O} \quad 3 \text{ GPM}$$

3.3.7.21 STEPS 24, 25, 26, 27, 28: ELECTROLESS PLATING

Capital Equipment Assumptions

This process step assumes several independent sequential operations which are outlined below:

1. 10:1 H₂O:HF etch + DIH₂O rinse
2. Sensitize surface
3. Electroless plating (Pd)
4. DIH₂O rinse and dry (centrifuge: Section 3.3.7.6)
5. Sinter
6. 10:1 H₂O:HF etch + DIH₂O rinse
7. Electroless plating (Ni)
8. DIH₂O rinse and dry (centrifuge: Section 3.3.7.6)
9. Sinter

Using this process, the first operation would require a hood as described in Section 3.3.7.7 (excluding the chemical recirculating system) where three of the tanks contain 10:1 H₂O:HF and the remaining three tanks are used for the DIH₂O rinse. (Expense items are the same as discussed in the previous section.) The longest portion of this process is the DIH₂O rinse, which is estimated to be 10 minutes. Since the etch portion of this process is approximately 5 seconds, the total process time will be assumed to be 10 minutes. Five minutes is added for load and unload operations, permitting four cycles/hour.

Thus:

$$\begin{array}{l} \underline{7.6 \text{ cm}}: \frac{50 \text{ wafers}}{\text{carrier}} \times \frac{4 \text{ carriers}}{\text{sink}} \times \frac{3 \text{ sinks}}{\text{hood}} \times \frac{4 \text{ cycles}}{\text{hour}} = \frac{2400 \text{ wafers}}{\text{hood-hour}} \\ \underline{12 \text{ cm}}: \frac{50 \text{ wafers}}{\text{carrier}} \times \frac{3 \text{ carriers}}{\text{sink}} \times \frac{3 \text{ sinks}}{\text{hood}} \times \frac{4 \text{ cycles}}{\text{hour}} = \frac{1800 \text{ wafers}}{\text{hood-hour}} \end{array}$$

The next operation requires sensitize, rinse, and Pd plating steps. Again, using a six sink hood, two sinks can be used for each step. These steps require times of 75 seconds, 10 minutes, and one minute respectively. As above, assuming that four cycles can be performed each hour, a throughput of $\frac{1600 \text{ (7.6 cm) wafers}}{\text{hood-hour}}$ and $\frac{1200 \text{ (12 cm) wafers}}{\text{hood-hour}}$ can be achieved.

Following the first plating operation, a DIH_2O rinse and dry operation is required. For this analysis, the centrifuge step, Section 3.3.7.6, will be utilized.

Once the wafers are rinsed and dried, an anneal must be performed. The most probable cost effective method is to transport the wafers through a furnace on a continuous belt. Assume two carriers, each containing 50 wafers, are placed on a belt. Also, assume the time necessary for these carriers to pass through the furnace is 30 minutes and that two new boats of wafers can be placed on the belt every 30 seconds. After the first 30 minutes, two boats containing a total of 100 wafers will emerge every 30 seconds. This results in a throughput of 200 wafers/minute = 12,000/hour. For this process step, a belt furnace costing \$35K and requiring 132 ft² is assumed. Each furnace will require an operator.

The next process operations evaluated include an etch, DIH_2O rinse, and electroless Ni plating operation. This is assumed to occur in a hood similar to that described in the sensitize, rinse, and Pd plate operation. The Ni plating operation will take five minutes. This results in only three operations/hour being performed in one hood, resulting in a throughput of 1200 wafers/hour for 7.6 cm diameter wafers and 900 wafers/hour for 12 cm diameter wafers.

Next, a DIH_2O rinse and dry operation, as previously described, is performed.

Finally, a low temperature (200°C - 400°C) anneal is accomplished in a belt furnace similar to that already described. For this analysis, a throughput

twice that of the first anneal will be assumed.

Expense and Material Items

The Ni and Pd platings will each cover 100% of the wafer back and 8% of the wafer front from solutions that have a plating efficiency of 35%. The unused Ni solution will not be reclaimed.

The Ni plating solution costs \$0.48/l. Of this, \$0.0157/l is Ni and can be associated with material plated onto the cell. Since 631.5 wafers (7.6 cm diameter) can be plated from a liter of solution, then a material cost of \$0.0249/1000 (7.6 cm diameter) wafers can be identified. The remainder, \$0.4648/l, can be associated with expense items in the Ni plating operation or \$0.74/1000 wafers. Since the plating cost is a direct function of the area being plated and the ratio of plated areas for 7.6 cm diameter cells to 12 cm diameter cells is 2.4931 then the material portion of the nickel operation on a 12 cm diameter cell will be \$0.062/1000 wafers and the expense portion will be \$1.84/1000 wafers.

In the case of the Pd plating operation, the solution cost is \$2.137/l. From this solution, 105 7.6 cm diameter wafers can be plated resulting in a cost of \$20.36/1000 wafers (materials). The unplated Pd remaining in solution is reclaimed at 2/3 original cost resulting in an expense of \$4.13/1000 wafers. Using the area ratio developed above, 12 cm diameter wafers will cost \$50.77/1000 wafers (materials) and \$10.30/1000 wafers (expense).

Additional expense items include those listed in Sections 3.3.7.6 and 3.3.7.7.

Material Items

These costs are shown in the expense calculations above.

3.3.7.22 STEP 29: SOLDER COATING

Capital Equipment Assumptions

This process step assumes an automatic solder system which contains a flux applicator, pre-heater, solderer, and a cleaning and drying section. Including a wafer transport system this apparatus is estimated to cost \$50K.

Other assumptions include:

- . solder fountain width is 15"
- . transport speed is 10 ft/min

Using these assumptions, four 7.6 cm diameter wafers or three 12 cm diameter wafers can be processed simultaneously. If the wafers are transported with one diameter spacing, then $\frac{20 \text{ wafers (7.6 cm)}}{\text{min.}} \times 4 \text{ tracks} = \frac{80 \text{ wafers}}{\text{min.}} \times \frac{4800 \text{ wafers}}{\text{hour}}$. Similarly, $\frac{12.7 \text{ wafers (12 cm)}}{\text{min.}} \times 3 \text{ tracks} = \frac{38.1 \text{ wafers}}{\text{min.}} = \frac{2286 \text{ wafers}}{\text{hour}}$.

Expense Items

Facility requirements include:

Electrical	15 KW
Exhaust	4000 CFM
DIH ₂ O	10 GPM

Flux will coat $200 \text{ ft}^2/\text{gal} = 185,806 \text{ cm}^2/\text{gal}$. Since both sides of the wafer must be totally fluxed, areas are 2X single side area. Therefore, 2048 (7.6 cm diameter) wafers and 1643 (12 cm diameter) wafers can be fluxed. At \$10/gal:

$$\begin{aligned} \underline{7.6 \text{ cm:}} \quad & \frac{\$10}{\text{gal}} \times \frac{1 \text{ gal}}{2048 \text{ wafers}} = \frac{\$4.88}{1000 \text{ wafers}} \\ \underline{12 \text{ cm:}} \quad & \frac{\$10}{\text{gal}} \times \frac{1 \text{ gal}}{1643 \text{ wafers}} = \frac{\$6.09}{1000 \text{ wafers}} \end{aligned}$$

Material Items

Solder:

$$\frac{\$2.68235/\text{lb}}{180.51 \text{ (7.6 cm diameter) wafers/lb}} = \frac{\$14.86}{1000 \text{ wafers}}$$

Using the ratio of areas, 12 cm diameter wafers will cost \$37.04/1000 wafers.

3.3.7.23 STEP 30: ELECTRICAL TEST-CELLS

Capital Equipment Assumptions

This process step requires an automatic wafer transport system, cell alignment stage, data acquisition system, and illumination source. These items are estimated to cost:

. Wafer transport system	\$20K
. Cell alignment stage	5K
. Data acquisition	16K
. Illumination source	1K
. Temperature controlled stage	<u>4K</u>
TOTAL	\$46K

It is estimated that a cell can be tested in 5 seconds resulting in a throughput of 720 cells per hour. Floor space is 100 ft² and one operator is required for each cell test station.

Expense Items

Electrical	2 KW
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3.3.7.24 STEPS 31, 32, 33, 34, 35: MODULE FABRICATION

Capital Equipment Assumptions

Equipment assumptions used in this analysis are, in many cases, based on equipment not yet developed. The procedure of panel assembly is listed below:

1. Cell align (aligns and attaches cells by reflow to interconnect substrate)
2. Clean (removes flux)
3. Assembly (places substrate with cells attached into pan, injects silicone, and places glass over cells)
4. Rivet/Weld (attaches bezel)
5. Cure (thermally cures silicone)

Using the process outlined above, the following equipment assumptions are made:

1. Cell align - For this operation, the interconnect substrate is attached to an indexing x-y table. Cells are aligned for X, Y and θ and placed on the substrate. Using localized heating, the cell is attached at this time. Following each cell attachment, the X-Y table indexes and another cell is aligned and placed on the substrate. It is anticipated that, by using a hybrid of today's technology equipment, this step can be achieved in this manner. Estimated cost of such a machine is \$80K. The area required for such a machine is expected to be 10' X 10'. Including support space, a total area of 200 ft² is necessary. Alignment time is assumed to be 5 seconds/cell resulting in a panel alignment time of 20 minutes for 7.6 cm diameter cells (238 cells X 5 sec./cell) and 8.25 minutes for 12 cm diameter cells

(99 cells X 5 sec./cell). Using a cassette fed system, one operator can handle this process step.

2. Clean - After cells are attached by solder reflow to the interconnect substrate, solder flux must be removed. For this process step, assume a belt transport system which will spray a cleaning agent. An aqueous flux is suggested such that the spray can be water. The floor space, throughput, and operator requirements are assumed to be 350 ft^2 , 15 panels/hour based on a 5 foot wide belt moving at 1 ft/min., and one operator. Capital cost is estimated to be \$35K.

3. Assembly - Cleaned interconnect substrates containing attached solar cells are placed into a pan assembly, covered with silicone from injector apparatus, and have a glass cover plate placed over the array. It is assumed that an automatic, belt transport system can perform this process at the same rate as described above in a machine requiring 500 ft^2 costing \$55K and requiring one operator.

4. Rivet/Weld - Assembled panels are indexed into an area where a bezel is placed over the panel after a peripheral sealant has been injected. Riveting occurs at a rate of 1 panel/minute = 60 panels per hour. This equipment is estimated to cost \$50K, require 144 ft^2 and one operator.

5. Cure - The final process used in panel assembly is a temperature cure which requires 2 hours. Assume a 6' high oven which is loaded from a belt and will contain 24 panels (2"/panel + 1" space). If a panel can be inserted into the oven in 5 seconds, then 2 minutes are necessary to load the oven which can be included in the 2 hour cure time. Floor space is estimated to be 25 ft^2 (5' X 5') for the oven plus 400 ft^2 (20' X 20') for staging and loading apparatus plus 175 ft^2 for work area = 600 ft^2 total. It is estimated that the oven will cost \$15K and the load apparatus \$20K, for a total of \$35K. One operator will be required.

Expense Items

Panel Assembly

7.6 cm	Item	Cost (K\$)	Area (ft ²)	Capacity (PPH)	Power (KW)	Exhaust (CFM)	DIH ₂ O (GPM)	N ₂ (L/m)	Staff (OPI)
	Cell Align	80	200	3	1.5	--	--	--	1
	Clean	35	350	15	1	400	10	25	1
	Assembler	55	500	15	4	400	--	--	1
	Riveter	50	144	60	2.5	--	--	--	1
	Cure	35	600	12	10	200	--	--	1

The only difference in this equipment and that required for 12 cm diameter cells is in the cell align step where the capacity will be 5.91 PPH (panels per hour).

Material Items

Pan Requirements

- Size: $48'' \times 48'' \times .02'' = 2304 \text{ in}^2 \times .02'' = 46.08 \text{ in}^3$
- Material: Cold rolled steel
- Bezel requirements, four pieces
 - $4 \times 2.5'' \times 48'' \times .03'' = 480 \text{ in}^2 \times .03'' = 14.4 \text{ in}^3$

Item	Unit \$	7.6 cm \$/W	12 cm \$/W
Pan	\$ 3.2145	.0213	.0205
Bezel	0.8394	.0056	.0054
Coating	2.7937	.0185	.0178
Glass	11.0202	.0729	.0703
Feedthrough	.60	.0040	.0038
Insulator	.092	.0006	.0006
Interconnect	9.6970	.0642	.0619
Silicone	5.4857	.0363	.0350
Gasket	.60	.0040	.0040
TOTAL	\$34.3425	.2272	.2191

3.3.7.25 STEP 36: ELECTRICAL TEST - MODULE

Capital Equipment Assumptions

Panel testing is assumed to use a Spectrolab LAPSS pulsed lamp system which costs \$80K. Automatic indexing of panels into the test area is expected to add \$15K to the equipment cost. A room 8' wide X 22' long is necessary for uniform illumination of a 4' X 4' panel. Additional area for the panel indexing system is expected to require that a total area of 250 ft² be provided for this process step. One operator is necessary for this equipment. 15 seconds will be allowed for this operation resulting in a 240 panel/hr rate.

Expense Items

Electrical

2.5 KW

3.3.8 OVERHEAD ASSUMPTIONS

The specific categories which contribute to overhead costs are presented in this section. Each category is itemized; in no case is any category merely taken as a percentage of some quantity, such as labor. Specific categories are presented below:

3.3.8.1 DIRECT FACTORY OVERHEAD

This section includes one foreman per shift and is independent of the range of factory sizes to be evaluated (a conservative assumption). Supervisors are required at one per 15 direct labor personnel in crystal and wafer processing areas and one per 25 direct labor personnel in the panel assembly area. Annual salaries are assumed to be \$16K for foreman and \$10K for supervisors. Foreman are hired during Phase II and supervisors are added in Phase

III as needed to accomodate the increasing direct labor employment level. Direct factory expense items are listed in a separate expense category.

3.3.8.2 ENGINEERING

The engineering area will maintain process integrity and perform Q.A. functions. The following engineering staff will remain constant over the range of annual production to be evaluated.

- (1) Manager @ \$23K/year
- (3) Engineers @ \$20K/year each
- (3) Technicians @ \$280/week each

Capital equipment is expected to cost \$185K and will be depreciated over 8 years on a straight line basis. Associated expenses are assumed to be 25% of the total engineering cost, excluding depreciation. All engineers will be hired in the first phase with technicians being added in Phase II.

3.3.8.3 PRODUCTION CONTROL

Since this factory produces only one product and the number of customers will remain essentially constant, annual production volume will only minimally effect the size of the production control operation. The following personnel will staff this area:

- (1) Manager @ \$22K/year
- (1) Secretary @ \$172/week
- (1) Scheduler @ \$18K/year
- (2) Clerks @ \$160/week
- (1) Customer Service Engineer @ \$18K/year
- (1) Order Entry Clerk @ \$172/week
- (4) Inventory Control @ \$174/week

This group will remain constant up to 5 MW annual production at which time one inventory control person will be added for each additional 5 MW of annual production. It is assumed that this group will provide warehouse personnel requirements. Capital equipment, depreciated as support equipment, will include fork-lifts, pallet trucks, and the storage racks. Expense items are assumed to be 5% of salaries. Production control will be initiated in Phase III.

3.3.8.4 BUILDING SERVICES

This cost category includes lighting and HVAC which are estimated to be 48¢/ft²/month; taxes and insurance which are estimated to be 25.3¢/ft²/month; and custodial services which are estimated to be 0.118 man/1000 ft² @ \$180/week. The square footage of the facility is based on the following assumptions. The total area figure (TOTAL SQ. FT.) presented later in Table II represents only that area which is used for direct manufacturing. In order to estimate the cost of the building as well as area related costs, an estimate of the total factory size must be made. These estimates assume:

$$\text{TOTAL SQ. FT.} \times 1.3 = \text{DFA (Direct Factory Area)}$$

This additional 30% is included in the overall factory size to account for hallways and storage areas within the manufacturing area.

$$\text{DFA} \times 1.2 = \text{FTL (FACTORY TOTAL)}$$

It is assumed that an additional 20% of the manufacturing area is required to warehouse a 30 day product inventory.

$$\text{FTL} \times 1.3 = \text{TBA (Total Building Area)}$$

This additional 30% of the total factory area is utilized for all support functions.

The results of this division of area are:

49% = direct manufacturing area

15% = hallway and storage areas within the manufacturing area

13% = warehouse area

23% = support area

Construction costs are assumed to be $\$80/\text{ft}^2$ for manufacturing areas and $\$30/\text{ft}^2$ for all other areas. The average cost to build a factory is then: $.49 \times (\$80/\text{ft}^2) + .51 \times (\$30/\text{ft}^2) = \$54.50/\text{ft}^2$. Two distinct factory areas are identified in this cost analysis. The first is direct manufacturing area which is determined by adding the areas required for each piece of equipment used in the several production areas. This manufacturing area, listed in Table 2 as TOTAL SQ. FT., represents 49% of the total factory area and, due to the high degree of utility facilitization, construction costs are estimated to be $\$80/\text{ft}^2$. The remaining, non-facilitized, support area (i.e., office, warehouse, etc.) represents 51% of the total factory area and can be constructed for an estimated $\$30/\text{ft}^2$. Using these ratios of construction costs and factory utilization, an average construction cost of $\$54.50/\text{ft}^2$ for the total factory area was determined. In this analysis, the method used to calculate total factory construction costs is to multiply the area required for direct manufacturing by the average construction cost ($\$54.50$) and divide by the percentage of area used for manufacturing (49%). This artificially allocates all of the construction costs to the direct manufacturing area for calculation purposes only, and for the results in an effective construction cost of $\$111.20/\text{ft}^2$ direct manufacturing area. The total construction cost of the factory, thus, is the product of this effective construction cost/ ft^2 and the TOTAL SQ. FT. from Table 11.

The cost of industrial property varies significantly throughout the U.S. For example, Phoenix, Arizona has industrial property in the \$12 - 15K/acre range while San Francisco sells similar property for \$95 - 125K/acre. The national average is approximately \$1/ft² or \$44K/ acre. In order to achieve a average cost estimate for a solar cell manufacturing plant, \$1/ft² will be used in this analysis. Furthermore, it will be assumed that the total area of the building will be 30% of the total property area. Since the manufacturing area (TSQFT) is 49% of the factory and the factory is 30% of the total property, the effective construction costs of \$111.20/ft² of direct manufacturing space will be increased to include property by \$6.80 resulting in an effective cost of \$118/manufacturing ft². Area calculations are utilized in the building services costs. Factory building costs form the base for the interest and depreciation figures. Building services are initiated in Phase II.

3.3.8.5 MAINTENANCE

Assumptions here are that one administrator at \$30K/year (1st shift only) and one supervisor at \$20K/year per shift for each 10 technicians are employed. Mechanical/electrical technicians at \$15K/year each are determined by the number and type of equipment used. Each type of machine is designated a maintenance coefficient in the data file to determine maintenance technician requirements for a particular process. Expense items are assumed to be 1.5X technician total salary and material items are assumed to be 1/3 of the total maintenance cost, (payroll + fringes + expense)/3. It is further assumed that the administrator and three supervisors are employed in Phase II with the remaining staff to be added in Phase III.

3.3.8.6 MANAGEMENT

The management section of overhead is assumed to contain a general manager at \$50K and four staff members at \$30K each. Expenses are 20% of these salaries. The general manager is included in Phase I, a staff member (finance manager) is added in Phase II, and the remaining staff is added in Phase III.

3.3.8.7 MARKETING/SALES

Due to the small customer base, the staff in this group is assumed to remain constant and to comprise one product marketer and one salesman, each with annual salaries of \$20K, and one clerk at \$172/week. Expenses are 1/2 of these salaries and commissions are 2.4 X salesman's salary. It is also assumed that there are no applications activities. The product marketer will begin in Phase II with the remaining staff added in Phase III.

3.3.8.8 PURCHASING

The purchasing function is assumed to remain constant with one purchasing agent at \$22K/year and expenses of 20% of salary. This category is initiated in Phase I.

3.3.8.9 FINANCE

Finance personnel include one accounts payable clerk, one accounts receivable clerk, and one payroll clerk each at \$172/week. Expenses are 20% of salaries. The accounts payable clerk and the payroll clerk are employed in Phase I and the accounts receivable clerk is employed in Phase III. This function is assumed independent of volume.

3.3.8.10 SECRETARY POOL

Two secretaries and two clerks, each with salaries of \$172/week, are assumed for this section. Expense items are assumed to exist in the several areas in which these employees work. One secretary begins in Phase I with the remaining three personnel beginning in Phase III.

3.3.8.11 DATA PROCESSING

This operation is constant and utilizes a leased computer and peripheral equipment at \$3500/month. The computer will provide inventory tracking, direct labor reporting, reject analysis, and management information services. One programmer/operator at \$20K is required. Expenses are assumed to be \$10K per year.

3.3.8.12 TRAINING

Training is considered to be one of the most important functions in the overhead section. As a result, one organizer at \$22K, nine trainers for crystal growth and wafer processing at \$170/week and three trainers for assembly at \$170/week will be employed in Phase II to become familiar with equipment and processes. In Phase III, these people perform an extensive training program for direct labor personnel. In Phase IV the training staff is reduced to five trainers in crystal growth and wafer processing and to one in assembly. In both situations, expenses are assumed to be 10% of salaries.

3.3.8.13 PERSONNEL

This section requires one employee in Phase I at \$22K with an additional clerk at \$170/week to be added in Phase II. Phases III and IV include these

two employees when volume is equal to 10 MW or less plus an additional employee at \$22K/year for each additional 10 MW of annual production. Expenses are 10% of salaries. The manager for this section is included in the Management section.

3.3.8.14 CAFETERIA

Equipment for the cafeteria is estimated to cost \$60K. Assuming that the cafeteria is self-sustaining and operates at a breakeven point, no labor or expense need be included. Depreciation on the equipment will begin in Phase III.

3.3.8.15 LEGAL

It is assumed that all legal matters will be performed by a contract attorney for \$18K/year beginning in Phase I.

3.3.8.16 SECURITY

Security guards will be employed in Phase III on a one employee per shift basis at \$170/week.

3.3.8.17 HEALTH

Nurses will begin in Phase III on a one nurse per shift basis at \$200/week. Expenses are 10% of salary.

3.3.8.18 FRINGE BENEFITS

For all indirect labor employees, fringe benefits are assumed to be \$2.3K/year times the number of employees regardless of salary or grade.

3.3.9 PROCESS YIELD AND MACHINE EFFICIENCY ASSUMPTIONS

The cost of performing any given process step (and the entire process sequence) is, in addition to expenses already defined, heavily dependent upon the yield through each process step. The yield of a given process step is simply defined as the number of acceptable units out of the process step divided by the number of acceptable units started into the process step. If a process step has well defined control ranges and is operated within those ranges, the yield should be 1.00 (or 100%). Since some variations can always be expected outside the control limits (including breakage from handling), the practically observed yields are always less than 1.00. Based upon volume extrapolations from today's known technology, yields have been assumed for each of the individual process steps which could be incorporated into the factory under consideration.

The yield of the overall process sequence is merely the product of the yields of each of the individual process steps in the sequence. A poor yield at any one process step, thus, can dramatically affect the total yield. Further, to obtain 100 units out of the process sequence, the number of units started must be 100 divided by the yield. This, of course, is also true for any individual process step or group of steps. All substrates which are started but which do not finish, thus, are wasted and have a great impact on the cost of a step (and the overall sequence). One of the most cost sensitive sets of assumptions is the set of process yield assumptions. Since these assumptions must be, in fact, estimated, they are more subjective than many of the other assumptions previously discussed. A careful evaluation of the results of this cost analysis must critically evaluate these yield assumptions.

A second set of assumptions which are partially subjective and which also are highly influential on processing costs are related to machine durability. In this analysis, it is assumed that each piece of processing equipment will be broken down and inoperative a certain portion of the time. It is further assumed that the more complex machinery will have more down-time. An ion implanter, therefore, will have significantly more down-time than a chemical exhaust hood.

The process step yield and machine efficiency assumptions are listed in Table 5.

3.3.10 ELECTRICAL AND DI WATER CONSUMPTION ASSUMPTIONS

Electrical consumption in the factory includes the requirements for operation of building services and equipment as well as the specific requirements for heating, ventilating, and air conditioning (HVAC) in each of the processing areas. The total electrical consumption assumes:

- (1) Steady-state operation of equipment requires 50% of the name-plate power (a 50% load factor).
- (2) Exhaust power is rated at 100% load factor based on 8766 hours per year.
- (3) HVAC power is rated at 40% load factor, based on 8766 hours per year.
- (4) Lighting requires 4 watts per square foot.

It is further assumed that:

- (5) Exhaust power requirement is 0.46 KW/1000 CFM and is assumed to operate continuously.

TABLE 5

PROCESS STEP YIELD AND MACHINE EFFICIENCY
 ASSUMPTIONS FOR EACH INDIVIDUAL PROCESS STEP.

		PROCESS YIELD%	MACHINE EFFICIENCY
1	CRYSTAL GROWTH	90.00	.90
2	CRYSTAL GRIND	99.90	.90
3	CRYSTAL CROPPING	99.90	.90
4	CRYSTAL SAW	95.00	.90
5	CLEAN-ETCH	99.80	.90
6	CENTRIFUGE	99.80	.96
7	TEXTURE ETCH	99.20	.93
8	COAT-BAKE	99.40	.92
9	ALIGN-EXPOSE	99.80	.94
10	DEVELOP-BAKE	99.40	.92
11	ETCH STOP APPLY	99.40	.92
12	BORON DIFFUSION	99.00	.88
13	PHOSPHORUS DIFF.	99.00	.88
14	DRIVE-IN DIFF.	99.40	.96
15	ION IMPLANT N	99.80	.80
16	ION IMPL-ADV N	99.80	.80
17	SILICON NITRIDE	99.20	.88
18	HI PRESS. SCRUB	99.60	.95
19	PLASMA CLEAN	99.80	.97
20	MESH ETCH 1	99.80	.93
21	MESH ETCH 2	99.80	.93
22	RINSE-DRY	99.80	.96
23	DIELECTRIC ETCH	99.80	.93
24	PLATING ETCH	99.80	.93
25	PD PLATE	99.00	.88
26	NI PLATE	99.00	.88
27	SINTER 1	99.80	.96
28	SINTER 2	99.80	.96
29	SOLDER COAT	99.80	.88
30	CELL TEST	94.80	.95
31	CELL ATTACH	99.70	.88
32	MODULE CLEAN	99.90	.88
33	MODULE ASSEMBLY	99.95	.88
34	RIVET-WELD	99.95	.88
35	CURE	99.95	.97
36	MODULE TEST	99.80	.95
37	ION IMPL-ADV P	99.80	.80
38	ION IMPLANT P	99.80	.80

(6) HVAC requirements must account for:

(a) Equipment heat dissipation equal to 12.5% of name-plate rating and

(b) conditioning of make-up air at 15 KW/1000 CFM.

DI water consumption assumes a 5400 hour work year. Total electrical and DI consumption for each equipment item and for the total factory can now be calculated utilizing these assumptions.

The consumption of electrical and DI water in the factory is dependent upon the particular building service or type of equipment and process step. Consumption can be classed either as continuous or as demand, and costs have been determined for each piece of equipment accordingly.

Many of the building services and pieces of equipment require full time usage of a particular service whether material is being processed or not. For this continuous usage, consumption is equal to the number of pieces of process equipment required, multiplied by both the individual equipment service requirement and the machine efficiency value (presented earlier in the equipment and process step assumptions). Those pieces of equipment that require the usage of a particular service only when material is being processed will use that service at a rate equal to the product of the machine utilization factor and, again, the product of the number of pieces of that equipment, the individual equipment service requirement and the machine efficiency value. Demand electrical items are then multiplied by 0.616, (5400 work hours/year)/(8766 hours/year), in order that weekends and holidays can be eliminated in determining the total annual electrical consumption. It should be noted that the machine utilization is factored into electrical

and DIH_2O consumption only; exhaust is assumed to operate continuously.

Once totals are established for each facility requirement in each process sequence, annual consumption is determined by multiplying the total by 8766 annual hours for electrical consumption and by 5400 annual work hours for DIH_2O consumption.

3.4 PRELIMINARY RESULTS

During the first month of this cost study, a preliminary analysis was performed utilizing early estimates of cost components. The "first-cut" analysis was intended to identify the basic feasibility of a \$2.00/watt solar cell utilizing near term technology while limiting the scope of the study to areas of future interest. These preliminary results of the costing study are shown in Tables 6, 7, and 8. Each table is presented in a matrix form relating the effects of each of three cell sizes analyzed for each of the three specified process sequences.

TABLE 6
PRELIMINARY RESULTS FOR PROCESS SEQUENCE TOTAL COST
(Dollars per Watt)

	ION IMPLANT	DIFFUSION	ADVANCED ION IMPLANT
7.6 cm Cells	2.351	1.753	1.410
12 cm Cells	2.012	1.444	1.259
12 cm Half Cells	2.042	1.471	1.286

TABLE 7

PRELIMINARY RESULTS FOR EQUIPMENT CAPITALIZATION
(Millions of Dollars)

	ION IMPLANT	DIFFUSION	ADVANCED ION IMPLANT
7.6 cm Cells	99	30	23
12 cm Cells	79	21	17
12 cm Half Cells	80	22	18

TABLE 8
PRELIMINARY RESULTS FOR FACTORY REQUIREMENTS
 (Thousand Square Feet)

	ION IMPLANT	DIFFUSION	ADVANCED ION IMPLANT
7.6 cm Cells	200	74	55
12 cm Cells	156	43	40
12 cm Half Cells	156	48	41

Table 6 shows preliminary results for the costs of the total process sequence. These costs are highest for the smaller, 7.6 cm diameter cells and for today's ion implantation technology, being near \$2.35/watt. For all process sequences, the 12 cm diameter solar cells exhibit the lowest cost. The halved 12 cm diameter cells are more expensive than the whole 12 cm cells due to the operation costs of halving the cells. The fact that half cells can result in a more efficient module packing factor, reducing the effective encapsulation cost/watt, cannot overcome the costs and yield losses associated with the halving operation. Of today's available technologies, the diffusion process sequence is projected to cost less than \$2.00/watt for all cell sizes studied, with the 12 cm cell costs being less than \$1.50/watt. The projected advanced ion implantation process is the most cost favorable, but it is not yet available.

The major reasons for the higher costs associated with the present ion Implantation technology are seen from analyzing the information in Tables 7 and 8. Table 8 presents preliminary factory size requirements. The inefficiency of today's ion implanters is reflected in both very heavy capitalization and large floor space projections. Again, the diffusion process sequence compares favorably to present ion implantation technology, while ultimately being supplanted by an advanced ion implantation technology. Since capital equipment depreciation is a major cost contribution, factory life is extremely important in determining the amount of depreciation per year. This is discussed in detail in a later section of this report.

As a result of this preliminary analysis, further comparison of the 12 cm diameter half-wafer solar cells to the whole 12 cm diameter cells was deemed

to be unnecessary. As a result, no further cost analysis was performed on half-wafer cells.

3.5 CALCULATIONS FOR THE COST ANALYSIS

For the calculations in this cost analysis, some of the assumptions common to each evaluation are held constant, while others are treated as variables in order to determine the sensitivity of the results to the assumptions. Parameters which are treated as constants in all calculations include such items as unit chemical costs, labor rates, process step yields, machine capacities, and machine efficiencies. Parameters which are treated as variables are annual production volume, cell efficiency (encapsulated), polycrystalline silicon cost, the length of each of the phases of the factory, interest rate, and electrical power rate. As a result of varying the life of the factory in each phase, the depreciation rate also becomes a variable, assuming complete depreciation by the end of the factory life.

Each of the variable parameters is given a nominal value within its variable range for the calculations. These values have been chosen such that small changes from the nominal value do not result in wide excursions in the final cost. This allows a more valid study of the sensitivity of final costs to variations in cost analysis parameters. The range of each of the variables, and their nominal values, are listed in Table 9. Sample calculations, each based upon a 12 cm diameter solar cell manufactured by a diffusion process at an annual volume of 25 megawatts are presented in the following sections. These calculations are typical of those utilized for all results.

TABLE 9

VARIABLE PARAMETER RANGES AND NOMINAL VALUES

<u>PARAMETER</u>	<u>RANGE</u>	<u>NOMINAL VALUE</u>
Annual Production Volume	0.5 to 100 megawatts	25 megawatts
Cell Efficiency (Encapsulated)	5% to 20%	14%
Polycrystalline Silicon Cost	0 to \$50/Kg	\$25/Kg
Building Phase (Phase I)	6 to 12 months	6 months
Equipment Phase (Phase II)	6 to 12 months	6 months
Labor Phase (Phase III)	6 to 12 months	6 months
Production Phase (Phase IV)	6 to 72 months	60 months
Interest Rate	5% to 15%	7%
Power Rate	2¢ to 25¢/KWH	2.5¢/KWH

3.5.1 CALCULATIONS FOR PROCESS SEQUENCE YIELD

The average hourly solar cell output volume required to meet any given annual production goal can be readily calculated when the solar cell size and efficiency are specified. This hourly number is that which would result from a process with a 100% process yield. Knowing the required output rate and the individual process step yields, the number of solar cells started into any process sequence can be calculated from the cumulative yield of the individual process steps. (The cumulative yield at a given process step is the product of all the individual process step yields including and following that step.) An example of this calculation, for a diffusion process utilizing 12 cm diameter cells at an annual production of 25 megawatts, is shown in the first three columns of Table 10.

3.5.2 YIELDED MACHINE CAPACITY

Having defined both a machine capacity and a machine efficiency in the assumptions, a yielded machine capacity is calculated from the product of the capacity and efficiency. This information is shown in the last three columns of Table 10. The key for the table is:

STEP YLD (%)	=	Step yield (%)
CUM YLD (%)	=	Cumulative Yield (%)
WAFERS PER HR	=	Wafers per hour
MACH EFF	=	Machine Efficiency
MACH CAP	=	Machine Capacity
YIELD CAP	=	Yielded Machine Capacity

TABLE 10

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY

PROCESS STEP	STEP YLD(%)	CUM YLD(%)	WAFERS PER HR	MACH EFF	MACH CAP	YIELD CAP
CRYSTAL GROWTH	90.0	68.8	4250	.90	60	54
CRYSTAL GRIND	99.9	76.4	3825	.90	1612	1451
CRYSTAL CROPPING	99.9	76.5	3821	.90	5796	5216
CRYSTAL SAW	95.0	76.6	3817	.90	34	31
CLEAN-ETCH	99.8	80.6	3627	.90	1368	1231
PLASMA CLEAN	99.8	80.8	3619	.97	600	582
HI PRESS. SCRUB	99.6	80.9	3612	.95	250	237
BORDN DIFFUSION	99.0	81.3	3598	.88	125	110
DRIVE-IN DIFF.	99.4	82.1	3562	.96	250	240
ETCH STOP APPLY	99.4	82.6	3540	.92	250	230
DIELECTRIC ETCH	99.8	83.1	3519	.93	2700	2511
CENTRIFUGE	99.8	83.3	3512	.96	400	384
PLASMA CLEAN	99.8	83.4	3505	.97	600	582
TEXTURE ETCH	99.2	83.6	3498	.93	900	837
CENTRIFUGE	99.8	84.3	3470	.96	400	384
PHOSPHORUS DIFF.	99.0	84.4	3463	.88	125	110
ETCH STOP APPLY	99.4	85.3	3428	.92	250	230
COAT-BAKE	99.4	85.8	3408	.92	250	230
ALIGN-EXPOSE	99.8	86.3	3387	.94	200	188
DEVELOP-BAKE	99.4	86.5	3381	.92	250	230
MESA ETCH 1	99.8	87.0	3360	.93	4500	4185
RINSE-DRY	99.8	87.2	3354	.96	1200	1152
PLASMA CLEAN	99.8	87.4	3347	.97	600	582
MESA ETCH 2	99.8	87.5	3340	.93	4500	4185
CENTRIFUGE	99.8	87.7	3333	.96	400	384
PLASMA CLEAN	99.8	87.9	3327	.97	600	582
HI PRESS. SCRUB	99.6	88.1	3320	.95	250	237
SILICON NITRIDE	99.2	88.4	3307	.88	250	220
COAT-BAKE	99.4	89.1	3280	.92	250	230
ALIGN-EXPOSE	99.8	89.7	3261	.94	200	188
DEVELOP-BAKE	99.4	89.8	3254	.92	250	230
DIELECTRIC ETCH	99.8	90.4	3235	.93	2700	2511
PLASMA CLEAN	99.8	90.6	3228	.97	600	582
HI PRESS. SCRUB	99.6	90.8	3222	.95	250	237
PLATING ETCH	99.8	91.1	3209	.93	1800	1674
PD PLATE	99.0	91.3	3202	.88	1200	1056
CENTRIFUGE	99.8	92.2	3170	.96	400	384
SINTER 1	99.8	92.4	3164	.96	12000	11520
NI PLATE	99.0	92.6	3158	.88	900	792
CENTRIFUGE	99.8	93.5	3126	.96	400	384
SINTER 2	99.8	93.7	3120	.96	24000	23040
SOLDER COAT	99.8	93.9	3114	.88	2286	2012
CELL TEST	94.8	94.1	3107	.95	720	684
CELL ATTACH	99.7	99.3	2946	.88	720	634
MODULE CLEAN	99.9	99.6	2937	.88	1485	1307
MODULE ASSEMBLY	99.9	99.7	2934	.88	1485	1307
RIVET-WELD	99.9	99.7	2933	.88	5940	5227
CURE	99.9	99.8	2931	.97	1188	1152
MODULE TEST	99.8	99.8	2930	.95	23760	22572
FINISHED PRODUCT	100.0	100.0	2923			

3.5.3 CALCULATIONS FOR MACHINE COST, LABOR, AND FLOOR SPACE REQUIREMENTS

Results of the previous calculations are used to calculate total equipment requirements from an actual number standpoint as well as capital cost and floor space requirements, Table 11. The equipment (machine) requirements in both decimal and rounded-up (actual) form are shown in this table to illustrate the effect of machine utilization. The actual number of machines required in a particular step is then multiplied by capital cost, labor requirements, and floor space requirements. Similar to the machine data, the labor also represents a rounded-up integer for each step. (Reduction in this one shift labor figure will occur in later calculations utilizing process grouping techniques.) Totals at the bottom of Table 11 show the cost of capital equipment necessary to fabricate product and the necessary floor space to perform this task.

The key for Table 11 is:

# MACH (DEC)	=	Number of machines in decimal form
# MACH (ACT)	=	Number of machines in rounded-up form
K\$ MACH	=	Individual machine cost in \$1000 units
TOTAL K\$	=	Total cost of machines in \$1000 units
LABOR MACH	=	Direct labor to operate one machine
TOTAL DL	=	Direct labor, rounded-up, to operate all machines
SQFT MACH	=	Individual machine floor space (ft ²)
TOTAL SQFT	=	Total machine floor space (ft ²)

TABLE 11

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY

PROCESS STEP	#MACH (DEC)	#MACH (ACT)	K\$ MACH	TOTAL K\$	LABOR MACH	TOTAL DL	SOFT MACH	TOTAL SOFT
CRYSTAL GROWTH	78.70	79	125.0	9875	.33	27	49	3871
CRYSTAL GRIND	2.64	3	50.0	150	.25	1	96	288
CRYSTAL CROPPING	.73	1	8.0	8	1.00	1	40	40
CRYSTAL SAW	123.13	124	35.0	4340	.05	7	40	4960
CLEAN-ETCH	2.95	3	75.0	225	1.00	3	360	1080
PLASMA CLEAN	6.22	7	15.0	105	.50	4	30	210
HI PRESS. SCRUB	15.24	16	56.4	225	.25	4	45	180
BORON DIFFUSION	32.71	33	65.3	270	.12	5	275	1135
DRIVE-IN DIFF.	14.84	15	65.3	123	.12	2	275	516
ETCH STOP APPLY	15.39	16	59.1	236	.12	2	80	320
DIELECTRIC ETCH	1.40	2	4.5	9	1.00	2	45	90
CENTRIFUGE	9.15	10	2.5	25	.25	3	30	300
PLASMA CLEAN	6.02	7	15.0	105	.50	4	30	210
TEXTURE ETCH	4.18	5	12.0	60	.50	3	45	225
CENTRIFUGE	9.04	10	2.5	25	.25	3	30	300
PHOSPHORUS DIFF.	31.48	32	65.3	262	.12	4	275	1100
ETCH STOP APPLY	14.90	15	59.1	222	.12	2	80	320
COAT-BAKE	14.82	15	59.1	222	.12	2	80	320
ALIGN-EXPOSE	18.02	19	31.3	593	1.00	19	40	760
DEVELOP-BAKE	14.70	15	57.9	218	.12	2	80	320
MESA ETCH 1	.80	1	4.5	4	1.00	1	45	45
RINSE-DRY	2.91	3	2.5	7	.25	1	30	90
PLASMA CLEAN	5.75	6	15.0	90	.50	3	30	180
MESA ETCH 2	.80	1	4.5	4	1.00	1	45	45
CENTRIFUGE	8.68	9	2.5	22	.25	3	30	270
PLASMA CLEAN	5.72	6	15.0	90	.50	3	30	180
HI PRESS. SCRUB	14.01	15	56.4	212	.25	4	45	180
SILICON NITRIDE	15.03	16	65.3	131	.12	2	275	550
COAT-BAKE	14.26	15	59.1	222	.12	2	80	320
ALIGN-EXPOSE	17.35	18	31.3	562	1.00	18	40	720
DEVELOP-BAKE	14.15	15	57.9	218	.12	2	80	320
DIELECTRIC ETCH	1.29	2	4.5	9	1.00	2	45	90
PLASMA CLEAN	5.55	6	15.0	90	.50	3	30	180
HI PRESS. SCRUB	13.59	14	56.4	199	.25	4	45	180
PLATING ETCH	1.92	2	4.5	9	1.00	2	45	90
PD PLATE	3.03	4	4.5	18	1.00	4	45	180
CENTRIFUGE	8.26	9	2.5	22	.25	3	30	270
SINTER 1	.27	1	35.0	35	1.00	1	132	132
NI PLATE	3.99	4	4.5	18	1.00	4	45	180
CENTRIFUGE	8.14	9	2.5	22	.25	3	30	270
SINTER 2	.14	1	35.0	35	1.00	1	132	132
SOLDER COAT	1.55	2	50.0	100	1.00	2	100	200
CELL TEST	4.54	5	46.0	230	1.00	5	100	500
CELL ATTACH	4.65	5	80.0	400	1.00	5	200	1000
MODULE CLEAN	2.25	3	35.0	105	1.00	3	350	1050
MODULE ASSEMBLY	2.24	3	55.0	165	1.00	3	500	1500
RIVET-WELD	.56	1	50.0	50	1.00	1	144	144
CURE	2.54	3	35.0	105	1.00	3	600	1800
MODULE TEST	.13	1	95.0	95	1.00	1	250	250
TOTAL				20577		190		27593

3.5.4 GROUPING OF LABOR WITHIN PROCESS CATEGORIES

The direct labor headcount for a single shift, shown in Table 11, is higher than necessary. It can be lowered by grouping processes together to more efficiently utilize available labor. This reduction reflects the fact that while an integral number of machines is necessary, only a fractional number of machines would be necessary to fulfill production requirements. These calculations are shown in Table 12.

The key for Table 12 is:

EQPT UTL (%)	=	Equipment Utilization (%)
LABOR UTL (%)	=	Labor Utilization (%)
LABOR/STEP	=	Labor per step
LABOR (DEC)	=	Direct labor represented in decimal form
LABOR (ACT)	=	Direct labor, next highest integer after factoring for absenteeism and turnover

Equipment utilization is the ratio of the decimal number of machines over the actual number of machines and represents the percentage of time (after factoring of maintenance time) a particular item must operate in order to produce the desired volume. Labor utilization is determined by multiplying the actual number of machines required for a particular step by the labor per machine figure (which was identified in the assumptions) and dividing by the integerized direct labor value from Table 11. Using the assumption that the number of direct labor personnel specified for a particular process step can perform that operation when the equipment is 100% utilized, then the actual labor

TABLE 12

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY

PROCESS GROUPING					
PROCESS STEP	EOPT UTL (%)	LABOR UTL (%)	LABOR /STEP	LABOR (DEC)	LABOR (ACT)
CRYSTAL GROWTH					
CRYSTAL GROWTH	99.6	96.2	27	26.0	
CRYSTAL GRIND	87.9	65.9	1	.7	
CRYSTAL CROPPING	73.3	73.3	1	.7	
TOTAL			29	27.4	29
WAFER PREP					
CRYSTAL SAW	99.3	87.9	7	6.2	
CLEAN-ETCH	98.2	98.2	3	2.9	
TOTAL			10	9.1	10
PHOTOLITHOGRAPHY					
ETCH STOP APPLY	96.2	96.2	2	1.9	
DIELECTRIC ETCH	70.1	70.1	2	1.4	
CENTRIFUGE	91.5	76.2	3	2.3	
PLASMA CLEAN	86.0	75.3	4	3.0	
TEXTURE ETCH	83.6	69.7	3	2.1	
ETCH STOP APPLY	99.4	93.2	2	1.9	
COAT-BAKE	98.8	92.6	2	1.9	
ALIGN-EXPOSE	94.8	94.8	19	18.0	
DEVELOP-BAKE	98.0	91.9	2	1.8	
MESA ETCH 1	80.3	80.3	1	.8	
RINSE-DRY	97.0	72.8	1	.7	
PLASMA CLEAN	95.8	95.8	3	2.9	
MESA ETCH 2	79.8	79.8	1	.8	
CENTRIFUGE	96.4	72.3	3	2.2	
COAT-BAKE	95.1	89.1	2	1.8	
ALIGN-EXPOSE	96.4	96.4	18	17.3	
DEVELOP-BAKE	94.3	88.4	2	1.8	
DIELECTRIC ETCH	64.4	64.4	2	1.3	
PLASMA CLEAN	92.4	92.4	3	2.8	
HI PRESS. SCRUB	97.1	85.0	4	3.4	
TOTAL			79	70.0	74
JCT/DIELECT FORM					
PLASMA CLEAN	88.8	77.7	4	3.1	
HI PRESS. SCRUB	95.3	95.3	4	3.8	
BORON DIFFUSION	99.1	81.8	5	4.1	
DRIVE-IN DIFF.	98.9	92.8	2	1.9	
CENTRIFUGE	90.4	75.3	3	2.3	
PHOSPHORUS DIFF.	98.4	98.4	4	3.9	
PLASMA CLEAN	95.3	95.3	3	2.9	
HI PRESS. SCRUB	93.4	87.6	4	3.5	
SILICON NITRIDE	93.9	93.9	2	1.9	
TOTAL			31	27.3	29
METALLIZATION					
PLATING ETCH	95.8	95.8	2	1.9	
PD PLATE	75.8	75.8	4	3.0	
CENTRIFUGE	91.7	68.8	3	2.1	
SINTER 1	27.5	27.5	1	.3	
NI PLATE	99.7	99.7	4	4.0	
CENTRIFUGE	90.5	67.8	3	2.0	
SINTER 2	13.5	13.5	1	.1	
SOLDER COAT	77.4	77.4	2	1.5	
TOTAL			20	15.0	16
ASSEMBLY					
CELL TEST	90.8	90.8	5	4.5	
CELL ATTACH	92.9	92.9	5	4.6	
MODULE CLEAN	74.9	74.9	3	2.2	
MODULE ASSEMBLY	74.8	74.8	3	2.2	
RIVET-WELD	56.1	56.1	1	.6	
CURE	84.8	84.8	3	2.5	
MODULE TEST	13.0	13.0	1	.1	
TOTAL			21	16.9	18
PROCESS TOTAL					176

utilization figure, listed in Table 12, is the product of the figure calculated above and machine utilization. For each process step, the decimal labor requirement is determined by multiplying the labor per step figure from Table 11 by the labor utilization figure in Table 12. To determine the actual direct labor required in a particular process category, the sum of all the individual process steps (decimal labor) within that particular category are multiplied by 1.05 to account for a 5% absentee/turnover rate and rounded up to the next highest integer. The purpose of listing labor requirements in both decimal and rounded-up form is to determine if sufficient personnel exist within a process category to perform the miscellaneous tasks not directly related to the manufacturing of product. Note that equipment utilization should not be confused with the actual percentage of time that a particular piece of equipment is used, but that it represents the percentage of available time that the piece of equipment is used; available time being total time reduced by maintenance, cleaning, and any other time in which equipment cannot be used.

3.5.5 FACILITY REQUIREMENT CALCULATIONS

Facility requirements are calculated for each process step and for the process sequence utilizing the requirements for individual pieces of equipment. The facilities necessary to perform each process step are shown in Table 13.

The key for Table 13 is:

PWR KW (1st)	=	Maximum rated (name-plate) electrical power in kilowatts for one machine.
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TABLE 13

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY

PROCESS STEP	IND EQPT FACILITY REQ				PROCESS STEP FACILITY REQ				EQPT UTL%
	PWR KW	VENT CFM	WTR GPM	# MACH	PWR KW	VENT CFM	WTR GPM	MACH EFF	
CRYSTAL GROWTH	55	40	.0	79	2399	2843	0	.90	99.6
CRYSTAL GRIND	1	40	.0	3	2	107	0	.90	87.9
CRYSTAL CROPPING	6	100	.0	1	2	89	0	.90	73.3
CRYSTAL SAW	1	0	.0	124	68	0	0	.90	99.3
CLEAN-ETCH	10	600	5.0	3	26	1619	13	.90	98.2
PLASMA CLEAN	1	40	.0	7	5	271	0	.97	88.8
HI PRESS. SCRUB	2	320	3.2	16	8	1215	12	.95	95.3
BORON DIFFUSION	140	125	.0	33	508	453	0	.88	99.1
DRIVE-IN DIFF.	140	125	.0	15	251	224	0	.96	98.9
ETCH STOP APPLY	11	480	.0	16	44	1766	0	.92	96.2
DIELECTRIC ETCH	1	450	3.0	2	2	837	5	.93	70.1
CENTRIFUGE	1	0	1.6	10	5	0	14	.96	91.5
PLASMA CLEAN	1	40	.0	7	5	271	0	.97	86.0
TEXTURE ETCH	1	500	.0	5	7	2325	0	.93	83.6
CENTRIFUGE	1	0	1.6	10	5	0	13	.96	90.4
PHOSPHORUS DIFF.	140	125	.0	32	492	439	0	.88	98.4
ETCH STOP APPLY	11	480	.0	15	41	1656	0	.92	99.4
COAT-BAKE	11	480	.0	15	41	1656	0	.92	98.8
ALIGN-EXPOSE	1	0	.0	19	15	0	0	.94	94.8
DEVELOP-BAKE	11	480	.0	15	41	1656	0	.92	98.0
MESA ETCH 1	1	450	3.0	1	1	418	2	.93	80.3
RINSE-DRY	1	0	1.6	3	1	0	4	.96	97.0
PLASMA CLEAN	1	40	.0	6	5	232	0	.97	95.8
MESA ETCH 2	1	450	3.0	1	1	418	2	.93	79.8
CENTRIFUGE	1	0	1.6	9	5	0	13	.96	96.4
PLASMA CLEAN	1	40	.0	6	5	232	0	.97	95.3
HI PRESS. SCRUB	2	320	3.2	15	8	1139	12	.95	93.4
SILICON NITRIDE	140	125	.0	16	246	219	0	.88	93.9
COAT-BAKE	11	480	.0	15	41	1656	0	.92	95.1
ALIGN-EXPOSE	1	0	.0	18	15	0	0	.94	96.4
DEVELOP-BAKE	11	480	.0	15	41	1656	0	.92	94.3
DIELECTRIC ETCH	1	450	3.0	2	2	837	5	.93	64.4
PLASMA CLEAN	1	40	.0	6	4	232	0	.97	92.4
HI PRESS. SCRUB	2	320	3.2	14	7	1063	11	.95	97.1
PLATING ETCH	1	450	3.0	2	2	837	5	.93	95.8
PD PLATE	1	450	2.0	4	3	1583	7	.88	75.8
CENTRIFUGE	1	0	1.6	9	4	0	12	.96	91.7
SINTER 1	15	100	.0	1	14	95	0	.96	27.5
NI PLATE	1	450	2.0	4	3	1583	7	.88	99.7
CENTRIFUGE	1	0	1.6	9	4	0	12	.96	90.5
SINTER 2	15	100	.0	1	14	95	0	.96	13.5
SOLDER COAT	15	4000	10.0	2	12	7039	13	.88	77.4
CELL TEST	2	0	.0	5	5	0	0	.95	90.8
CELL ATTACH	11	400	.0	5	28	1759	0	.88	92.9
MODULE CLEAN	1	400	10.0	3	1	1055	19	.88	74.9
MODULE ASSEMBLY	4	400	.0	3	4	1055	0	.88	74.8
RIVET-WELD	2	0	.0	1	0	0	0	.88	56.1
CURE	10	200	.0	3	15	582	0	.97	84.8
MODULE TEST	2	0	.0	1	0	0	0	.95	13.0
TOTAL					4482	41235	190		

VENT CFM	=	Exhaust in cubic feet per minute for one machine
WTR GPM	=	Deionized water in gallons per minute for one machine
# MACH	=	Number of machines required for the process step
PWR KW (2nd)	=	Electrical power in kilowatts for the number of machines in the step (includes machine efficiency, utilization and demand, but not 50% load factor)
VENT CFM	=	Exhaust in cubic feet per minute for the process step
WTR GPM	=	Deionized water in gallons per minute for the process step
MACH EFF	=	Machine efficiency
EQPT UTL %	=	Equipment utilization %

3.5.6 TOTAL EXPENSE AND MATERIAL CALCULATIONS

Utilizing data assumed and calculated previously, expense items for the individual process steps and process sequence can now be calculated.

Table 14 illustrates total incurred expenses, which include process expenses, electrical expenses, and DIH_2O expenses. Also presented in Table 14 are the total material cost items. Process expenses are the sum of all expendable items used in the manufacturing of solar cells. These items include, for example, chemicals, and are calculated by determining the cost

TABLE 14

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 SILICON = \$25.00/KILOGRAM POWER RATE = 2.5 CENTS/KWH

EXPENSE & MATERIAL ITEMS

PROCESS STEP	PROCESS EXP (K\$)	ELECT EXP (K\$)	WATER EXP (K\$)	TOTAL EXP (K\$)	MATL (K\$)
CRYSTAL GROWTH	2465.0	293.3	.0	2758.3	.0
CRYSTAL GRIND	988.0	.4	.0	988.4	.0
CRYSTAL CROPPING	2201.2	.4	.0	2201.6	.0
CRYSTAL SAW	5791.1	8.2	.0	5799.3	.0
CLEAN-ETCH	342.6	5.5	13.6	361.7	2296.4
PLASMA CLEAN	2.9	1.1	.0	4.0	.0
HI PRESS. SCRUB	.0	2.7	12.9	15.6	.0
BORON DIFFUSION	29.8	61.9	.0	91.7	.0
DRIVE-IN DIFF.	13.2	30.7	.0	43.9	.0
ETCH STOP APPLY	111.4	7.9	.0	119.3	.0
DIELECTRIC ETCH	14.1	1.4	5.6	21.1	.0
CENTRIFUGE	2.6	.7	14.1	17.3	.0
PLASMA CLEAN	2.9	1.0	.0	4.0	.0
TEXTURE ETCH	23.5	4.2	.0	27.6	.0
CENTRIFUGE	2.6	.6	13.9	17.1	.0
PHOSPHORUS DIFF.	118.1	60.0	.0	178.1	.0
ETCH STOP APPLY	107.9	7.4	.0	115.3	.0
COAT-BAKE	107.3	7.4	.0	114.7	.0
ALIGN-EXPOSE	2.6	1.9	.0	4.4	.0
DEVELOP-BAKE	127.4	7.4	.0	134.8	.0
MESA ETCH 1	7.4	.7	2.8	10.9	.0
RINSE-DRY	.8	.2	4.5	5.5	.0
PLASMA CLEAN	2.5	1.0	.0	3.5	.0
MESA ETCH 2	7.7	.7	2.8	11.2	.0
CENTRIFUGE	2.3	.6	13.4	16.3	.0
PLASMA CLEAN	2.5	.9	.0	3.5	.0
HI PRESS. SCRUB	.0	2.6	12.1	14.6	.0
SILICON NITRIDE	27.8	30.0	.0	57.8	.0
COAT-BAKE	103.3	7.4	.0	110.7	.0
ALIGN-EXPOSE	2.5	1.8	.0	4.3	.0
DEVELOP-BAKE	122.6	7.4	.0	130.0	.0
DIELECTRIC ETCH	13.4	1.4	5.6	20.4	.0
PLASMA CLEAN	2.5	.9	.0	3.4	.0
HI PRESS. SCRUB	.0	2.5	11.2	13.7	.0
PLATING ETCH	6.4	1.4	5.6	13.4	.0
PD PLATE	188.3	2.7	7.1	198.1	877.9
CENTRIFUGE	2.3	.6	12.7	15.6	.0
SINTER 1	1.9	1.9	.0	3.8	.0
NI PLATE	45.2	2.7	7.1	55.0	1.1
CENTRIFUGE	2.3	.6	12.6	15.4	.0
SINTER 2	1.9	1.9	.0	3.8	.0
SOLDER COAT	102.4	11.5	13.7	127.6	622.8
CELL TEST	.0	.6	.0	.6	.0
CELL ATTACH	.0	6.0	.0	6.0	.0
MODULE CLEAN	.0	1.6	19.9	21.5	.0
MODULE ASSEMBLY	.0	2.1	.0	2.1	.0
RIVET-WELD	.0	.1	.0	.1	.0
CURE	.0	2.7	.0	2.7	.0
MODULE TEST	.0	.0	.0	.0	5488.6
TOTAL	13100.0	598.7	191.0	13889.7	9286.7

per 1000 wafers produced multiplied by the number of wafers processed in a particular process step per hour and the number of production hours in a year (5400). Wasted silicon is included in this category. Also included in this category are items which are dependant on the number of machines used as well as items which depend on the number of machines used factored by that machine's efficiency and utility factor. Electrical expense is the product of the total electrical power (as defined in Section 3.3.10), 8766 annual hours, and a variable power rate which is nominally $2\frac{1}{2}\text{¢/KWH}$. DIH_2O expense is the product of deionized water consumed per year times \$.0031/gallon. Material items are calculated on a per 1000 wafer basis as well as a variable initial silicon cost figure.

The key for Table 14 is:

PROCESS EXP (K\$)	=	Process expenses in 1000 dollar units
ELECT EXP (K\$)	=	Electrical power expenses in 1000 dollar units
WATER EXP (K\$)	=	Deionized water expenses in 1000 dollar units
TOTAL EXP (K\$)	=	Total expenses in 1000 dollar units
MATL (K\$)	=	Material costs in 1000 dollar units

3.5.7 OVERHEAD CALCULATIONS

Calculations of the overhead associated with each of the four factory phases are presented in Tables 15 through 18. In each phase, the total indirect labor census, payroll, and associated costs are identified. In addition, the indirect expenses, depreciation, interest, materials, and

TABLE 15

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 DIRECT LABOR CENSUS = 528 POWER RATE = 2.5 CENTS/KWH

OVERHEAD (K\$)			PHASE 1 = 6 MONTHS					
	CENSUS	PAYROLL	FRINGE	EXP	DEP	MAT	COM	TOTAL
DIRECT FACTORY	0	.0	.0	.0	.0	.0	.0	.0
ENGINEERING	4	46.0	4.6	16.8	.0	.0	.0	67.4
PRODUCTION CONT	0	.0	.0	.0	.0	.0	.0	.0
BLDG SERVICES	0	.0	.0	.0	.0	.0	.0	.0
MAINTENANCE	0	.0	.0	.0	.0	.0	.0	.0
MANAGEMENT	1	25.0	1.1	5.0	.0	.0	.0	31.1
MARKETING/SALES	0	.0	.0	.0	.0	.0	.0	.0
PURCHASING	1	11.0	1.1	2.2	.0	.0	.0	14.3
FINANCE	2	19.4	2.3	3.9	.0	.0	.0	25.6
SECRETARY POOL	1	4.4	1.1	.0	.0	.0	.0	5.6
DATA PROCESSING	0	.0	.0	.0	.0	.0	.0	.0
TRAINING	0	.0	.0	.0	.0	.0	.0	.0
PERSONNEL	1	11.0	1.1	1.1	.0	.0	.0	13.2
CAFETERIA	0	.0	.0	.0	.0	.0	.0	.0
LEGAL	0	.0	.0	9.0	.0	.0	.0	9.0
SECURITY	0	.0	.0	.0	.0	.0	.0	.0
HEALTH	0	.0	.0	.0	.0	.0	.0	.0
TOTAL	10	116.9	11.5	38.0	.0	.0	.0	166.4

TABLE 16

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 DIRECT LABOR CENSUS = 528 POWER RATE = 2.5 CENTS/KWH

OVERHEAD (K\$)			PHASE 2 = 6 MONTHS					
	CENSUS	PAYROLL	FRINGE	EXP	DEP	MAT	COM	TOTAL
DIRECT FACTORY	3	24.0	3.4	.0	.0	.0	.0	27.4
ENGINEERING	7	67.8	8.1	25.3	.0	.0	.0	101.2
PRODUCTION CONT	0	.0	.0	.0	.0	.0	.0	.0
BLDG SERVICES	1	4.7	1.1	247.7	.0	.0	.0	253.5
MAINTENANCE	4	45.0	4.6	5.0	.0	.0	.0	54.6
MANAGEMENT	2	40.0	2.3	8.0	.0	.0	.0	50.3
MARKETING/SALES	1	10.0	1.1	5.0	.0	.0	.0	16.1
PURCHASING	1	11.0	1.1	2.2	.0	.0	.0	14.3
FINANCE	2	19.4	2.3	3.9	.0	.0	.0	25.6
SECRETARY POOL	1	4.4	1.1	.0	.0	.0	.0	5.6
DATA PROCESSING	0	.0	.0	.0	.0	.0	.0	.0
TRAINING	13	64.0	14.9	6.4	.0	.0	.0	85.4
PERSONNEL	2	22.0	2.3	2.2	.0	.0	.0	26.5
CAFETERIA	0	.0	.0	.0	.0	.0	.0	.0
LEGAL	0	.0	.0	9.0	.0	.0	.0	9.0
SECURITY	0	.0	.0	.0	.0	.0	.0	.0
HEALTH	0	.0	.0	.0	.0	.0	.0	.0
TOTAL	37	312.5	42.5	314.7	.0	.0	.0	669.7

TABLE 17

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 DIRECT LABOR CENSUS = 528 POWER RATE = 2.5 CENTS/KWH

		OVERHEAD (K\$)		PHASE 3 = 6 MONTHS					
	CENSUS	PAYROLL	FRINGE	EXP	DEP	MAT	COM	TOTAL	
DIRECT FACTORY	30	159.0	34.5	.0	.0	.0	.0	193.5	
ENGINEERING	7	67.8	8.1	25.3	11.6	.0	.0	112.7	
PRODUCTION CONT	15	82.3	17.2	3.3	6.2	.0	.0	109.1	
BLDG SERVICES	7	32.9	8.0	247.7	.0	.0	.0	288.6	
MAINTENANCE	106	832.5	121.9	1046.2	.0	666.9	.0	2667.5	
MANAGEMENT	5	85.0	6.0	17.0	.0	.0	.0	108.0	
MARKETING/SALES	3	24.4	3.4	12.2	.0	.0	14.0	54.1	
PURCHASING	1	11.0	1.1	2.2	.0	.0	.0	14.3	
FINANCE	3	13.3	3.4	2.7	.0	.0	.0	19.5	
SECRETARY POOL	4	17.9	4.6	.0	.0	.0	.0	22.5	
DATA PROCESSING	1	10.0	1.1	26.0	.0	.0	.0	37.1	
TRAINING	13	64.0	14.9	6.4	.0	.0	.0	85.4	
PERSONNEL	4	37.4	4.6	3.7	.0	.0	.0	45.7	
CAFETERIA	0	.0	.0	3.7	.0	.0	.0	3.7	
LEGAL	0	.0	.0	9.0	.0	.0	.0	9.0	
SECURITY	3	13.2	3.4	.0	.0	.0	.0	16.7	
HEALTH	3	15.6	3.4	1.5	.0	.0	.0	20.6	
TOTAL	205	1466.6	236.0	1407.1	17.8	666.9	14.0	3808.4	

TABLE 18

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 DIRECT LABOR CENSUS = 528 POWER RATE = 2.5 CENTS/KWH

		OVERHEAD (K\$)		PHASE 4 = 60 MONTHS					
	CENSUS	PAYROLL	FRINGE	EXP	DEP	MAT	COM	TOTAL	
DIRECT FACTORY	42	2190.0	483.0	.0	.0	.0	.0	2673.0	
ENGINEERING	7	678.5	80.5	253.0	115.5	.0	.0	1127.5	
PRODUCTION CONT	15	823.5	172.5	32.9	62.5	.0	.0	1091.4	
BLDG SERVICES	7	329.0	80.5	2476.6	.0	.0	.0	2886.1	
MAINTENANCE	106	8325.0	1219.0	10462.5	.0	6668.8	.0	26675.3	
MANAGEMENT	5	850.0	60.0	170.0	.0	.0	.0	1080.0	
MARKETING/SALES	3	244.5	34.5	122.5	.0	.0	140.0	541.5	
PURCHASING	1	110.0	11.5	22.0	.0	.0	.0	143.5	
FINANCE	3	133.5	34.5	27.0	.0	.0	.0	195.0	
SECRETARY POOL	4	179.0	46.0	.0	.0	.0	.0	225.0	
DATA PROCESSING	1	100.0	11.5	260.0	.0	.0	.0	371.5	
TRAINING	7	375.0	80.5	37.5	.0	.0	.0	493.0	
PERSONNEL	4	374.0	46.0	37.4	.0	.0	.0	457.4	
CAFETERIA	0	.0	.0	37.5	.0	.0	.0	37.5	
LEGAL	0	.0	.0	90.0	.0	.0	.0	90.0	
SECURITY	3	132.5	34.5	.0	.0	.0	.0	167.0	
HEALTH	3	156.0	34.5	15.5	.0	.0	.0	206.0	
TOTAL	211	15000.5	2429.0	14044.4	178.0	6668.8	140.0	38460.7	

sales costs are identified for each phase and for each overhead category.

3.5.8 CALCULATION SUMMARY

For each phase, the computer program allows a variable time input.

A summary of costs for each of the four phases is shown in Table 19. Included in this table are material, expense, labor, overhead, interest, and depreciation for each phase. Totals of costs within each phase, totals of costs within a category for all four phases, and a total cost for the life of the factory are included in this table. This information is listed in actual K\$, \$/W, and percent of total cost for each category. Additionally, the selling price^{*} is determined by:

$$\text{Selling price (\$/Watt)} = \frac{\text{Total Cost}}{\text{Total Watts Produced} \times .85}$$
$$\text{Where Total Watts Produced} = \left(\frac{\text{Phase IV Months}}{12 \text{ months}} \times \frac{.25 \text{ Phase III Months}}{12 \text{ months}} \right) \times \text{Annual Watts Produced.}$$

Three further assumptions are that the manufacturer is in a 50% tax bracket, after tax profit is 7.5%, and 25% of the annual production is realized in Phase III.

* It is recognized that different methods of determining profit can be utilized in these calculations. Accordingly, it has been left as the last calculation. The reader can, if he chooses, utilize the manufacturing cost value presented in Table 19 to calculate a selling price based upon his own method of profit determination.

TABLE 19

DIFFUSION PROCESS 12.0 CM DIAMETER CELL
 25.0 MEGA WATT ANNUAL PRODUCTION 14 % CELL EFFICIENCY
 SILICON = \$25.00/KILOGRAM POWER RATE = 2.5 CENTS/KWH
 DIRECT LABOR CENSUS = 528 INTEREST RATE = 7.0 %

SUMMARY (K\$)

		MAT	EXP	LAB	OVR	INT	DEP	TOTAL
PHASE 1	6 MD	0	0	0	166	258	0	424
PHASE 2	6 MD	0	30	0	670	1879	38	2617
PHASE 3	6 MD	2322	3472	1956	3808	2890	1998	16446
PHASE 4	60 MD	46434	69449	29172	38461	16920	19981	220416
TOTAL COST		48755	72951	31127	43105	21946	22018	239903
TOTAL \$/WATT		.3805	.5694	.2429	.3364	.1713	.1718	1.8724
%		20.3	30.4	13.0	18.0	9.1	9.2	100.0

SELLING PRICE = 2.20 \$/WATT

3.6 RESULTS AND DISCUSSION

Results of the cost analysis are presented in this section. The results are shown in graphical form, and illustrate a sensitivity analysis of major cost parameters.

Due to the breadth of assumptions and variables incorporated into this analysis, erroneous conclusions could be drawn if a single value of cost for a manufacturing process were given. Accordingly, the results presented here examine the sensitivity to a group of important variable parameters. These parameters, presented earlier in Table 9, are the cell size, the manufacturing process, the cost of polycrystalline silicon, the encapsulated solar cell efficiency, the interest rate on borrowed money, the electrical power rate, the annual production volume, and the effect of production phase duration. Each of these parameters was assigned a nominal value, chosen such that the overall cost was relatively insensitive to small changes in this (nominal) value. Each of these parameters was individually varied over a broad range of values while all other parameters were held constant at their nominal values, allowing examination of cost sensitivity to the individual parameters.

Specific results for a given set of assumptions may, of course, still be obtained from the data. Such specific results must be viewed with the caveat that the result is only as accurate as the input assumptions. The absolute value of the cost data will change as a function of the assumptions. The trend of the costs, as a function of the key parameters varied here, is the most important information in the presented data, with the absolute value of the data being considered as being within an error band dependent upon the assumptions.

Each of the cost sensitivity graphs has costs plotted as a function of two solar cell diameters, 7.6 cm and 12 cm, for the chosen diffusion process sequence. It is reasonable to assume that the true costs will fall within the range of these two cost curves. In addition to the diffusion process sequence curves, a curve is also shown for the advanced ion implantation process sequence, incorporating an ion implanter yet to be developed. This curve is probably the lower bound for manufacturing costs for the 1982 time-frame. On each graph, the nominal value of the varied parameter is indicated by a dashed line.

A reminder is necessary at this time. A major cost assumption dealt with technology readiness for this study for the 1982 time-frame. This assumption limits the technology and automation of the process to essentially the present status. This cost analysis, thus, should not be utilized to make projections for 1985 and beyond! There should be no concern, thus, that \$0.50/watt is not shown on the curves presented here.

3.6.1 INFLATION FACTORS AND COST/PRICE CONSIDERATION

The present cost analysis is being performed with the most current technology and equipment information. Accordingly, all prices and costs used here reflect dollars with mid-1977 values. These, of course, can be directly compared only to other mid-1977 cost analyses unless a scaling factor to adjust for inflation is utilized. The dollar value basis for the LSSA Project is in 1975 dollars, and is defined as the value of dollars on January 1, 1975. A generalized inflation factor, which lumps all cost categories together, has been defined and is listed in Table 20. Accordingly, to arrive at approximate 1975 dollars, the costs identified in this study may be divided by a factor between 1.156 and 1.17. Different cost factors have inflated at different rates,

TABLE 20

LSSA PRICE DEFLATOR TABLE
DATED FOR 1978

QUARTER	1975	1976	1977	1978
1	1.024	1.081	1.136	1.198 (C)
2	1.036	1.094	1.156	1.121 (C)
3	1.053	1.107	1.170	1.230 (C)
4	1.071	1.121	1.183 (C)	

For a given year and quarter divide price by that number in table. Result = that price in January 1, 1975 dollars.

C = extrapolations

however, giving only an approximate value for the 1975 reference if such a factor is utilized. A precise adjustment would require different inflation adjustments for each individual cost item in labor, materials, overhead, etc. Since this cost analysis has many assumptions and, as specified earlier, is intended primarily to show sensitivity to certain important cost parameters, it has not been deemed fruitful to try to incorporate the additional complexity associated with utilizing such precise inflation adjustments. Further, due to its imprecise nature, the general inflation factor from Table 20 has not been utilized in this study. Accordingly, the cost data reported here are in mid-1977 dollars. Inflation adjustments are left to the reader.

The reader is reminded that data presented here is manufacturing cost data, while goals are selling price figures. The cost will be less than the price by an amount equal to the pretax profit. Since, in addition, the costs reported here are in mid-1977 dollars and price goals are quoted in 1975 dollars, confusion may arise in later discussions. It is suggested that, within the accuracy of the other assumptions, the pretax profit may be considered to be approximately equal to the deflator factor between 1975 and mid-1977 dollars. In this case, the data presented here as costs can be considered as comparable to 1975-based prices.

3.6.2 EFFECT OF POLYCRYSTALLINE SILICON COST ON MANUFACTURING COST

The effect of varying the cost of polycrystalline silicon over the range of zero to \$50/Kg is shown in Figure 2. The relation is linear against the manufacturing cost. For the smaller, 7.6 cm diameter solar cell and the nominal fixed values of the other parameters, the manufacturing cost is greater than \$2.00/watt at all prices of polycrystalline silicon. For these same nominal values a polycrystalline silicon cost of near \$40/Kg can result in a manu-

FIGURE 2. EFFECT OF POLYCRYSTALLINE SILICON COST ON MANUFACTURING COST

Annual Production Volume = 25 Megawatts
 Encapsulated Cell Efficiency = 14%
 Building Phase = 6 Months
 Equipment Phase = 6 Months
 Labor Phase = 6 Months
 Production Phase = 5 Years
 Interest Rate = 7%
 Power Rate = 2.5¢/KWH
 Cost Reference = Mid-1977 Dollars

facturing cost of less than \$2.00/watt for 12 cm diameter solar cells produced by a diffusion process.

3.6.3 EFFECT OF ENCAPSULATED CELL EFFICIENCY ON MANUFACTURING COST

The manufacturing cost is heavily dependent upon encapsulated solar cell efficiency, as shown in Figure 3. As the efficiency increases, such categories as labor, encapsulation materials, and capital investment (especially in the crystal growth area) decrease rapidly. At the nominal values cited, the diffusion process sequence requires greater than a 13% encapsulated cell efficiency for the larger diameter cell to achieve \$2.00/watt manufacturing cost.

3.6.4 EFFECT OF INTEREST RATE ON MANUFACTURING COST

Over the broad range of interest rates from 5% to 15%, the manufacturing cost for solar cells changes by less than 15%, Figure 4. The manufacturing cost, thus, is relatively insensitive to this parameter when compared with sensitivities to other parameters.

3.6.5 EFFECT OF ELECTRICAL POWER RATE ON MANUFACTURING COST

The manufacturing cost of solar cell modules is, over a wide range of power rates, quite insensitive to the electrical power rate. Analysis ranging from 2 cents per kilowatt hour to 25 cents per kilowatt hour, shown in Figure 5, indicates only an approximate 10% change in manufacturing cost between extremes of the range. The manufacturing cost is least sensitive to this important parameter (of all the parameters studied for sensitivity).

3.6.6 EFFECT OF ANNUAL PRODUCTION VOLUME ON MANUFACTURING COST

Manufacturing costs are extremely sensitive to annual production volume as seen in Figure 6. Manufacturing costs cannot approach \$2.00/watt until

FIGURE 3: EFFECT OF ENCAPSULATED CELL EFFICIENCY ON MANUFACTURING COST

FIGURE 4: EFFECT OF INTEREST RATE ON MANUFACTURING COST

Annual Production Volume = 25 Megawatts
 Encapsulated Cell Efficiency = 14%
 Polycrystalline Silicon Cost = \$25/Kilogram
 Building Phase = 6 Months
 Equipment Phase = 6 Months
 Labor Phase = 6 Months
 Production Phase = 5 Years
 Power Rate = 2.5¢/KWH
 Cost Reference = Mid-1977 Dollars

FIGURE 5: EFFECT OF ELECTRICAL POWER RATE ON MANUFACTURING COST

Annual Production Volume = 25 Megawatts
 Encapsulated Cell Efficiency = 14%
 Polycrystalline Silicon Cost = \$25/Kilogram
 Building Phase = 6 Months
 Equipment Phase = 6 Months
 Labor Phase = 6 Months
 Production Phase = 5 Years
 Interest Rate = 7%
 Cost Reference = Mid-1977 Dollars

annual volumes above 5 megawatts are achieved. The cost category contributors to this large production volume sensitivity are illustrated in Figures 7 and 8 for the 12 cm diameter cell manufactured by the diffusion sequence. Figure 7 plots each cost category as a function of the dollar contribution, while Figure 8 replots the same data for each cost category as a percent of the total cost. The manufacturing cost sensitivity is overwhelmingly predominated by one cost category: overhead. The overhead assumptions, Section 3.3.8 indicate that there are certain fixed costs which must be diluted with volume to reduce costs.

Beyond the overhead contribution, the interest, depreciation, and labor cost categories indicate more efficient labor, factory, and equipment utilization with increased volume (an expected result). Expense and material items predominate at increased volumes, requiring reductions in consumed materials to reduce long range costs.

3.6.7 EFFECT OF FACTORY LIFE ON MANUFACTURING COSTS

The duration of the production phase of factory life is very influential on manufacturing costs, while the duration of the building, equipment, and labor phases is much less significant. These factors are plotted in Figure 9 for each of the three size-process sequence combinations shown in previous figures. The production phase must be at least of 3 years duration to approach \$2.00/watt manufacturing costs.

Contribution of individual cost categories to the total cost are shown for the 12 cm cell manufactured by the diffusion process in Figure 10 as actual cost contributors, and in Figure 11 as a percentage of the total cost. For short factory production times, depreciation is the dominant cost factor. This reflects the fact that equipment must be fully depreciated by the end of

FIGURE 7: EFFECT OF ANNUAL PRODUCTION VOLUME ON MANUFACTURING COSTS
SHOWN AS DOLLAR FUNCTION OF INDIVIDUAL COST CATEGORIES

FIGURE 8: EFFECT OF ANNUAL PRODUCTION ON MANUFACTURING COSTS
SHOWN AS PERCENT CONTRIBUTION OF INDIVIDUAL COST CATEGORIES

FIGURE 10: EFFECT OF PRODUCTION PHASE DURATION ON MANUFACTURING COSTS
SHOWN AS DOLLAR FUNCTIONS OF INDIVIDUAL COST CATEGORIES

FIGURE 11: EFFECT OF PRODUCTION PHASE DURATION ON MANUFACTURING COSTS
SHOWN AS PERCENT CONTRIBUTIONS OF INDIVIDUAL COST CATEGORIES

the factory life. Also, consumed materials, reflected as expense and materials items, predominate for long factory lives.

Two major effects of factory life associated with depreciation and total costs become apparent. The first deals with salvage value of the equipment, and the second involves introduction of advanced manufacturing technologies.

3.6.7.1 SALVAGE VALUE OF EQUIPMENT

The argument has been presented in numerous forums that outmoded equipment from solar cell manufacturing can be absorbed at a reasonable salvage value into the existing semiconductor industry. While this may be factual at very low solar cell production volumes, it is fallacious at reasonable solar cell volumes.

As will be presented in Section 3.7, the major equipment capital investment is in the crystal growth area. Absorption of crystal pullers of the size assumed in this study (the so called "olympic class" size) must occur into the silicon semiconductor industry.

An evaluation of the marketability of this equipment in the 1978 - 1985 time frame shows, that at best, limited resale can be achieved. Specifically, crystal pullers in the "olympic class", (≥ 20 Kg melt capacity) that have an original value of \$125K each represent nearly 50% of the initial capital equipment investment and greater than 4% of the total manufacturing cost. For an annual manufacturing volume of 25 MW, about 80 such crystal pullers are necessary. This quantity of crystal pullers represents approximately 40% of the estimated number (200) of large pullers currently existing in the world. It is further found that of the 200 units now in existence, utilization may currently be something less than 50%. Smaller capacity pullers are now rapidly becoming obsolete, saturating a resale market. The semiconductor manufacturing market could not be expected to absorb the quantity of crystal pullers estimated here.

It is, therefore, concluded that the total depreciation of equipment within the factory life is a reasonable requirement.

3.6.7.2 OBSOLESCENCE BY NEW TECHNOLOGY INTRODUCTIONS

Cost projections for solar cell modules show an anticipated price (in 1975 dollars) of \$2.00/watt in 1982, \$1.50/watt in 1983, \$1.00/watt in 1984, and \$0.50/watt by 1986. It is assumed that this price reduction will be achieved through major technology advances which will reduce the costs of polycrystalline silicon, single crystal silicon substrates, solar cell processing, and encapsulation. Further, it is assumed that these technology advances will be so significant that present technology will, in essence, be obsoleted.

The more optimistic data presented in previous sections show manufacturing costs with present technology and large volumes to reach nearly \$1.50/watt. Little or no further reductions can be expected beyond that point, and even that point may not be achievable with present technology.

A manufacturer deciding to build a factory which utilizes present technology (a necessary factor if the factory is to be operative in 1982) to achieve a selling price near \$2.00/watt faces extreme risks. If the price goal of \$1.50/watt for 1983 or \$1.00/watt for 1984 is realized by a competing advanced technology, and if the manufacturer's cost in his 1982, \$2.00/watt factory is above \$1.50/watt, he cannot compete in the market in 1983, and must close or lose money. The factory life, then, is essentially one year. Observing the data in Figure 9, the manufacturer cannot achieve a cost of \$2.00/watt with a one year factory life. A further restraint exists. If the total available market in 1982 is 25 megawatts, no one manufacturer is likely to control much more than 5 to 10 megawatts of that market. Referring back to Figure 6 for manufacturing costs at 5 to 10 megawatts annual production and combining that information with the data in Figure 9, an

even higher manufacturing cost results. The obvious conclusion is not to build the factory.

Several alternatives exist to this argument, but risks must be assumed by some group in any case.

The first option is to build the factory as soon as possible such that product manufactured at a \$2.00/watt cost can be sold at a premium in 1980 and 1981, lengthening production life and increasing profitability using today's technology. Alternatively, the manufacturer may forward contract his production for 1983 and 1984 at \$2.00/watt to a customer who doubts the availability of cheaper modules in that time-frame. In either case, sufficient market must exist to purchase his entire production. (It must be further assumed that a sufficiently sized market will exist only if the price is low enough to support it!)

Another alternative is merely to wait until the technology advances occur, and implement them in the factory which drives the \$2.00/watt factory out of business. In doing so, the manufacturer must assume that he can capture sufficient market share with his new technology and low price that he is not excluded from entering the market at that late date, risking his business on a sudden volume jump rather than on a continuously increasing volume.

Still another alternative is that the advanced technology will not be timely. If advances are sufficiently slowed, by 2 years, for example, the factory could be justified economically. On the contrary, however, if technology advances were accelerated, it is already too late to build the \$2.00/watt factory.

If a major portion of the costs could be eliminated, the factory could be built. From this study, the most effectively reduced major costs are those associated with capital equipment. If such equipment were provided, or if a market could be found to absorb it cost-effectively at the end of a short factory life, the factory could be built and run profitably.

3.7 DISTRIBUTION OF MANUFACTURING COSTS BETWEEN PROCESS AREA GROUPINGS

The manufacturing process sequence for fabrication of solar cell modules can be conveniently considered to be composed of three process sub-sequences: silicon wafer (or sheet) formation, cell manufacturing, and module fabrication (including interconnection and encapsulation). For the defined nominal values of all variable parameters, a cost breakdown has been made (for each of the cost categories) between these three process sub-sequences. Data are presented in Tables 21 through 24. Table 21 shows calculated dollar costs for each category by sub-sequence. Table 22 shows these calculated dollars as a percentage of the total cost. Table 23 shows the percentage by individual cost category totals of each sub-sequence. Table 24 presents the percentage costs by cost category within each process sub-sequence. While many observations can be made, several of them are striking. First, the single largest cost item involves expenses incurred in wafer fabrication. This is primarily a result of silicon wasted from crystal cropping and wafer sawing. Major cost reductions can be envisioned with a direct sheet growth process. Second, the largest capital contribution (seen as a function of depreciation) is again in the wafer fabrication area. Third, automation of cell processing is a fruitful cost reduction measure. Finally, reduced encapsulation requirements for cells will dramatically reduce encapsulation materials costs.

3.8 A SAMPLE FACTORY LAYOUT: 5 MEGAWATT ANNUAL PRODUCTION

The factory layout shown in Figures 12 and 13 represents the equipment facilitization, and area necessary to fabricate 5 megawatts of silicon solar cell modules annually. For this illustration, 12 cm diameter cells and a diffusion process are selected. All other variables are the "nominal" values used throughout this report. This facility was selected for illustration

FIGURE 12: SAMPLE PLAN VIEW OF A FACTORY CAPABLE OF PRODUCING 12 cm SOLAR CELLS AT AN ANNUAL PRODUCTION VOLUME OF 5 MEGAWATTS.

TABLE 21: Cost, in dollars, in each cost category for wafer preparation, cell fabrication, and module fabrication. Costs are for a 12 cm diameter cell manufactured by a diffusion process. All variable parameters are at the defined nominal values.

COST CATEGORY		WAFER	CELL	MODULE	TOTAL
Material	K\$	12166	7962	29327	49455
Expense	K\$	63613	9192	145	72951
Labor	K\$	6910	21945	2303	31127
Overhead	K\$	24699	15216	3190	43105
Interest	K\$	9615	10055	2399	22002
Depreciation	K\$	11912	7354	2796	22018
TOTAL	K\$	128915	71724	40161	240658

TABLE 22: Costs from Table 21 as a percent of the total cost for each cost category and process sub-sequence.

		WAFER	CELL	MODULE	TOTAL
Material	%	5.0	3.3	12.1	20.5
Expense	%	26.6	3.8	0.1	30.5
Labor	%	2.8	8.9	0.9	12.6
Overhead	%	10.3	6.4	1.3	18.0
Interest	%	4.0	4.2	1.0	9.1
Depreciation	%	5.0	3.1	1.2	9.2
TOTAL	%	53.8	29.7	16.6	100.0

TABLE 23: Costs from Table 21 as a percent of each cost category.

		WAFER	CELL	MODULE	TOTAL
Material	%	24.6	16.1	59.3	100
Expense	%	87.2	12.6	0.2	100
Labor	%	22.2	70.5	7.4	100
Overhead	%	57.3	35.3	7.4	100
Interest	%	43.7	45.7	10.9	100
Depreciation	%	54.1	33.4	12.7	100

TABLE 24: Costs from Table 21 as a percent of each process sub-sequence.

		WAFER	CELL	MODULE
Material	%	9.4	11.1	73.0
Expense	%	49.5	13.0	0.4
Labor	%	5.2	30.0	5.6
Overhead	%	19.2	21.5	8.0
Interest	%	7.4	14.1	6.0
Depreciation	%	9.3	10.4	7.0
TOTAL		100.0	100.0	100.0

purposes to show the size of a factory that would probably be necessary based on potential market size and the probable market share of any given manufacturer.

In the crystal growth area, sixteen large volume Czochralski crystal pullers are shown. These crystal pullers are 98.4% utilized and the area requires six direct labor personnel per shift.

The wafer preparation area contains all crystal sawing and etching operations. It is from this area that all solar cell material is prepared.

The three silicon solar cell processing areas (junction formation, photolithography, and metallization) are located contiguous to each other in order to establish an efficient material flow between the several processing steps. In each area, the machinery used, its utilization, and labor requirements are determined for maximum cost effectiveness.

Testing of finished silicon solar cells, assembly of these cells into modules, and subsequent testing of modules is located in the assembly area. The output from this area feeds directly into a shipping warehouse which is designed to accomodate a one month manufacturing volume.

The remainder of the factory, which is not shown in detail, is intended for all manufacturing support functions. Required industrial services are shown on the corner of the building in close proximity to all of the required usage points.

For this example, a total of 111 direct labor personnel and 93 indirect personnel are required. Parking and other related facilities are designed for this number of people.

4.0 CONCLUSIONS

A number of significant conclusions may be drawn from this cost analysis.

4.1 CELL EFFICIENCY

Future solar cell modules must have high conversion efficiency to be cost effective, the higher the efficiency the better. Solar cells with less than 13% to 14% encapsulated efficiency are unlikely to meet a \$2.00/watt selling price goal if Czochralski crystal growth, sawing, and high quality encapsulation are required. At the defined nominal values of the variable parameters, a cell efficiency of greater than 13% is required. At lower production volumes or in factories with useful lives less than five years, a still greater cell efficiency would be required. Processes for either wafer production or cell fabrication which result in lower cell efficiencies are unsuitable for future goals.

4.2 INCREASED ELECTRICAL POWER COSTS

As electrical power costs escalate in the future, the effect on the manufacturing cost of solar cells is relatively small. This leads to the conclusion that as alternative energy sources increase in price, solar cell energy production becomes increasingly cost effective and attractive.

4.3 COST INFLUENCES OF THE BUSINESS CYCLE

The manufacturing cost of solar cell modules is relatively insensitive to the interest rate on borrowed money. Accordingly, manufacturing costs for solar cell modules will be stable in the normal business cycle of fluctuating interest rates.

4.4 RISKS FOR THE 1982 - \$2.00/WATT GOAL

The risks, without additional incentives, are too great for a manufacturer to build a factory utilizing available technology to meet a \$2.00/watt goal in 1982. Technology advances can readily obsolete such a factory before it can be run long enough to be profitable. Due to competition, it is probable that no single manufacturer will have a market share of greater than 5 to 10 megawatts in a total market near 25 megawatts in 1982. This volume is marginal in effecting sufficient efficiency of operation to meet the \$2.00/watt goal.

One (or both) of two courses is open to achieve the \$2.00/watt goal at volume. First, forward contracting of several years production at \$2.00/watt can be considered. Second, capital equipment costs can be significantly reduced in either case, the government is the only probable source of such funding. Without such funding, it is questionable whether or not \$2.00/watt can be achieved in 1982.

4.5 RESEARCH AND DEVELOPMENT FUNDING

Several areas of technology advancement would be especially fruitful in reducing costs. Significant savings can be achieved if capital and expense costs can be reduced in the crystal growth and sawing areas. The cost of polycrystalline silicon should be minimized, but, by itself, is not sufficient to reduce costs to very long range goals. The crystal growth and sawing capital costs could be reduced if there is developed by that time an effective direct silicon sheet growth technology (which will, later, permit ultimate goals to be achieved). Other fruitful areas include automation of processing to reduce labor contributions to costs, and minimization of encapsulation requirements to lower costs of materials consumed.

5.0 RECOMMENDATIONS

No specific recommendations are given in this reporting period.

6.0 CURRENT PROBLEMS

No specific problems have occurred to date of this report.

7.0 WORK PLAN STATUS

The work plan, as previously noted, is behind schedule. Efforts are expanding to correct delays.

8.0 LIST OF ACTION ITEMS

No items requiring unusual action have come to light during this report period.

9.0 MILESTONES

Status of the program is shown in the Milestone Prediction and Accomplishment Chart Figure 14.

FIGURE 14

MILESTONE ACCOMPLISHMENT AND PREDICTION CHART

PREDICTED

ACCOMPLISHED

	A	M	J	J	A	S	O	N	D	J
Financial Management and Cost Reports	▲	▲	▲	▲	▲	▲	△	△	△	△
Monthly Technical Progress Reports		▲	▲		▲			△		
Quarterly Reports						△	▲			
Annual Report	▲									
Final Report										△
Progress Meetings		▲					▲			
Task Integration Meetings					▲				△	

FIGURE 14(continued)
MILESTONE PREDICTION CHART
REPORTS AND DOCUMENTATION

△ SCHEDULE

▲ DELIVERED