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PROCESSING EXPERIMENTS ON NON-CZOCHRALSKI SILICON SHEET (MEPSDU SUPPORT CONTRACT)

FINAL REPORT

APRIL 1981

JPL CONTRACT NO. 955844

PREPARED BY

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THE JPL LOW-COST SOLAR ARRAY PROJECT IS SPONSORED BY THE U.S. DEPARTMENT OF ENERGY AND FORMS PART OF THE SOLAR PHOTOVOLTAIC CONVERSION PROGRAM TO INITIATE A MAJOR EFFORT TOWARD THE DEVELOPMENT OF LOW-COST SOLAR ARRYS. THIS WORK WAS PERFORMED FOR THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY BY AGREEMENT BETWEEN NASA AND DOE.

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ABSTRACT

A program of six months duration was performed to support and promote the further development of processing techniques which may be successfully and cost-effectively applied to low-cost non-Czochralski silicon sheet for solar cell fabrication. Results are reported in the areas of process technology, cell design, cell metallization, and production cost simulation.

1.0 SUMMARY

There are four general areas of work which were pursued to enhance the processing and utilization of non-Czochralski silicon sheet.

In the process technology area, empirical studies were performed to evaluate the effects of texture-etching non-Cz substrates, and to determine etch rates for isotropic caustic etching, both of which might be used as surface preparation techniques prior to solar cell processing. Silicon substrate drying techniques were evaluated, and drying experiments were performed. Considerations for solar cell substrate handling have been formulated, with particular application to vacuum and controlled ambient processing.

Cell design efforts resulted in the development of a computational program (in the BASIC language) for determining optimum metallization patterns for rectangular, non-Cz substrates. The computational technique and mathematical foundation for the program are described.

Metallization experiments were performed to characterize the differences between non-Cz substrates and Cz wafers with respect to nickel contact formation and thermal cycle degradation. Feasibility of using electroless copper to form the conductive layer on top of a nickel contact was established.

A detailed narrative description of the current Motorola solar cell/module costing program is presented. Included is a discussion of the costing methodology, the required inputs to the program, and the simulation output formats. Differences and similarities of the Motorola program to the JPL SAMIS procedure have been characterized.

2.0 INTRODUCTION

The JPL Low Cost Solar Array (LSA) Project, through the Phase I and Phase II efforts of the Automated Array Assembly Task, has sponsored the development of high volume, low cost process sequences suitable for production of commercial terrestrial silicon solar cells and photovoltaic modules. Much of this development work has been executed with single crystal Czochralski silicon wafers and substrates. Under the present contract, Motorola further developed low-cost processes for the manufacture of solar cells from non-Czochralski (non-Cz) silicon sheet forms, using Ribbon-to-Ribbon (RTR) substrates in particular, and other non-Cz material such as Westinghouse web-dendritic samples and Wacker-Silso cast poly substrates, as available.

Particular development emphasis was placed on material preparation, metallization, and solar cell production technology requirements which may be unique for non-Cz silicon sheet substrates. Where practical and desirable, processes presently available to the LSA Project for production of solar cells from single crystal silicon wafers were adapted and utilized for the non-Cz substrates.

An additional task undertaken was the evaluation of non-Cz process sequence cost effectiveness by using both a Motorola cost analysis program and the JPL SAMICS procedure. A comparison between the two costing techniques has been formulated.

3.0 TECHNICAL DISCUSSION

3.1 PROCESS TECHNOLOGY

As a rapid, and yet meaningful, means of evaluating non-Cz material preparation and production technology development, a baseline cell fabrication sequence using a simple phosphorus diffusion and mesa etch technique has been employed. The basic cell process sequence is as follows:

1) Blanket phosphorus diffusion, PH_3 at 900°C;
2) Mesa junction etch, photoresist with a plasma etch for silicon;
3) Silicon nitride coat, LPCVD Si_3N_4 at 780°C;
4) Ohmic pattern, plasma etch;
5) Metal plate, nickel-copper or palladium-nickel-copper.

3.1.1 MATERIAL PREPARATION: TEXTURING

The sequence listed above has been used to evaluate the effects and usefulness of texturing the surfaces of non-Cz substrates. Since non-Cz substrates, and in particular RTR ribbon silicon, may consist of large grains of single crystal silicon with various orientations, the result of using a texture etch process is not predictable as it is for <100> Cz wafers. In addition, each non-Cz silicon ribbon may have different grain orientation patterns, and so care must be exercised in judging the effects of texturing the surface. One particular ribbon may texture very well while another may be much less affected by the texturing solution.

To circumvent the question of uniformity for non-Cz substrates and yet make a side-by-side comparison of textured and non-textured ribbon cell performance, a special preparation sequence was added ahead of the baseline process. Silicon ribbons were first coated with silicon nitride on both front and back to serve as a mask against attack in the texture etch solution. Then, using photoresist, the entire back and one half of the front of each ribbon was protected, lengthwise, and the nitride was etched from the other half of the front. The resist was stripped and the exposed silicon was textured. Then the remaining nitride was stripped. This results in a ribbon substrate which is front surface textured along one half of its width, while the other half is in the as-grown condition. On such substrates, adjacent pairs of cells 1 cm x 2 cm are formed by the baseline process. Thus, one cell of each cell pair is textured and one is non-textured. This geometry is diagrammed in Figure 1.1.

The first experiment initiated to study the effects of surface preparation for p-type, non-Cz (RTR) substrates consisted of 10 ribbons prepared as described above. In all, 65 pairs of textured/non-textured cells were established, although some of these cells are not useful because of mechanical imperfections. Such imperfections consist of substrate fractures and defects in mesa etched junctions and metal contacts. Because of possible non-uniformities down the length of non-Cz ribbons, only cell pairs for which both of the adjacent textured and non-textured cells were intact are included in the data analysis.

Table 1.1 lists data for 48 pairs of textured/non-textured cells. In many cases short circuit current was larger for the textured cell of the pair (32 out of the 48 examples) while in some cases I_{SC} was greater for the non-textured cell (15 out of the 48 examples). For those cells where increased current was associated with texturing, the average increase was 2.1 mA or about 4.3%. For those cells where decreased current was associated with texturing the average decrease was 1.6 mA or about 3.2%. Overall, the average for the 48 pairs was an increase of 0.9 mA, or about 1.9%, which might be attributed to texturing. This is considerably less than the 8 - 9% increase which may be

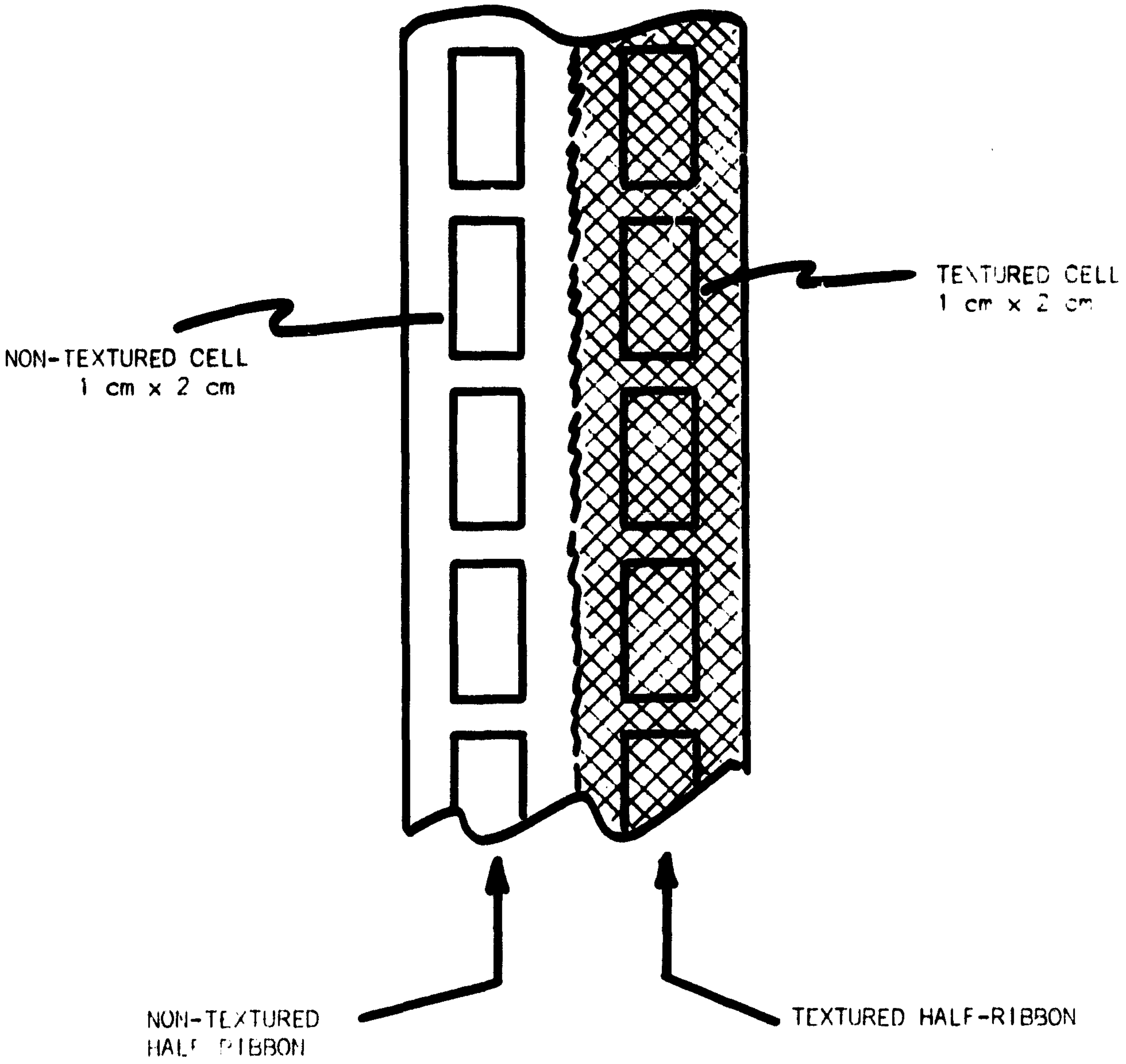

FIGURE 1.1: SCHEMATIC OF SUBSTRATES USED FOR TEXTURE ETCH AND SURFACE ETCH STUDIES.

TABLE 1.1: CELL PAIR DATA (SHORT CIRCUIT CURRENT, I_{SC}) FOR TEXTURED/NON-TEXTURED CELL COMPARISON

		TEXTURED I_{SC} (mA)	NON-TEXTURED I_{SC} (mA)	INCREASE DUE TO TEXTURE
RIBBON	1			
CELL	3	49.3	48.1	1.2
	4	49.5	48.1	1.4
	5	48.6	48.1	0.5
	7	49.9	48.8	1.1
	8	47.5	47.9	-0.4
	9	45.4	49.5	-4.1
	10	45.7	49.4	-3.7
	11	45.8	49.3	-3.5
RIBBON	2			
CELL	1	50.2	49.2	1.0
	2	49.2	47.4	1.8
	3	47.9	45.8	2.1
	4	47.9	47.1	0.8
	5	46.8	45.8	1.0
	6	48.7	49.3	-0.6
	7	49.4	50.6	-1.2
	9	51.8	50.0	1.8
	10	49.7	51.4	-1.7
RIBBON	3			
CELL	1	51.5	51.0	0.5
	2	53.0	50.5	2.5
	3	53.5	50.1	3.4
	4	53.9	48.0	5.0
	5	54.0	50.6	3.4
	6	51.2	51.7	-0.5
RIBBON	4			
CELL	2	48.1	49.0	-0.9
	3	46.0	48.4	-2.4
	4	47.9	48.2	-0.3
	9	50.3	48.1	2.2
	10	47.4	48.1	-0.7
	11	48.0	48.4	-0.4

TABLE 1.1 (Continued)

		TEXTURED I_{SC} (mA)	NON-TEXTURED I_{SC} (mA)	INCREASE DUE TO TEXTURE
RIBBON	5			
CELL	1	47.2	49.9	-2.7
	2	50.2	50.8	-0.6
	3	50.3	50.0	0.3
	4	51.1	47.7	3.4
	5	51.3	46.7	4.6
	6	50.0	48.8	1.2
	7	49.1	48.2	0.9
RIBBON	6			
CELL	2	48.6	38.5	10.1
	3	50.0	49.7	0.3
	4	48.9	48.4	0.5
RIBBON	7			
CELL	3	52.0	51.6	0.4
RIBBON	8			
CELL	1	55.0	52.0	3.0
	2	55.2	53.2	2.0
	3	54.6	49.4	5.2
	4	55.2	52.0	3.2
RIBBON	9			
CELL	3	55.0	53.4	1.6
	4	55.0	55.0	0.0
	5	55.3	54.2	1.1
RIBBON	10			
CELL	1	59.4	58.6	0.8
AVERAGE		50.4 mA	49.5 mA	0.93 mA
STD. DEV.		3.1 mA	2.9 mA	2.5 mA
% STD. DEV.		6.2%	5.8%	

expected when incorporating textured surfaces for solar cells fabricated on single crystal Czochralski substrates (which already employ an effective AR coating).

A second experiment was established to corroborate the results of the first. This second experiment consisted of 12 ribbons with cells fabricated by the baseline processes previously discussed to provide side-by-side pairs of textured/non-textured comparison cells. Of the ribbons processed, six provided cells useful for evaluating surface comparisons. Twelve out of 27 cell pairs appeared to allow direct evaluation of textured surface effects. In general, the results of this experiment supported the observations of the first experiment in that there was little difference of statistical significance between the performance of textured and non-textured multicrystalline silicon ribbon (RTR). The short circuit current comparison data for these cells are given in Table 1.2.

The improvement in light absorption, and hence short circuit current, obviously depends on the degree to which various grain orientations present in non-Cz substrates may be textured. Different non-Cz materials will possess different groups of grain orientations, and each class of material must be evaluated separately to determine if a texture-etching process is beneficial.

To address, in part, the question of material differences, a number of wafers sliced from Wacker-Silso cast polycrystalline ingots were also processed in the fashion described above to form pairs of textured/non-textured cells. The results of this experiment are tabulated in Table 1.3. Nine substrate slices were processed to form cell pairs identical in size and configuration to those of the first and second experiments. Unlike the first two experiments, comparison of the cell pairs on the cast poly substrates predicts a consistent improvement in generation current for the textured cell. For the 27 sample pairs of Table 1.3, the textured cells generate an average of 3.1% more current than the non-textured

TABLE 1.2: CELL PAIR DATA FOR SECOND EXPERIMENT COMPARING TEXTURED/NON-TEXTURED CELLS

	TEXTURED I_{SC} (mA)	NON-TEXTURED I_{SC} (mA)	INCREASE DUE TO TEXTURE
RIBBON 3*			
CELL 2	44	49	-5
3	44	49	-5
RIBBON 4*			
CELL 1	51	49	2
RIBBON 5*			
CELL 2	47	49	-2
3	49	49	0
4	47	49	-2
6	50	49	1
RIBBON 8			
CELL 2	46.0	43.2	2.8
3	46.3	44.7	1.6
5	46.0	43.3	2.7
RIBBON 10			
CELL 4	43.3	42.2	1.1
RIBBON 12			
CELL 4	42.8	43.3	-0.5
AVERAGE	46.4mA	46.6mA	-0.3mA
STD. DEV.	2.6ma	3.0mA	2.7mA
% STD. DEV.	5.7%	6.4%	

*Data taken to nearest mA.

TABLE 1.3: CELL PAIR DATA (SHORT CIRCUIT CURRENT) FOR TEXTURED/NON-TEXTURED CELL COMPARISON ON CAST POLYCRYSTALLINE SILICON SUBSTRATES.

	TEXTURED I_{SC} (mA)	NON-TEXTURED I_{SC} (mA)	INCREASE DUE TO TEXTURE
SLICE A			
CELL 1	54.2	51.0	3.2
3	53.0	51.2	1.8
SLICE B			
CELL 1	52.9	51.5	1.4
2	52.5	51.6	0.9
3	51.8	50.4	1.4
SLICE C			
CELL 1	52.3	51.0	1.3
2	54.4	51.0	3.4
3	54.4	51.9	2.5
4	52.3	48.7	3.6
SLICE D			
CELL 1	49.8	49.5	0.3
2	54.1	51.6	2.5
3	50.1	51.4	-1.3
SLICE E			
CELL 1	52.5	50.6	1.9
2	48.9	49.4	-0.5
SLICE F			
CELL 1	54.8	50.1	4.7
2	52.5	49.9	2.6
3	54.1	49.8	4.3
SLICE G			
CELL 1	51.6	49.5	2.1
2	50.5	49.6	0.9
3	52.4	52.2	0.2
4	52.3	51.0	1.3
SLICE H			
CELL 1	53.2	52.4	0.8
2	52.5	52.3	0.2
3	53.5	52.6	0.9
SLICE I			
CELL 1	49.8	49.0	0.8
2	52.0	51.3	0.7
3	51.1	49.8	1.3

TABLE 1.3: (Continued)

	TEXTURED I_{SC} (mA)	NON-TEXTURED I_{SC} (mA)	INCREASE DUE TO TEXTURE
AVERAGE	52.4mA	50.8mA	1.6mA
STD. DEV.	1.6mA	1.1mA	1.4mA
% STD. DEV.	3.0%	2.2%	

cells. The consistency of the results of this experiment may be attributed to the relatively small grain size of the cast polycrystalline substrates which were processed. Each cell consisted of a large number of grains and tended, on the average, to approximate the same grain structure exhibited by every other cell. Even so, the net effect of texturing is less beneficial than that for a <100> oriented single crystal surface.

3.1.2 MATERIAL PREPARATION: ISOTROPIC ETCHING

An experimental evaluation of caustic etching techniques for thinning or smoothing Cz or non-Cz substrates has been accomplished. The thickness of a silicon substrate can be reduced, and the smoothness of its surface increased, by etching the substrate in sodium hydroxide solutions at elevated temperatures.

In practice, a solution of approximately 10% by weight is used and is prepared by diluting commercially available 15 weight percent aqueous sodium hydroxide solution with half of its volume of D.I. water. For example, to 3 liters of 15% NaOH solution, 1.5 liters of D.I. water is added. The solution is then heated to its boiling point of 102°C and is ready for use.

Silicon substrates are loaded into teflon etch boats and are covered or weighed down to prevent floating. The etch process evolves considerable quantitites of gas which may interfere with etching. For this reason, substrates are positioned vertically when etching, and a weight is used to restrain the waters in case they become bouyant. Etching proceeds in the absence of agitation, since the gas bubbles formed provide liquid movement sufficiently vigorous to assure an even etching. After etch, the silicon surfaces are rinsed in D.I. water and dried.

During etching, the silicon surface is generally changed to a gently quilted topography regardless of its original appearance; both flat polished and very rough surfaces adopt the quilted configuration.

Silicon substrates are reduced in thickness by varying amounts, depending on the method of preparation of the substrate (initial surface roughness) and the crystalline nature of the silicon (orientation, grain boundaries, etc.). Representative etch rates have been determined for three specific types of material: smooth Cz wafers, Wacker-Silso polycrystalline slices, and Motorola RTR substrates.

Standard Cz wafers of <100> orientation (1 Ω-cm, boron doped) have been determined to etch at the rate of 0.129 mils/minute per surface. Hence, bare wafers, exposed to the etch solution on both sides, will be thinned at the rate of 0.258 mils/minute with the boiling 10% NaOH etch. The experimental data from which this rate is derived are graphed in Figure 1.2.

Experiments with Wacker-Silso polycrystalline slices (4 inch square) indicated that an approximate thickness loss of 0.30 mils/minute (0.15 mil per side) would be obtained under the same etch conditions. This is quite similar to standard Czochralski wafer etch rates. It is apparent that sodium hydroxide etching is an inexpensive and rapid method for removing saw damage from such slices.

Experiments with Motorola RTR substrates have yielded faster (and more variable) etch rates. Thickness losses have ranged between 0.40 and 0.55 mils/minute when simultaneously etching both sides of a ribbon. A difference between RTR and Silso substrates is that the RTR material etched for this experiment has very few (and mostly benign) grain boundaries, but regions within grains of high dislocation density, whereas the Silso slices have active (and many) grain boundaries, but few dislocations within the grains. An etching process may be useful for smoothing surface fluctuations in RTR material; however, since original surfaces are smooth and clean, it is not known at this time whether any surface etching prior to cell fabrication is necessary.

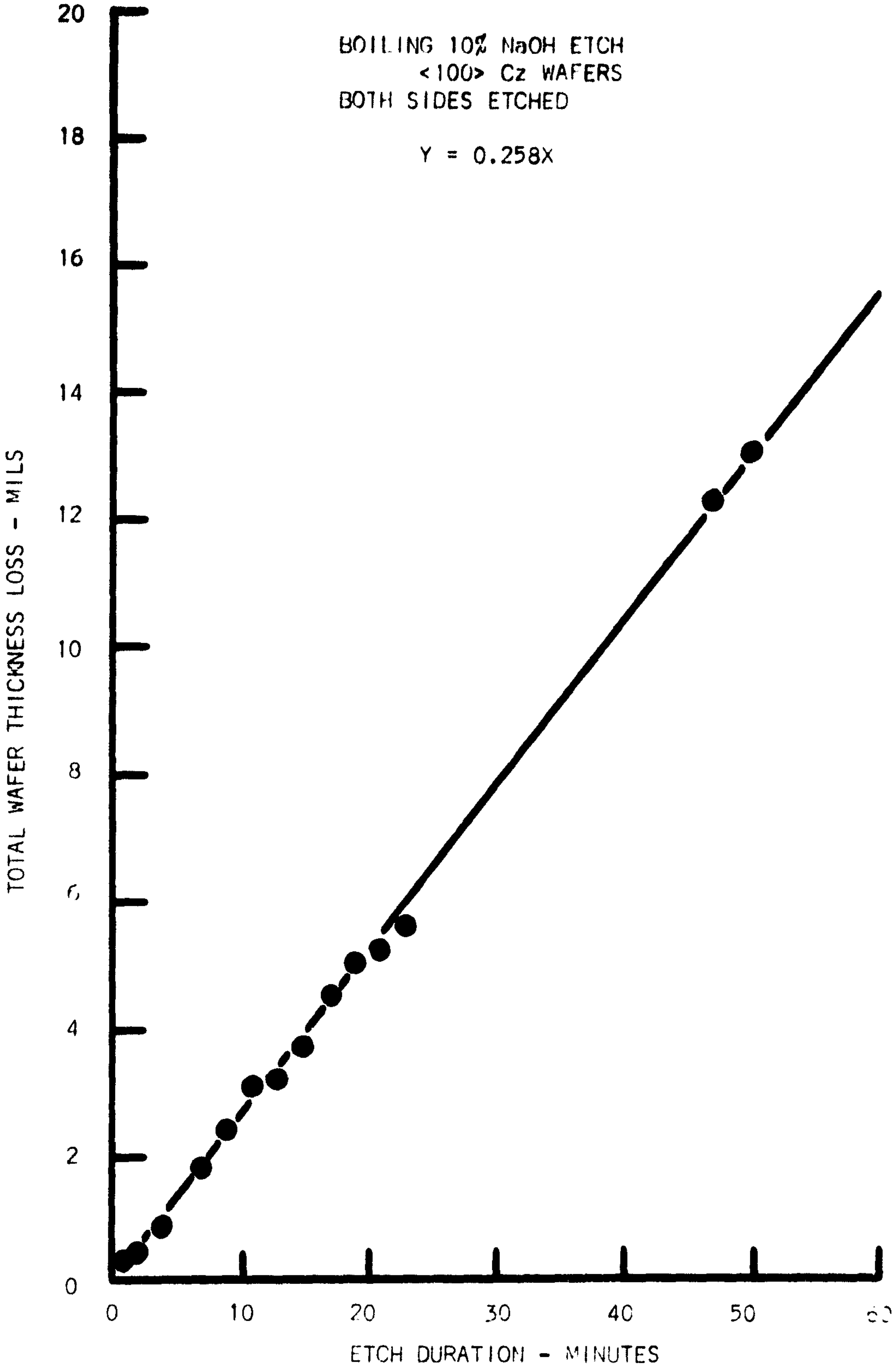

FIGURE 1.2: REDUCTION OF THICKNESS FOR BARE SILICON WAFERS IN CAUSTIC ETCH (BOTH SIDES ETCHED).

3.1.3 SILICON SUBSTRATE AND SOLAR CELL DRYING

At present, silicon substrates are fabricated into solar cells by a variety of processes. Some of these, such as diffusion, silicon nitride passivation, plasma etching, etc. are done with the substrates in a dry state. Other processes are carried out using wet chemical methods. Examples include initial substrate cleaning, texture etching, and metal plating. The use of both wet and dry processing steps may require that solar cells be dried several times in the course of their manufacture.

A brief overview of a laboratory wafer process scheme in use at Motorola will illustrate areas in the sequence where drying is important. An example process is as follows:

1. piranha clean
2. rinse
3. texture etch
4. rinse
5. dry and store
6. piranha clean
7. rinse
8. dry
9. diffuse junction
10. plasma etch back
11. nitride deposition
12. plasma pattern ohmic contact grid
13. metallize
14. rinse
15. dry
16. sinter

17. plate

18. rinse

19. dry

20. encapsulate

In the above process, drying occurs four times. In order to establish an efficient process, it is desirable to conduct wafer drying quickly and with a minimum expenditure of energy. In addition, the matter of cleanliness must be considered. Certain processes, such as diffusion, are particularly sensitive to dust or other soil on the wafer surface. After wet process steps, deionized water rinses of high purity are usually used in order to ensure wafer cleanliness; however, contamination of water after purification and before or during use as a rinse is possible, and contamination of a freshly rinsed, wet wafer surface by dust in the air has been demonstrated to occur.

Any drying process used must be evaluated to determine if it dries the wafer surface in such a way that surface cleanliness adequate for the next process step is maintained or restored. In the example process sequence listed, dryings at steps 8 and 15 require high cleanliness since the subsequent diffusion and sinter steps will give unsatisfactory results if soil is present. The dryings at steps 5 and 19 need not be as stringently clean. After step 5, substrates are cleaned again before the next sensitive process, and by step 19 silicon surfaces are sealed in layers of silicon nitride, oxide, and metal -- any minor contamination of a non-corrosive nature which is not optically objectionable may be tolerated.

3.1.3.1 DRYING TECHNIQUES CONSIDERED

3.1.3.1.1 CENTRIFUGAL DRYING

One of the most popular methods of silicon wafer drying is by the rapid revolution of a carrier of wafers in a circle of approximately 45 cm diamter.

Centrifugal forces developed cause adherent water on wafers to fly off the surface. Since the water is not evaporated from the surface, contaminants dissolved and suspended in the water are removed from the wafer surface along with the water. In some cases a blast of nitrogen or air is used to assist in water removal.

Centrifugal drying yields good results with the reasonably thick wafers used in integrated circuit production and most of today's solar cell production because these wafers are fairly strong. For future solar cell production, only thin wafers offer the economy necessary for low-cost products, and the use of polycrystalline material for further cost savings results in solar cells that may be significantly less rugged than the standard wafers now in use. Tests of 5 mil thick, large grain polysilicon ribbon in a centrifugal dryer indicate that material of this type is indeed more susceptible to damage from the centrifugal force employed, and that other types of drying methods may be better suited to high volume solar cell production with such substrates.

3.1.3.1.2 FORCED AIR DRYING

Water can be blown off of a solar cell surface by means of a cold air blast. This method retains the main advantage of centrifugal drying -- water and its contaminants are physically removed without drying the contaminants onto the surface. The use of forced cold air would work best on single substrates where a directed air stream would have access to the wet wafer surface. The treatment of substrates one at a time requires, however, that they be unloaded from their carrier - an operation which may significantly prolong processing time.

Drying of substrates in a carrier is also possible and has been developed as a commercial process. Drying by this means requires a high-velocity air stream (the commercial process uses air moving at 60 miles per hour). In addition to the direct force of air on the wafer surface, an additional source of stress may result from the necessary back-and-forth vibration of the substrates in the carrier which a high speed wind can induce. Excessive stress is the likely result, especially if thin multicrystalline substrates are subjected to the process.

3.1.3.1.3 INFRARED HEAT DRYING

Substrates can be effectively dried by the application of heat. Radiant heat applied to substrates will dry moisture without the danger of direct mechanical stress. This method, however, will work very slowly for items such as teflon carriers, which heat slowly and typically present water in the form of large drops rather than the thin film of water that adheres to solar cell surfaces.

In the case of drying silicon wafers in standard teflon carriers, the use of radiant heat requires the entire carrier and its contents to be heated in order to remove the moisture present in a few large drops that may remain only on the carrier - an inefficient system in terms of energy use. In addition, contaminants in the water film will not be removed. Rather, water will be evaporated, leaving soils behind on the wafer surface.

3.1.3.2 EXPERIMENTAL DRYING INVESTIGATIONS

By means of experiment, three drying methods were studied which held the promise of success because of the following factors:

1. whole carriers of wafers can be processed at one time
2. wafer drying is comparatively fast
3. drying is accomplished gently
4. necessary equipment is commercially available (although modification may be required).

These methods are: forced hot air drying, microwave drying, and solvent drying.

For these experiments, lots of 25 3-inch round wafers were used. The wafers were anisotropically textured on both sides and had been exposed to DI rinse water overnight so that a thin hydrophilic oxide had formed on the surface. The wafers were at all times kept in standard Fluoroware teflon carriers and drying was performed without removal from the carriers.

Immediately after withdrawal of the carrier and wafer from the rinse water, an average of 32 grams of water remained on the wafer lot. It was found that by mere gentle manual shaking of the carrier in air for ten seconds, an average of 23 grams of water could be removed by the action of gravity alone. Tests of drying efficiency took place on lots that had been gently shaken for ten seconds after removal from rinse; the lots had an average water burden of 9 grams.

3.1.3.2.1 OVEN DRYING

The simplest drying method employed a laboratory forced-air oven oeprating at 150°C. The use of forced hot air promoted drying only by vaporization of water, since the air flow in the oven was not vigorous enough to mechanically remove water, but merely served to maintain even heat distribution. The results showed that drying of both wafers and carriers could be accomplished in from five to six minutes. As with all heat drying methods, contaminants present in the rinse water would be left on the wafer surface after drying. (No contamination was noted by gross visual examination.) The oven method of drying can accommodate multiple lots and uses equipment that is inexpensive and reliable. If filtered air is used in such an oven and very clean rinse water is used, it appears that ovens can be used for drying operations before encapsulation or metal plating. It is not yet known if cleanliness of the oven drying method is sufficient or consistent enough to be used prior to diffusion processes.

3.1.3.2.2 MICROWAVE DRYING

Microwave ovens designed for domestic cooking operate by generating a beam of microwaves of a frequency that is preferentially absorbed by water molecules and converted to heat. It was thought that this selective heating of water on wafer surfaces would prove to be an effective and efficient drying technique. However, silicon wafers apparently absorb the specific microwave energy more efficiently than does water. A lot of 25 wafers in a teflon carrier placed in a domestic microwave oven dried in twenty seconds, while individual wafers took ten to fifteen seconds. The drying effect was found to be caused by strong heating of the wafers; the teflon carrier remained wet. Prolonged microwave exposure was used in an attempt to dry the carrier. After six minutes of exposure, the wafers became hot enough to melt the carrier at the points of contact, while water droplets still remained on the carrier. Although measurement of wafer temperature was not conducted, it can be estimated that the wafer temperature exceeded 250°C. Microwave exposure of single wafers was capable of producing dull red heat ($\simeq 450^{\circ}$C) in five minutes. Attempts to use quartz carriers to withstand the heat of drying wafers proved successful, but drying of the carrier took five to six minutes - no better performance than that afforded by a hot-air oven. Aside from the fact that impurities in water would be dried upon wafer surfaces by microwave drying, the strong silicon heating effect may argue against this drying method. Temperatures in the vicinity of 400°C would speed solid state diffusion in processed wafers to the point where surface contaminants (in particular, metallics) might enter the silicon and cause device degradation.

3.1.3.2.3 DISPLACEMENT DRYING

Another drying concept exploits the fact that some liquids (e.g. methyl alcohol, freon, etc.) dry more quickly than water. By placing a carrier of wet wafers in a liquid such as hot methyl alcohol, water will be rinsed from the wafer surface, along with impurities, and replaced with alcohol. Upon withdrawing the wafers from the alcohol, rapid drying in air will take place. This simple example can be considerably refined. In order to eliminate a combustion hazard, liquids such as freon or freon-alcohol mixtures can be used. The mechanism of drying can also be altered. If TTF freon (1,1,2-trichloro-1,2,2-trifluorethane) is mixed with a few percent of an alcohol such as isopropyl, ethyl, or methyl, a dense solution results in which water is slightly soluble. Due to the solution's density (≈ 1.5 g/mL) carriers of wet wafers submerged in the solution will be at least partially dried by virtue of the fact that adherent water will be squeegeed off of the silicon by the solution and will float on the surface of the solution where it can be removed by skimming. Small amounts of water that remain in cracks or other surface irregularities will be dissolved away by the alcohol in the solution. Withdrawal of the wafers from the solution permits evaporation of the volatile freon-alcohol, and especially fast (5-20 seconds) drying is possible if the solution is hot.

The displacement technique offers advantages over other methods: speed, cleanliness, simplicity, and lack of mechanical stress on wafers. Typical processing time for a lot of wafers is 3 minutes or less. Because water is displaced rather than evaporated, contaminants in the rinse water are removed from the surface. The use of recirculating filters or even small distillation units will keep the small volume of freon-alcohol solution clean so that its evaporation from wafers does not deposit soil. Since drying involves only immersion and withdrawal of wafers from a solution, mechanical stress is very low. In terms of mechanical complexity, a drying system using displacement is equivalent in complexity to a standard vapor degreaser. Dryers are also available commercially (Crest Ultrasonics Corp., Trenton, NJ; Branson Cleaning Equipment Co., Shelton, CT). Although some technical details have not been studied - such as optimum composition of the solution, alternatives to freon, exact process cost, etc. - the displacement process appears to offer advantages over other methods.

3.1.4 MATERIAL HANDLING CONSIDERATIONS: VACUUM PROCESSING APPLICATIONS

Various process technologies have been proposed for solar cell fabfication. Vacuum processing has been discussed extensively, but often it has been rejected as obviously too expensive or unnecessarily complex. Vacuum processing, however, offers improvements in process control, increased processing alternatives or flexibility, and advantageous safety and enviornmental considerations not readily available in similar atmospheric processes. Continual development of vacuum processing technologies and more analytical approaches to process selection and equipment design can show that vacuum processes are cost effective alternatives in the fabrication of high efficiency solar cell devices. Some of the vacuum technologies which may be applied to solar cell fabrication are listed in Table 1.4.

Vacuum processing may prove to be the only acceptable approach for the application of very thin films such as improved antireflection coatings. Required process control and uniformity may not be attainable at atmospheric pressures. For example, uniformities of ± 2% are easily available from low pressure chemical vapor deposition or ion implantation. On the other hand, atmospheric deposition or diffusion processes cannot offer better than ± 10% uniformity. Since very small amounts of pure gases can be used efficiently at vacuum pressures, toxic gas processes can be established with greater environmental safety and with lower consumable material cost. Also, contamination levels may be reduced or controlled more easily at reduced pressure. Equally pertinent is the fact that very thin, fragile non-Cz substrates may be processed more easily. For example, cleaning in an acid bath may result in considerable breakage and handling complexity for thin ribbon type material compared to low pressure oxygen plasma cleaning. However, transport of the substrates into a vacuum system can be a significant technical problem and cost factor. The transport technique may be the major cost driver which will determine the economic utility of a given vacuum process and is the primary subject of this review.

TABLE 1.4: SOME VACUUM PROCESSES FOR SOLAR CELL DEVICE FABRICATION

Sputtering	Deposition of thin films Metallization contact deposition Etching of thin films.
Molecular Beam Epitaxy	Deposition of multilayer devices Deposition of epitaxy junctions
Ion implantation	Junction formation Material modification/heating
Plasma etching	Pattern etching Surface cleaning Surface texturing
Ion Beam	Primary ion deposition of material Secondary ion deposition of material Reactive or mechanical etching
Chemical Vapor Deposition	Deposition of thin films.

Requirements for a substrate transport technique for a vacuum processing system can be influenced by several factors. Of primary concern is sufficient machine throughput to be cost effective. In most cases, the process equipment may be designed to allow for high processing throughput. However to obtain maximum capacity, the transport time must be less than the designed process cycle interval. The processing variables may also affect the method of transport. Some reactive vacuum processes are so susceptible to atmospheric (oxygen or water vapor) contamination that a load-lock chamber may be required to reduce these effects. Desired process controls may also determine requirements of the transport configuration. Processing 1 or 2 substrates per cycle allows for more feedback data to maintain tighter parameter control limits compared to large (25-50 substrate) batch processing. Finally, the integration of machine-to-machine material automation should be also considered as a design requirement.

With a number of variables to consider, a systematic approach should be used to define all the transport and handling requirements. Such an approach was developed after a review of existing semiconductor processing vacuum equipment and current design trends.

The three major design areas are represented in the diagram of Figure 1.3. The vacuum process chamber design is primarily effected by the physical parameters of the particular process but must also allow for high material throughput. Examples of modification to a chamber for increased handling speed are found in several recent commercial plasma etchers and sputter systems. These have been designed with continuous in-situ load zones on fixed rotating pallets instead of using pallets which must be removed between cycles. So, a careful examination of process variables and the chamber parameters is a critical step in the equipment design analysis.

The next major design area is the actual transfer method of loading material into the process chamber. A schematic diagrma of numerous possible alternatives is shown in figure 1.4. Direct loading a batch of substrates into a vented chamber between discrete process cycles, path (a), is the historical method. A batch can be loaded into a vacuum load-lock prechamber (b) and then into the process chamber either as a batch (c) or transferred as single substrates (d). Another very prevalent technique is to load a batch into the machine (e) and transfer single substrates into the vented process chamber (f) or through a vacuum load-lock (g). Finally, single substrates can be loaded into the machine and then into process chamber directly (h) or through a load-lock (i). The trend toward an automation and improved processing control is resulting in more single substrate handling along with the use of vacuum load-locks, path (i).

The last design area is the machine to machine transfer and loading method. This becomes more important when considering line-level automation. Currently, batch (cassette) handling is most frequent. However, as the next level of automation, cassettes are loaded into the machine or auxiliary transfer unit with the substrates being handled individually through several interconnected machines or stations. The integrated circuit photolithography systems are currently leading the effort toward this first level of automated handling. There are also some commercial efforts at a totally automated process line, and each of these has opted for single substrate handling technology.

In selecting the transport method for a vacuum processing system design, there are some general criteria that may be used. (1) Single substrate handling can be used in conjunction with very short individual substrate processing times or where sequential or continuous processing of multiple substrates, each for moderate times, results in very short cycle intervals. It has the advantage of higher automation, but also requires inherently short processing times. (2) Batch loading can only be economical for long cycle processes with high loading densities. It has the advantage of being less complex, but can incur added

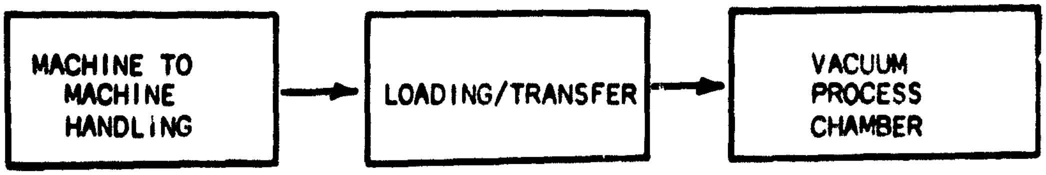

FIGURE 1.3: DIAGRAM OF MATERIAL TRANSPORT FOR VACUUM PROCESSING.

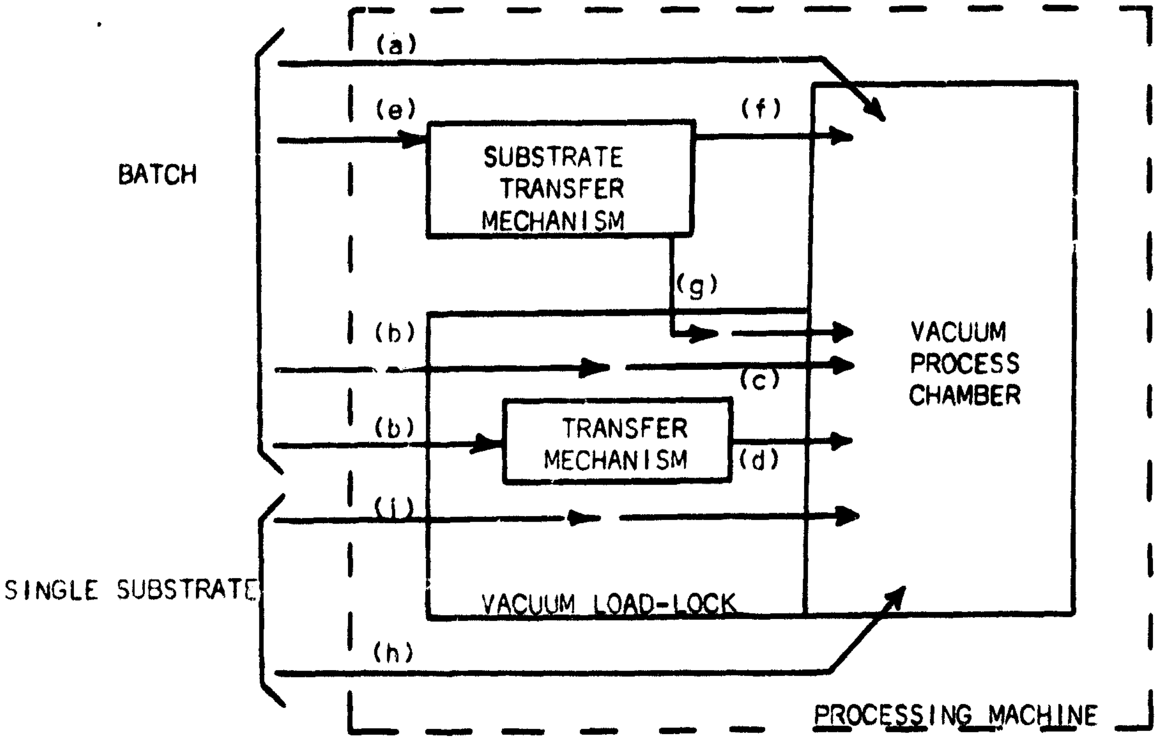

FIGURE 1.4: SCHEMATIC DIAGRAM OF SUBSTRATE LOADING METHODS FOR VACUUM PROCESSING.

costs associated with the use of carriers or pallets. (3) The use of load-lock chambers is justified primarily by control of process parameters and contamination. Also, for moderate process times, machine capacity can be increased by reducing the pumping cycle time for the main process chamber. Load-lock chambers are very complex and costly, but new designs and their impact on throughput make them very cost effective. (4) In general, changing between batch and single substrate handling adds the requirement for transfer mechanisms, so frequent changing between methods should be carefully reviewed.

The foregoing discussion has been oriented toward vacuum processing, but the same analysis may be applied in general to any processing requiring a controlled ambient, whether pressures be above, below, or at atmospheric pressure.

3.1.5 THERMAL STRESS RELIEF

An early objective of the development program for processing non-Cz substrates was to evaluate the potential cost-effectiveness of employing thermal annealing cycles to reduce stress inherent in the bulk silicon, thereby, improving material handling characteristics and perhaps solar cell characteristics. This was quickly determined to be an unnecessary process step (and therefore not cost-effective) because no difficulties related to stress were encountered in the baseline process evaluations of textured cells, discussed in Section 3.1.1.

3.1.6 IMPURITY GETTERING

The cost-effectivness of various gettering processes was considered briefly but de-emphasized early in the program. Gettering of fast diffusing impurities must usually be tailored to the specific silicon substrate material being processed. Since the primary non-Cz material for this study was RTR silicon sheet (only small quantities of other non-Cz materials were available), impurity gettering did not prove cost-effective. RTR sheet performance is thought to be dominated by silicon crystal defects such as dislocations, rather than by contamination and impurities.

Nevertheless, some small degree of insurance through phosphorus gettering might have been obtained because of the baseline process sequence outlined at the start of Section 3.1. The blanket phosphorus diffusion followed by etching of the phosphorus-diffused layer from the back side of the silicon sheet would provide a minimal gettering effect for extremely fast diffusing species.

3.2 CELL DESIGN

The use of particular solar cell metal contact pattern designs has often been based on tradition or trial-and-error. The increasing use of non-Cz substrates however will demand more careful attention to metallization patterns if maximum performance is to be achieved from what may be lesser quality substrates. Metallization design cannot be left to chance.

A computational procedure has been developed for optimizing metallization pattern designs for rectangular substrates. This procedure accounts for tradeoffs between shadowing and ohmic losses for any specified level of solar cell performance. The subsections that follow provice a general explanation of methods for quantifying pattern performance and achieving optimum designs. Computational programs developed to implement these methods are also detailed.

3.2.1 BASIC APPROACH

It has been shown (*) that the geometrical parameters of front-and back-surface metallization patterns for a solar cell of conventional configuration can be chosen so as to optimize overall cell efficiency for a substrate of given performance under specified illumination.

In this method, the pattern parameters are chosen so as to achieve a stationary value of the overall efficiency taken in the form

$$\eta=\eta^{O}F[1-(P_{sh}/P_{i})]-(P_{\Omega}/P_{i}) \qquad (1)$$

under variations of the pattern parameters. The overall efficiency, η, is defined as the ratio of maximum electrical power at the output terminals to the

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(*) "Design of Metallization for Higher-Efficiency Solar Cells," N. G. Sakiotis, Proceedings 14th IEEE Photovoltaic Specialists Conference - 1980, pp 433-448, (1980).

power associated with incident illumination over the portion of the spectrum accountable in the cell performance. The substrate conversion efficiency, η^O is defined as the ratio of maximum electrical power generated to the fraction of the incident power absorbed by the substrate; T is the optical transmission coefficient of the exposed portion of the front surface and P_{sh}/P_I is the fraction of the incident power lost due to shadowing of the front surface. The quantity P_Ω/P_I, the fractional ohmic dissipation, is the ratio of the total electrical dissipation over the cell structure to the incident power.

For solar cells with a fully metallized ohmic back surface and/or substrate thickness greater than approximately 8 mils, such that reflection of illumination from the back surface may be neglected, maximum overall efficiency is achieved under the necessary condition,

$$\frac{d}{d(P_{sh}/P_I)} (P_\Omega/P_I) = -\eta^O T. \qquad (2)$$

Solar cell metallization patterns have at least two degrees of freedom and the η-optimization condition, (2), is generally not sufficient to determine the pattern parameters. Additional conditions are necessary, depending upon the number of degrees of freedom of the particular pattern.

Patterns of linear collectors of uniform linewidth and spacing exhibit two degrees of freedom. Optimum parameters can be determined for these patterns under the additional condition that the collector linewidth be such as to minimize the ohmic dissipation over the pattern for a given fractional coverage of the surface by the collectors.

Since practical considerations impose a lower limit to achievable collector linewidths, the optimum linewidth may not be achievable. Under such circumstances, specification of the minimum practical linewidth, enables one to determine the parameters of a collector pattern that provides the best overall efficiency for that linewidth.

Implementation of this method requires that dependence of the fractional ohmic dissipation, P_Ω/P_I, and the shadow fraction, P_{sh}/P_I, be formulated in terms of the goemetric parameters of the pattern. This is done in the following sections for the type of pattern applicable to the present work, namely rectangular geometries intended for operation under 1-sun illumination, generally multibussed, and utilizing linear collection grids of constant width and spacing.

Tacit assumptions are made throughout, that the front surface metallization has negligible effect upon the characteristics of the solar-cell junction and that the metal-semiconductor contact is such as to permit the contact resistance to be included in an effective sheet resistance of the metal.

3.2.2 PATTERN ZONES AND ELEMENTS

The analysis of a solar-cell metallization pattern is facilitated by conceptually subdividing the pattern into zones such that:

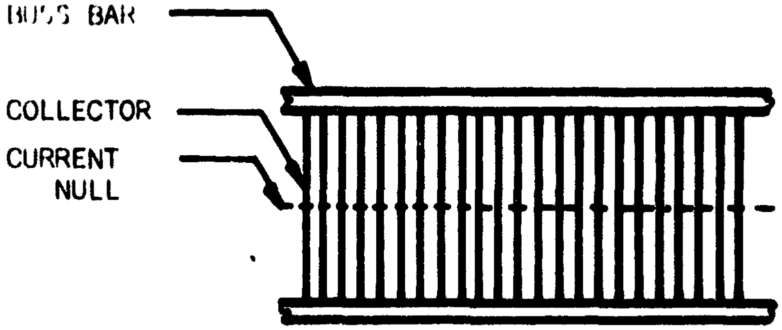
(a) the collectors of each zone are of similar geometry, in terms of readily measurable parametrized quantities.

(b) the current collected by each zone can be defined in terms of the parameters of that zone alone;

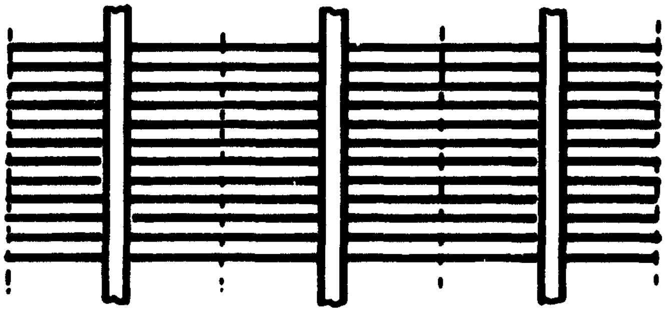
(c) the total current collected by the pattern is the sum, over the zones, of the current collected by each zone.

Patterns of more than one zone are usually, but not necessarily, associated with a multiplicity of busses, as illustrated by the examples of pattern zones in Figure 2.1.

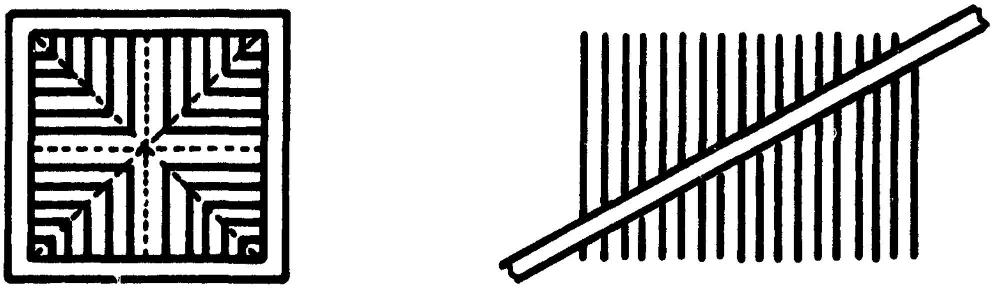
Pattern zones can be further subdivided into zone elements, usually such that each zone element is associated with one collector and encompasses the surface



TWO RECTANGULAR ZONES



SIX RECTANGULAR ZONES



EIGHT RIGHT TRIANGULAR ZONES

TWO RIGHT TRIANGULAR ZONES

FIGURE 2.1: SCHEMATIC EXAMPLES OF MULTIZONE PATTERNS FOR RECTANGULAR CELLS.

$$(P_\Omega/P_i)_z = KJR_s\left[w^2\left(\frac{1-F}{F}\right) + r\,(R_c/R_s)\,\langle\ell^2\rangle\right]\frac{(1-F)^2}{F} \qquad (3)$$

where $K = (1/12)\,T\,(J/p_i)$; p_i is the intensity of the incident illumination; R_s and R_c are the effective sheet resistances of the cell surface and collector metallization, respectively; F is the fraction of the zone area covered by the collector metallization; $\langle\ell^2\rangle$ is the area-weighted mean of the squares of the collector lengths over the zone, given in this case by

$$\langle\ell^2\rangle = (w/FA_z)\sum_i \ell_i^3$$

in which A_z is the zone area and the sum is over the collectors of the zone.

3.2.3. ZONE OPTIMIZATION

As discussed above, the general condition for maximum overall efficiency for the patterns under consideration requires an additional constraint in order to determine the parameters of a particular pattern configuration. This constraint can be profitably imposed by requiring the fractional ohmic dissipation of each zone to be minimum with respect to the collector linewidth, for a given fractional collector shadowing loss,

$$\frac{\partial}{\partial w}(P_\Omega/P_i)_z\Big|_F = 0, \text{ for each pattern zone,} \qquad (4)$$

thereby optimizing the collector linewidth within each zone.

From (4), this zone-optimization condition requires that the collector linewidth be given by

$$w^{2+n} = 2n\,(\beta_c/R_s)\,\langle\ell^2\rangle\,F/(1-F), \text{ for each pattern zone} \qquad (5)$$

where the dependence of the effective collector sheet resistance, R_c, upon the collector linewidth is modelled in the form

$$R_c = \beta_c/w^n \qquad (7)$$

in which β_c and n are quantities determined by a two-parameter fit of (7) to empirical curves of $R_c(w)$. For idealized uniform collectors of rectangular crossection, n=0 and β_c is the ratio of the bulk resistivity, ρ_c, to the collector thickness. In the somewhat more realistic case of uniform collectors of semicircular crossection, n=1 and $\beta_c = (8/\pi)\rho_c$. In actuality, collectors can be of more complex crossection, depending upon linewidth, texture of the cell surface, the particular metal system and the processes used to define the lines, to deposit the metal and to form the ohmic metallurgical bond. Consequently, the parameters β_c and n are best determined empirically for a particular set of circumstances. It is of importance to theoretical estimates to note that the value of n for narrow, plated-silver and solder-dipped lines on textured single-crystal surfaces has been observed to correspond more closely to unity than to the zero value associated with the commonly-assumed rectangular crossection.

Under the zone optimization condition, (4), the fractional ohmic dissipation of the optimized zone has the form

$$(P_\Omega/P_i)_z = (\frac{n+2}{2})\ KJR_c <\ell^2> \frac{(1-F)^2}{F} \qquad (7)$$

and the surface and collector contributions to the zone dissipation are related through

$$(P_\Omega/P_i)_s = \frac{n}{2}\ (P_\Omega/P_i)_c \quad . \qquad (8)$$

In the case of collectors of idealized rectangular crossection ($n=0$), the zone-optimization condition, (5), requires that the line-width vanish and therefore cannot be satisfied. Practically, it indicates the use of the smallest linewidth that can be fabricated. For such collectors, (8) indicates that the zone dissipation can be expected to be dominated by the collector contribution, for sufficiently narrow linewidths. For collectors of $n>0$, there exists a non-zero optimum linewidth and a definite ratio of surface to collector contributions to the ohmic dissipation. For collectors of semicircular crossection ($n=1$), the surface contribution is one half that of the collector, at the optimum linewidth which varies with the metal bulk resistivity and surface sheet resistance as $(\rho_c/R_s)^{1/3}$.

The practical limitation to zone optimization is the realization of the optimum linewidth. For metals of high conductivity (silver, copper), (5) results in values of linewidth less than 2 mils for R_s in the range of 30-50 $\Omega/$. Such linewidths are not feasible under some present production processes. When the optimum linewidth cannot be achieved, the linewidth must be fixed at the minimum feasible value. This constraint together with the η-optimization condition, (2), then results in the optimization condition

$$\frac{\partial}{\partial F}(P_\Omega/P_I)\Big|_w = 0, \text{ for each pattern zone} \qquad (9)$$

which provides the optimum collector spacing in each zone for the minimum feasable linewidths.

3.2.4 EFFICIENCY OPTIMIZATION OF COLLECTION AREA

3.2.4.1 ZONE-OPTIMIZED PATTERNS

For a multi-zone pattern, the fractional ohmic dissipation and fractional shadowing loss over all zones of the pattern are taken as

$$(P_\Omega/P_I)_g = \sum(P_\Omega/P_I)_z\, A_z/\sum A_z$$

$$F_g = \sum A_z F_z/\sum A_z$$

where the indicated sums are over all zones and the sum of the zone areas will be referred to as the grid area. Application of the n-optimization condition, (2), when $(P_\Omega/P_I)_z$ is of the zone-optimized form, (8), then yields

$$\sum_z \{(\langle \ell^2 \rangle)_z^{2(1-k)}\, [2ky_z^{(2k+1)} + (2k+1)\, y_z^{2k}\,]\} = n^o T/\alpha \qquad (10)$$

where $y_z = (F_z-1)/F_z$

$k = (n+1)/(n+2)$

$\alpha = KJR_s\, (\frac{n+2}{2})\ [2n\, (\beta_c/R_s)]^{2(1-k)}$

and it is assumed that R_s is uniform over the exposed surfaces and that β_c and n are uniform over all collectors.

Although (10) is of a form that permits the metal coverage to be tailored for each zone so as to compensate for non-uniform illumination, we shall specialize the remainder of this discussion to the case in which F is uniform over all zones. In this case (10) simplifies to an equation for the common value of y,

$$2ky^{(2k+1)} + (2k+1)y^{2k} = n^o T/\alpha \sum_z(\langle \ell^2 \rangle)_z^{2(1-k)} \qquad (11)$$

Solution of (11) for y yields the uniform value of F_g which together with the zone-optimized values of w for each zone, from (5), determines the parameters of a collector grid pattern that is optimized for the specified quantities on the right-hand size of (11).

3.2.4.2 PATTERNS OF SPECIFIED COLLECTOR LINEWIDTH

For situations in which the collector linewidth is specified at a minimum feasible value, the n-optimization condition under fixed w, (9) yields the following cubic in y, for F_z uniform over all zones:

$$a_3 y^3 + a_2 y^2 + a_1 y^1 + a_0 = 0 \qquad (12)$$

where, $a_3 = 2w^3$

$a_1 = 2\ (R_c/R_s)\sum_z <\ell^2>$

$a_0 = n^{o} F_g/KJR_s$

$a_2 = (1/2)\ (a_1 + 3a_o)$.

Solution of (12) for y together with the specified value of linewidth determines the best collector spacing for the specified quantities that determine the coefficients a_1 and a_o.

3.2.5 EFFECTS OF BUSSES

The effects of busses in the pattern depend on the manner in which the solar cell is utilized. In concentrator applications, for instance, peripheral busses have no effect if they do not overlie the junction area. In flat-plate applications all busses make a principal contribution to the loss of illumination due to shadowing.

When busses are fabricated in the form of relatively heavy strips of a metal of high conductivity, bonded to metallized areas of the cell surface, the effective resistance of the buss structure can be sufficiently small so as to render the ohmic dissipation over the busses of secondary importance.

In general, it is necessary to specify the number and location of busses so as to minimize their effect on the overall cell performance. In addition to direct contributions to the ohmic and shadowing losses of the pattern, busses affect pattern performance by determining the size and shape of the zones of the collector grid. For the configurations under consideration, this is reflected in the value of the quantity $\sum \langle \ell^2 \rangle_z$ in (11) and (12). A systematic method of deisgn to achieve maximum performance for busses of specified width and sheet resistance is developed in section 3.2.6.

3.2.5.1 BUSS VOLTAGE DROP AND OHMIC DISSIPATION

Buss dimensions can be determined so as to maintain the maximum voltage drop over a buss at a value less than the largest voltage drop associated with a zone, which in turn, should be small as compared to the thermal voltage, $V_T = kT/q$, for a high performance solar cell.

The maximum voltage drop along a buss of constant width, w_b, that is sinking current from a set of closely-spaced parallel collectors of uniform coverage factor, F_g, and of length described by f(x), where x is distance along the buss can be readily shown to be approximated by

$$V_b = JR_b(w_b)^{-1}(1-F_g)\int_0^{L_b}\int_0^{x} f(\mu)\,d\mu\,dx$$

where R_b and L_b are the effective sheet resistance and length of the buss and J is the (uniform) current density over the area of collection associated with the buss. For a rectangular grid area of (x) = constant this reduces to

$$V_b = (1/2)\, r_b I_b \qquad (13)$$

where r_b is the total resistance of the buss and I_b is the terminal buss current.

Under the same conditions, the fractional ohmic dissipation over the buss, relative to the associated grid area, A_c, is given for a general zone shape by the integral approximation

$$(P_\Omega/P_I)_b = 12KJA_cR_b\ (w_b)^{-1}(1-F_g)^2 \left[\int_0^{L_b}\left[\int_0^x f(\mu)d\mu\right]^2 dx/A_c^2\right]$$

For a rectangular grid area, this reduces to

$$(P_\Omega/P_I)_b = 4Kr_bI_b\ (1-F_g) \tag{14}$$

Expressions (13) and (14) provide a ready estimate of the relative magnitudes of the buss contributions to the overall voltage drop and ohmic dissipation of a rectangular cell. For a buss structure designed so as to maintain $V_b \ll V_T$, i.e., of a total resistance such that

$$R_bI_b \ll 2V_T,$$

it follows that

$$(P_\Omega/P_I)_b \ll 8K\ (1-F_g)V_T$$

For the representative values $V_T = 0.026V$, $K = 0.03\ A/W$, $F_g = 0.05$, this yields $(P_\Omega/P_I)_b \ll 0.6\%$. Consequently, a buss structure for a rectangular pattern designed for a reasonably small value of voltage drop over the buss will also maintain the ohmic dissipation along the buss at a level that is secondary to that of the collector grid.

3.2.6 MULTIZONE PATTERNS FOR RECTANGULAR CELLS

On economic grounds, non-Czochralski solar cell substrates can be expected to be substantially larger in area than wafers sawn from pulled ingots. Metallization patterns in non-Czochralski substrates can consequently be expected to consist of a larger number of zones, serviced by a larger number of busses in order to efficiently handle the increased cell current. This places increased importance on optimum design of the buss system, since otherwise substantial amounts of unnecessary loss due to ohmic dissipation and/or shadowing can be readily incurred.

3.2.6.1 CROSS-BUSSED UNIFORM RECTANGULAR PATTERNS

Consider a cross-bussed uniform rectangular pattern of k parallel busses of equal width and sheet resistance. If all busses are internal to the pattern, as illustrated in Figure 2.2a, then each buss carries the current of two zones and the pattern contains 2k rectangular zones. If the pattern has two edge busses, as illustrated in Fig. 2.2b, each edge buss carries the current of one zone and the pattern contains 2(k-1) rectangular zones.

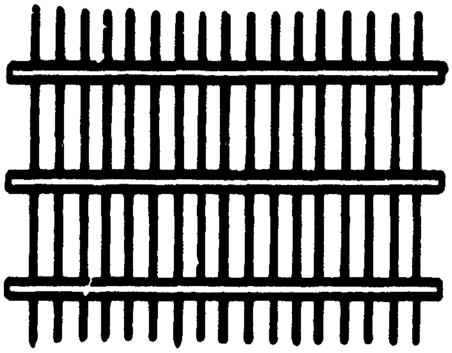
Most of the conclusions that follow apply to both types of buss configuration and it is sufficient to discuss only patterns that contain internal busses as more appropriate for 1-sun flat-plate applications.

It follows from (3) that the fractional ohmic dissipation over the grid area of 2k zones is given by

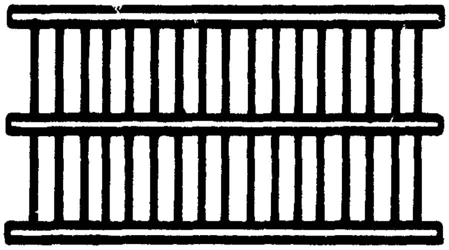
$$(P_\Omega/P_i)_g = KJR_s \left[w^2 \frac{(1-F)}{F} + 4(R_c/R_s)L^2\, G(k) \right] \frac{(1-F)^2}{F} \tag{15}$$

where $$G(k) = L^{-2} \sum_{j=1}^{2k} \langle \ell^2 \rangle_j (A_j/A) = \sum_{j=1}^{2k} (\ell_j/L)^3$$

and $$L = \sum_{j=1}^{2k} \ell_j$$



(a) SIX-ZONE PATTERN WITH INTERIOR BUSSES ONLY.



(b) FOUR-ZONE PATTERN WITH EDGE BUSSES.

FIGURE 2.2: ILLUSTRATION OF MULTI-BUSSED PATTERNS.

and ℓ_j is the collector length in the jth zone.

It can be readily shown either from symmetry considerations or by the method of Lagrange multipliers that G(k) has the minimum value,

$$G(k) = (2k)^{-3}$$

corresponding to equal values of ℓ_j over the zones,

$$\ell_j = L/2k$$

Consequently, the fractional ohmic loss over the grid area can be minimized by locating the busses so as to achieve equal collector lengths over the zones. Moreover, the grid fractional ohmic loss is then just that of a single zone, relative to the grid area, and is independent of the number of busses. Relative to the total pattern area, the minimum value is

$$(P_\Omega/P_i)_g = KJR_s\left[w^2\frac{(1-F_g)}{F_g} + 4(R_c/R_s)(L/2k)^2\right]\frac{(1-F)^2}{F}\ (L/W) \qquad (16)$$

where $L/W = 1-kw_b/W)$.

These results can also be shown to be valid in edge-bussed patterns.

From (14), it follows that the fractional ohmic dissipation over the k busses, relative to the total grid area A, is given by

$$(P_\Omega/P_i)_b = 4KJR_b(AD/w_b)\ (1-F_g)^2\ F(k) \qquad (17)$$

where $$F(k) = \sum_{j=1}^{k} (A_j/A)^2 \quad ; \quad A = \sum_{j=1}^{k} A_j$$

and A_j is the grid area served the the jth buss and D is the length of each buss within the pattern area.

In the same manner as above, it follows that F(k) has the minimum value

$$F(k) = k^{-1}$$

corresponding to $A_j = A/k$.

For internally-bussed rectangular patterns, this result, requiring that each buss serve an equal fraction of the grid area, is equivalent to the condition on the collector lengths above. The resulting optimum fractional ohmic buss dissipation, relative to the total pattern area, is given by

$$(P_\Omega/P_I)_b = 4KJR_b D^2 (L/kW_b)\ (1-F_g)^2\ (L/W) \tag{18a}$$

or equivalently,

$$= 4KJR_b\ (A/k)\ (1-F_g)^2\ (L/W) \tag{18b}$$

Expression (18b) shows that the minimum fractional dissipation relative to the total grid area is equivalent to that of a single buss serving an area equal to the grid area reduced by a factor k.

In conclusion, the total fractional ohmic dissipation of the pattern is minimized with respect to buss placement by equally-spaced busses, located symmetrically with respect to the centerline of the pattern. This can be shown to hold for edge-bussed patterns as well.

The reduction in ohmic dissipation that is gained by increasing the number of busses is offset by the increase in the buss shadowing factor

$$F_b = kw_b/W, \tag{19}$$

relative to the total pattern area. As the number of busses is increased, the loss due to the increased shadowing eventually becomes larger than the reduction in ohmic dissipation. Clearly, there exists an optimum number of busses of given width or, more generally, there exists an optimum value of buss shadowing factor for a given grid pattern and given sheet resistances. This optimum can be obtained from the requirement

$$\partial \eta / \partial k = 0 \qquad (20)$$

applied to (1).

For given values of grid shadowing factor and sheet resistances the optimum value of F_b satisfies the formal relation

$$\eta F_b = 2 \, (P_\Omega / P_i)_{g,c} + (P_\Omega / P_i)_b \qquad (21)$$

where the first term on the right -hand side refers to the collector ohmic dissipation. This relation shows a trend toward greater buss shadowing for cells of lower efficiency and for patterns of greater ohmic dissipation in the metal pattern.

Although (20) leads to a cubic equation for the optimum number of busses for uniform, parallel busses of given sheet resistance, the sensitivity of the overall efficiency to the number of busses in the vicinity of the optimum number is usually small and it is more practical to evaluate the effect of the number of busses by repeating calculations of particular quantities over a range of values of k.

3.2.7 CHARACTERIZATION OF PATTERN PERFORMANCE

From (1), the loss in overall solar-cell efficiency, $\Delta \eta$, accountable to the front-surface metallization can be written as

$$\Delta\eta = (\Delta\eta)_{sh} + (\Delta\eta)_{\Omega} \tag{22}$$

where

$$(\Delta\eta)_{sh} = \eta^{o}T(P_{sh}/P_{I}) \; ; \quad P_{sh}/P_{I} = F_{g} + F_{b}, \tag{23}$$

$$(\Delta\eta)_{\Omega} = (P_{\Omega}/P_{I})_{g} + (P_{\Omega}/P_{I})_{b} \tag{24}$$

and the fractions are with respect to the total pattern area.

It has been shown (*) that the degradation, ΔF, in the fill factor of a solar cell due to series resistance can be adequately estimated by

$$\Delta F = \frac{P_{\Omega}/P_{I}}{\eta^{o}} \tag{25}$$

for reasonably small values of series resistance, typical of high-efficiency cells.

Consequently, the performance of a metallization pattern can be usefully characterized by the following parameters which give a direct measure of the effect upon the overall performance of the solar cell:

Loss of efficiency,	$\Delta\eta$
Loss of fill factor,	ΔF
Ohmic loss of efficiency,	$(\Delta\eta)_{\Omega}$

For purposes of analysis and diagnosis, these parameters can be detailed in terms of the contributions due to the grid and buss structure as indicated above.

---

*Task I Report, Sandia Laboratories, Contract No. 07-7079, p. 34.

3.2.7.1 EVALUATION OF THE CONVERSION EFFICIENCY

The substrate conversion efficiency, η^o, is a key parameter in the design of optimized metallization patterns. It is also a very useful measure of the performance of solar cell substrates. Unfortunately, evaluations of η^o by means of a computation involving the material parameters is not judged to be practical because of the detailed characterization that is required in terms of both "intrinsic" and process-dependent parameters, many of which are difficult and/or time-consuming in obtaining.

A more practical approach is to empirically evaluate η^o in a self-consistent manner from the defining relation, (1), as follows:

1. Fabricate a cell on the substrate of interest utilizing an anti-reflection coating of known transmission coefficient, T.
2. Calculate (P_{sh}/P_I) and (P_Ω/P_I), based on an initial estimate of η^o.
3. Measure the value of cell efficiency, μ.
4. Evaluate η^o from (1):

$$\eta^o = [\eta + (P_\Omega/P_I)]/T\ [1-(P_{sh}/P_I)]$$

5. Repeat step 2, utilizing the vaue of η^o obtained in step 4.
6. Repeat steps 4 and 5 until the value of η^o is bracketed to within the desired accuracy.

3.2.8 COMPUTATIONAL PROGRAM

A computational program has been developed in BASIC language to facilitate the design and evaluation of front-surface metallization patterns applicable to non-Czochralski substrates. The program is primarily designed for internally-bussed, rectangular-grid patterns of uniform collector width and spacing with optimally-located uniform busses. The program provides three basic computations:

I) Values of optimum collector linewidth and spacing.

II) Value of optimum collector spacing for a specified collector linewidth.

III) Values of the performance parameters of section 3.2.7 for specified values of collector linewidth and spacing.

These computations require the quantities listed in Table 2.1 to be specified. Provisions are included to permit variations of these specified parameters. The collector spacing is conveniently expressed in terms of the grid period, p = s+w.

The computation of optimum grid parameters, (Computation I), is done by an iterative procedure to obtain the real root of the form

$$b_o\ [b_1 y^{b_2} + B_2 y^{b_1}] - = 0$$

to within .01% of the value of the root.

This furnishes the solution of (12), for the optimum value of y. The associated optimum viaue of linewidth is then obtained from (6) and the otpimum value of grid period is obtained from p = w(1+y).

In computation II, the optimum value of y for a given linewidth is obtained by an algebraic solution of (13). This is then used to obtain the optimum grid period for the given value of linewidth.

Computation III calculates the performance parameters and the contributions due to the surface, collector metallization and buss structures for specified values of collector linewidth and grid period from the following relations:

Grid Ohmic	$(P_\Omega/P_i)_g$	from (16)
Buss Ohmic	$(P_\Omega/P_i)_b$	from (18a)

TABLE 2.1

INPUT DATA FOR PROGRAM

1. Pattern dimensions
2. Substrate sheet resistance, conversion efficiency factor

$$K = J_{SC}/P_i$$

3. Collector parameters β_c, n
4. Buss sheet resistance, width
5. Number of busses.

Buss Shadow	F_b	from (19)
Grid Shadow	F_g	from $(1-F_b)$ F
Ohmic Loss of Efficiency	$(\Delta\eta)_\Omega$	from (24)
Shadow Loss of Input	(P_{sh}/P_I)	from (23)
Loss of Efficiency	$\Delta\eta$	from (22)
Loss of Fill Factor	ΔF	from (25).

The grid ohmic parameter is further detailed into contributions from the surface and collector.

Figure 2.3 is a flow chart of the computational program in its present form, as applicable to execution in a HP85 desk-top computer. The three basic computations are key-selectable and the computation of performance parameters in all cases. In addition to the basic computations, the program shown in Figure 2.3 includes a number of procedures to provide a high degree of flexibility in handling the necessary input data, providing means for storing and retrieving data for various designs in randomly-accessible tape files and for modifying the values of specified parameters.

Table 2.2 is a listing of the program steps. The program symbols are correlated with the algetraic symbols of this report in Table 2.3.

Tables 2.5 and 2.6 show the performance parameters obtained for metallization ptterns for a solar cell fabricated on a ribbon substrate. The specified input parameters are listed in Table 2.4. The parameters of Table 2.5 correspond to an optimum pattern, those of Table 2.6 to a pattern optimized for a collector line-width of 3 mils. The metallization utilizes copper as the principal conductor in both cases. The resulting metallization pattern utilizing 3-mil collectors is shown in Figure 2.4.

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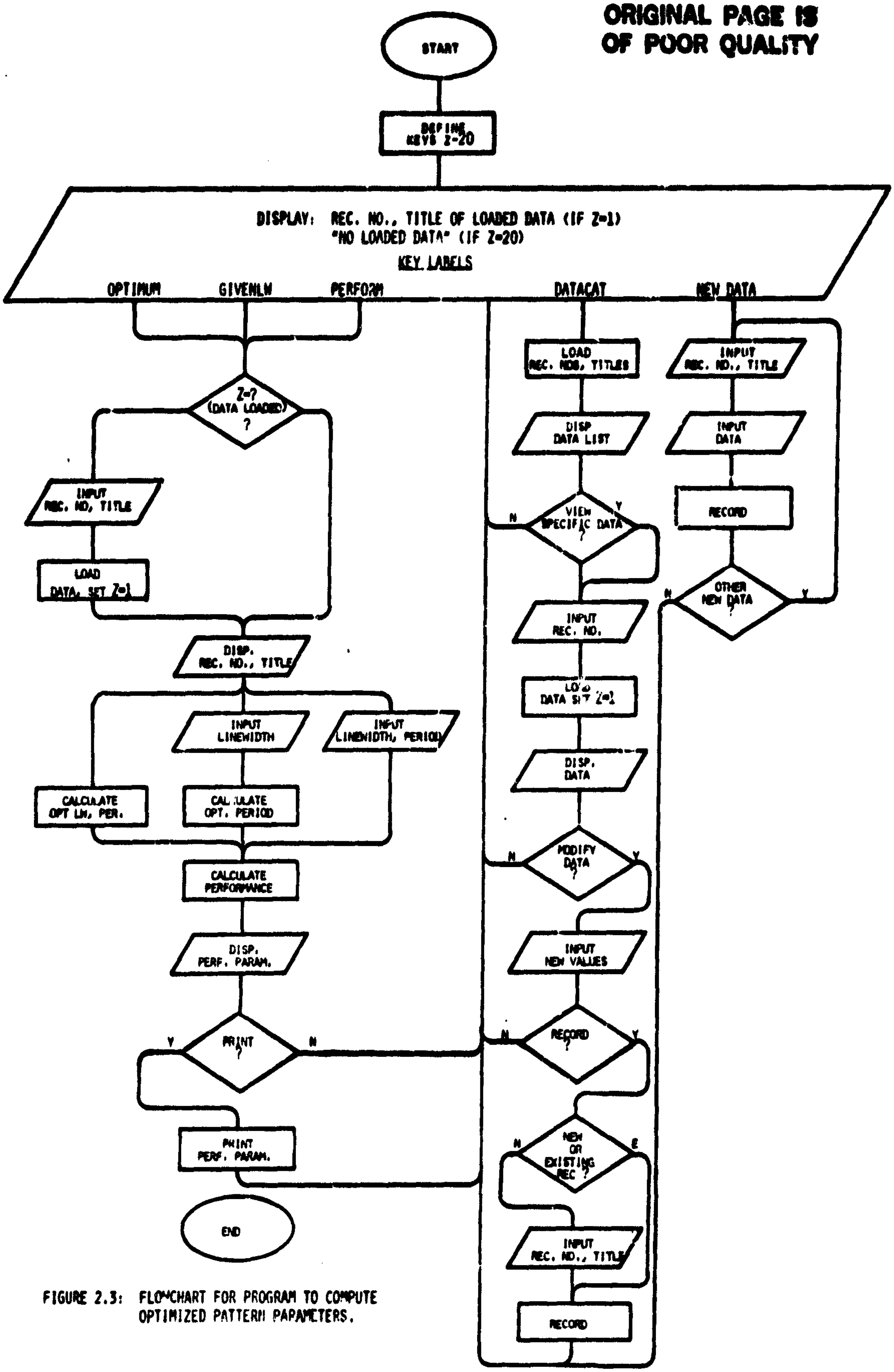

FIGURE 2.3: FLOWCHART FOR PROGRAM TO COMPUTE OPTIMIZED PATTERN PARAMETERS.

TABLE 2.2: COMPUTATIONAL PROGRAM FOR HP85

```
 10 REM ***"METPAT"***
 20 ON KEY# 1,"DATACAT" GOTO 180
 30 ON KEY# 2,"OPTIMUM" GOTO 840
 40 ON KEY# 3,"GIVNLNW" GOTO 107
    0
 50 ON KEY# 4,"PRFRMNC" GOTO 134
    0
 60 ON KEY# 5,"NEWDATA" GOTO 620
 70 Z=0
 80 CLEAR
 90 KEY LABEL
100 ON Z+1 GOTO 110,130
110 DISP "NO DATA LOADED"
120 GOTO 90
130 DISP "REC NO ";R;T$;" IS LOA
    DED "
140 DISP "TO CHANGE INPUT'INIT'T
    HEN 'CONT'"
150 DISP
160 DISP "SELECT TASK"
170 GOTO 90
180 REM **DATA CATALOG**
190 CLEAR
200 ASSIGN# 1 TO "DATAFL"
210 DISP "REC NO","TITLE"
220 DISP "------","-----"
230 FOR I=1 TO 15
240 READ# 1,I ; F,T$
250 ON ERROR GOTO 280
260 DISP "  ";R;"  ",T$
270 NEXT I
280 ASSIGN# 1 TO *
290 DISP
300 DISP
310 DISP "TO VIEW/LOAD SPECIFIC
    DATA"
320 DISP "INPUT REC NO,ELSE 0"
330 INPUT R
340 IF R=0 THEN 80
350 GOSUB 1980
360 CLEAR
370 DISP USING 2080 ; "#",R,T$
380 DISP "SUBSTRATE"
390 DISP USING 2090 ; "W0=",W0,"
    cm","D=",D,"cm"
400 DISP USING 2100 ; "H=",H,"SQ
    A/W","E0=",E0
410 DISP "R1=";R1;"Ω/sq"
420 DISP "COLLECTOR"
430 DISP USING 2100 ; "R0=",R0,"
    Ω-cmN","N=",N
440 DISP "BUSS"
450 DISP USING 2120 ; "M=",M,"W3
    =",W3,"cm"
460 DISP USING 2110 ; "R3=",P3,"
    Ω/sq"
470 DISP "MODIFY DATA (Y/N)",
480 INPUT A$
490 IF A$="N" THEN GOTO 80
500 DISP "INPUT NEW VALUES THEN
    PRESS CONT"
```

```
510 PAUSE
520 DISP "MODIFICATIONS MADE ","
    ENTER INTO RECORD(Y/N)";
530 INPUT A$
540 IF A$="N" THEN 80
550 DISP "NEW RECORD(N) OR MODIF
    Y EXISTING(E)";
560 INPUT A$
570 IF A$="E" THEN GOSUB 2030
580 DISP "INPUT REC. NO.,TITLE",
590 INPUT R,T$
600 GOSUB 2040
610 GOTO 80
620 REM **RECORD NEW DATA**
630 CLEAR
640 DISP "INPUT REC.NO.,TITLE OF
     NEW DATA"
650 INPUT R,T$
660 DISP ">ENTER SUBSTRATE"
670 DISP "W0,D (CM),"
680 DISP "H(SQA/W),E0(FRAC),"
690 DISP "SHEET R (OHMS/SQ) "
700 INPUT W0,D,H,E0,R1
710 DISP ">ENTER COLLECTOR"
720 DISP "R0(OHM-CM^N),N,"
730 INPUT R0,N
740 DISP ">ENTER BUSSES"
750 DISP "NUMDER,WIDTH (MILS)"
760 DISP "SHEET R (OHMS/SQ)"
770 INPUT M,W3,R3
780 W3=W3*.00254
790 GOSUB 2030
800 CLEAR
810 DISP "DATA RECORDED.OTHER NE
    W DATA? (Y/N)"
820 INPUT A$
830 IF A$="N" THEN GOTO 80 ELSE
    GOTO 640
840 REM **OPTIMUM Y**
850 C$="OPTIMUM LINEWIDTH"
860 CLEAR
870 GOSUB 1890
880 DISP "WORKING"
890 L0=(N+2)*H*R1*((R0/R1)^2/(4*
    N^N))^(1/(2+N))
900 G1=1/M^2
910 S0=(G1*L^2)^(2/(2+N))
920 A0=L0*S0
930 K=(N+1)/(N+2)
940 K1=2*K+1
950 K2=K1-1
960 Y=(E0/(2*A0*K))^(1/K1)-1/K2
970 P0=K2*Y^K1+K1*Y^K2
980 E=P0*A0/E0-1
990 IF ABS(E)<.0001 THEN 1030
1000 D0=K2/K1*Y
1010 Y=Y-E/D0
1020 GOTO 970
1030 B1=N*R0*G1*L^2
1040 B2=2*Y*R1
```

TABLE 2.2: CONTINUED

```
1050 W=(B1/B2)^(1/(2+N))
1060 GOTO 1430
1070 REM **GIVEN LINEWIDTH**
1080 CLEAR
1090 GOSUB 1890
1100 DISP "ENTER LINEWIDTH (MILS
     )"
1110 INPUT W
1120 W=W*.00254
1130 C$="  GIVEN LINEWIDTH"
1140 R2=R0/W^N
1150 G1=1/M^2
1160 C0=-E0/(H*R1)
1170 C1=2*(R2/R1)*G1*L^2
1180 C3=2*W^2
1190 C2=C1/2+3*C3/2
1200 B0=C1/C3/3-(C2/C3/3)^2
1210 B2=2*(C2/C3)^3/27
1220 B3=C1*C2/C3^2/3
1230 B4=C0/C3
1240 B1=(B3-B4-B2)/2
1250 B5=B1^2+B0^3
1260 IF B5<0 THEN 1310
1270 Y1=(B1+SQR(B5))^(1/3)
1280 Y2=(B1-SQR(B5))^(1/3)
1290 Y=Y1+Y2-C2/(3*C3)
1300 GOTO 1430
1310 T0=ACS(B1/SQR(-B0^3))
1320 Y=2*SQR(-B0)*COS(T0/3)-C2/(
     3*C3)
1330 GOTO 1430
1340 REM **PERFORMANCE**
1350 CLEAR
1360 GOSUB 1890
1370 DISP "ENTER COLLECTOR LINEW
     IDTH,PERIOD (MILS)"
1380 INPUT W,P
1390 W=W*.00254
1400 P=P*.00254
1410 Y=(P-W)/W
1420 C$="GIVEN PATTERN"
1430 F=1/(1+Y)
1440 G1=1/M^2
1450 G2=1/M
1460 R2=R0/W^N
1470 S3=M*W3/W0
1480 S2=(1-S3)*F
1490 S=S2+S3
1500 T=S*E0
1510 T2=S2*E0
1520 T3=S3*E0
1530 A1=H*Y^3*F
1540 O1=A1*R1*W^2*(L/W0)
1550 O2=A1*R2*L^2*G1/Y*(L/W0)
1560 A3=4*H*(1-F)^2
1570 O3=A3*R3*(L/W3)*G2*D^2*(L/W
     0)
1580 O=O1+O2+O3
1590 D1=O/E0
1600 D2=E0*S+O
```

TABLE 2.2: CONTINUED

```
1610 W=W/.00254
1620 P=W/F
1630 CLEAR @ Q=1
1640 DISP USING 2130 ; "#",R,T$,
     C$
1650 DISP USING 2140 ; "LINEWIDT
     H",W,"mils"
1660 DISP USING 2140 ; "PERIOD
      ",P,"mils"
1670 DISP
1680 DISP USING 2150 ; "LOSS OF
     EFFICIENCY     ",D2*100,"%"
1690 DISP USING 2150 ; "LOSS OF
     FILL FACTOR    ",D1
1700 DISP USING 2160 ; "SHADOW L
     OSS OF INPUT",S*100,"%"
1710 DISP USING 2160 ; "COLL",S2
     *100,"%"
1720 DISP USING 2160 ; "BUSS",S3
     *100,"%"
1730 DISP
1740 DISP USING 2150 ; "OHMIC EF
     FICIENCY LOSS ",O*100,"%"
1750 DISP USING 2160 ; "SURF",O1
     *100,"%"
1760 DISP USING 2160 ; "COLL",O2
     *100,"%"
1770 DISP USING 2160 ; "BUSS",O3
     *100,"%"
1780 DISP USING 2150 ; "SHADOW E
     FFICIENCY LOSS",T*100,"%"
1790 DISP USING 2160 ; "COLL",T2
     *100,"%"
1800 DISP USING 2160 ; "BUSS",T3
     *100,"%"
1810 IF Q=2 THEN 1870
1820 DISP "                   ";"PRI
     NT (Y/N)";
1830 INPUT A$
1840 IF A$="N" THEN 80
1850 CRT IS 2 @ Q=2
1860 GOTO 1640
1870 CRT IS 1 @ Q=1
1880 GOTO 80
1890 IF Z=1 THEN 1950
1900 DISP "INPUT DATA REC NO "
1910 DISP "TO CONSULT DATACAT IN
     PUT 0"
1920 INPUT R
1930 IF R=0 THEN 180
1940 GOSUB 1980
1950 CLEAR
1960 DISP R;T$
1970 RETURN
1980 ASSIGN# 1 TO "DATAFL"
1990 READ# 1,R ; R,T$,W0,D,H,E0,
     R1,R0,N,M,W3,R3
2000 ASSIGN# 1 TO *
2010 Z=1
2020 L=W0-M*W3
```

TABLE 2.2: CONTINUED

```
2030 RETURN
2040 ASSIGN# 1 TO "DATAFL"
2050 PRINT# 1,R ; R,T$,W0,D,H,E0
     ,R1,R0,N,M,W3,R3
2060 ASSIGN# 1 TO *
2070 RETURN
2080 IMAGE 11X,A,2Z,X,6A/
2090 IMAGE K,Z.3D,K,13X,K,Z.3D,K
2100 IMAGE K,D.3DE,X,K,4X,K,Z.3D
     ,K
2110 IMAGE K,D.3DE,X,K/
2120 IMAGE K,Z,19X,K,Z.3D,K
2130 IMAGE A,2Z,3X,6A,2X,K
2140 IMAGE K,X,DDD.DD,X,K
2150 IMAGE K,3X,Z.3D,A/
2160 IMAGE K,4X,DD.3D,A/
2170 END
```

TABLE 2.3

CORRELATION OF SYMBOLS

ALGEBRAIC SYMBOL	Defined in section	PROGRAM SYMBOL
W	Figure 2.2	W0
D	Figure 2.2	D
K	3.2.3	H
n^o	3.2.1, 3.2.7.1	E0
R_s	3.2.3	R1
β_c	3.2.3.1	R0
n	3.2.3.1	N
k	3.2.4.1	M
w_b	3.2.5.1	W_3
R_b	3.2.5.1	R_3
w	3.2.3	W
γ	3.2.4.1	Y
p	3.2.8	P
F_g	3.2.4.1	F
L	3.2.6.1	L
$G(k)$	3.2.6.1	G_1
$F(k)$	3.2.6.1	G_2
$(P_\Omega/P_i)_s$	Appendix A	01
$(P_\Omega/P_i)_c$	Appendix A	02
$(P_\Omega/P_i)_b$	3.2.6.1	03
$(\Delta\eta)_\Omega$	3.2.7	0
$(P_{sh}/P_i)_b$	3.2.4.1	S_2
$(P_{sh}/P_i)_g$	3.2.6.1	S_3
$(\Delta\eta)_{sh}$	3.2.7	S
$(\Delta\eta)_{sh,c}$	3.2.7	T2
$(\Delta\eta)_{sh,b}$	3.2.7	T3
$\Delta\eta$	3.2.7	D2
ΔF	3.2.7	D1

TABLE 2.4: SPECIFIED INPUT PARAMETERS FOR RIBBON PATTERNS

```
                 #01 RTRPM1
SUBSTRATE
W0=5.050cm                  D=1.480cm
H=8.533E-004 SQA/W         E0=0.150
R1= 30 Ω/sq
COLLECTOR
R0=5.000E-006 Ω-cmN         N-1 000
BUSS
M=1                        W3=0.102cm
R3=1.700E-004 Ω/sq
```

TABLE 2.5: PERFORMANCE PARAMETERS FOR OPTIMUM RIBBON PATTERN

```
#01   RTRPM1   OPTIMUM LINEWIDTH
LINEWIDTH   1.36 mils
PERIOD     68.24 mils

LOSS OF EFFICIENCY          0.814%
LOSS OF FILL FACTOR         0.015
SHADOW LOSS OF INPUT        3.971%
COLL      1.959%
BUSS      2.012%

OHMIC EFFICIENCY LOSS       0.219%
SURF        .071%
COLL        .142%
BUSS        .006%
SHADOW EFFICIENCY LOSS      0.596%
COLL        294%
BUSS        .302%
```

TABLE 2.6: PERFORMANCE PARAMETERS FOR RIBBON PATTERN WITH LINEWIDTH OF 3 MILS.

```
#01   RTRPM1     GIVEN LINEWIDTH
LINEWIDTH   3.00 mils
PERIOD    107.83 mils

LOSS OF EFFICIENCY          0.935%
LOSS OF FILL FACTOR         0.015
SHADOW LOSS OF INPUT        4.738%
COLL      2.726%
BUSS      2.012%

OHMIC EFFICIENCY LOSS       0.224%
SURF        .173%
COLL        .046%
BUSS        006%
SHADOW EFFICIENCY LOSS      0.711%
COLL        .409%
BUSS        302%
```

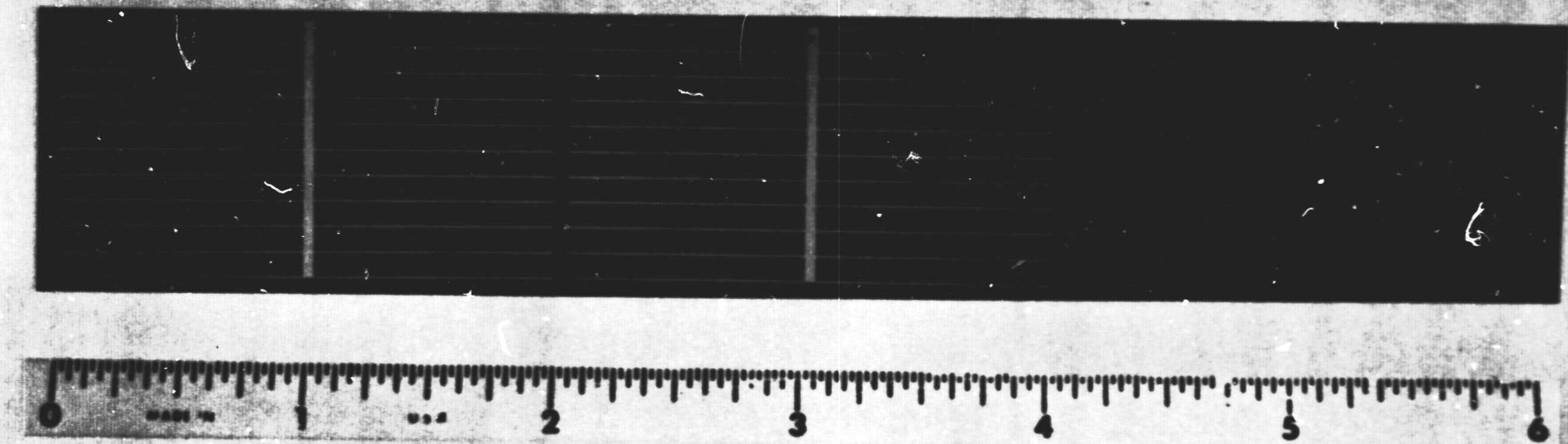

FIGURE 2.4: METALLIZATION PATTERN RESULTING FROM CHOICE OF 3 MIL COLLECTORS.

3.3 METALLIZATION

A prime candidate for forming low cost contacts to non-Cz substrates is metal plating. Most of the previous experience with plating ribbons has indicated that non-uniformities in substrate crystallinity may result in non-uniformities in metal plating, particularly in initiating electroless nickel plating. Because of this, palladium was often used as the plated contact layer.

It has been previously established that nickel can be used for contacts to Cz wafers. It would be desirable to do this for non-Cz substrates as well. To do this successfully requires studies in two areas: 1) uniform and repeated plating initiation and 2) sintering and thermal stress tolerance of nickel contacts to multi-crystalline silicon. Work in these two areas has been performed.

3.3.1 ELECTROLESS NICKEL PLATING

It has been observed that increasing the ammonium hydroxide content of the electroless nickel solution results in improved plating and coverage of RTR solar cells. The electroless nickel bath containing nickel sulfate and sodium pyrophosphate, previously reported for JPL Contract No. 954847, is being used. Increasing the ammonia content of this bath by a factor of 2 or 3 has given substantial improvements. Also, surface cleaning and increased bath operating temperature have led to a satisfactory direct nickel plating process for non-Cz substrates. The plating formulation presently being employed is listed below.

REAGENT	CONCENTRATION
Nickel Sulfate ($NiSO_4 . 6H_2O$)	25 g/ℓ
Sodium pyrophosphate ($Na_4P_2O_7 . 10H_2O$)	50 g/ℓ
Ammonium Hydroxide (58% NH_4OH)	66 ml/ℓ
Sodium Hypophosphite ($NaH_2PO_2 . H_2O$)	25 g/ℓ
Temperature	70°C

3.3.2 NICKEL SILICIDE FORMATION

Investigation of the plating process has included the use of Scanning Auger Microanalysis (SAM) depth profiling. This offers a very valuable tool in the evaluation of the plated layers and the extent of silicide formation during heat treatments. The surface is analyzed using Auger spectroscopy as an ion beam (Argon) simultaneously sputters through the material. Several analyses were performed on polished <100>, single crystal silicon wafers with a typical 0.4 μ N+ junction, which were plated with approximately 1000Å of electroless nickel (over the entire surface). Also, grid lines of processed solar cells with chemically polished surfaces were analyzed. The resulting SAM depth plots are shown in Figures 3.1 and 3.2. The samples were then sintered at 300°C for 30 minutes in a nitrogen ambient. These resulted in SAM depth profiles as shown in Figures 3.3 and 3.4.

In the SAM depth profiles, atomic composition in percentage (A.C.%) of the major elements is plotted as a function of the ion beam sputtering time. This time can be calibrated to a given sputter rate. Some interpretation is always involved with this technique since the ion and electron beams can become slightly misaligned over a period of time. This, along with surface and layer irregularities, results in the appearance of mixing or smearing at the interfaces. However, if the as-plated sample plot is used as a reference, changes can be easily interpreted. The analysis shows a uniform 6 to 8% phosphorus content in the plated electroless nickel layers, which is consistent with published data. The phosphorus does not appear to affect or interfere with the silicide formation. A slight amount of oxygen appears at the as-plated nickel-silicon interface and remains at the nickel-nickel silicide interface after sintering. Also, varying amounts of nickel surface oxidation are indicated during the heat treatment cycle.

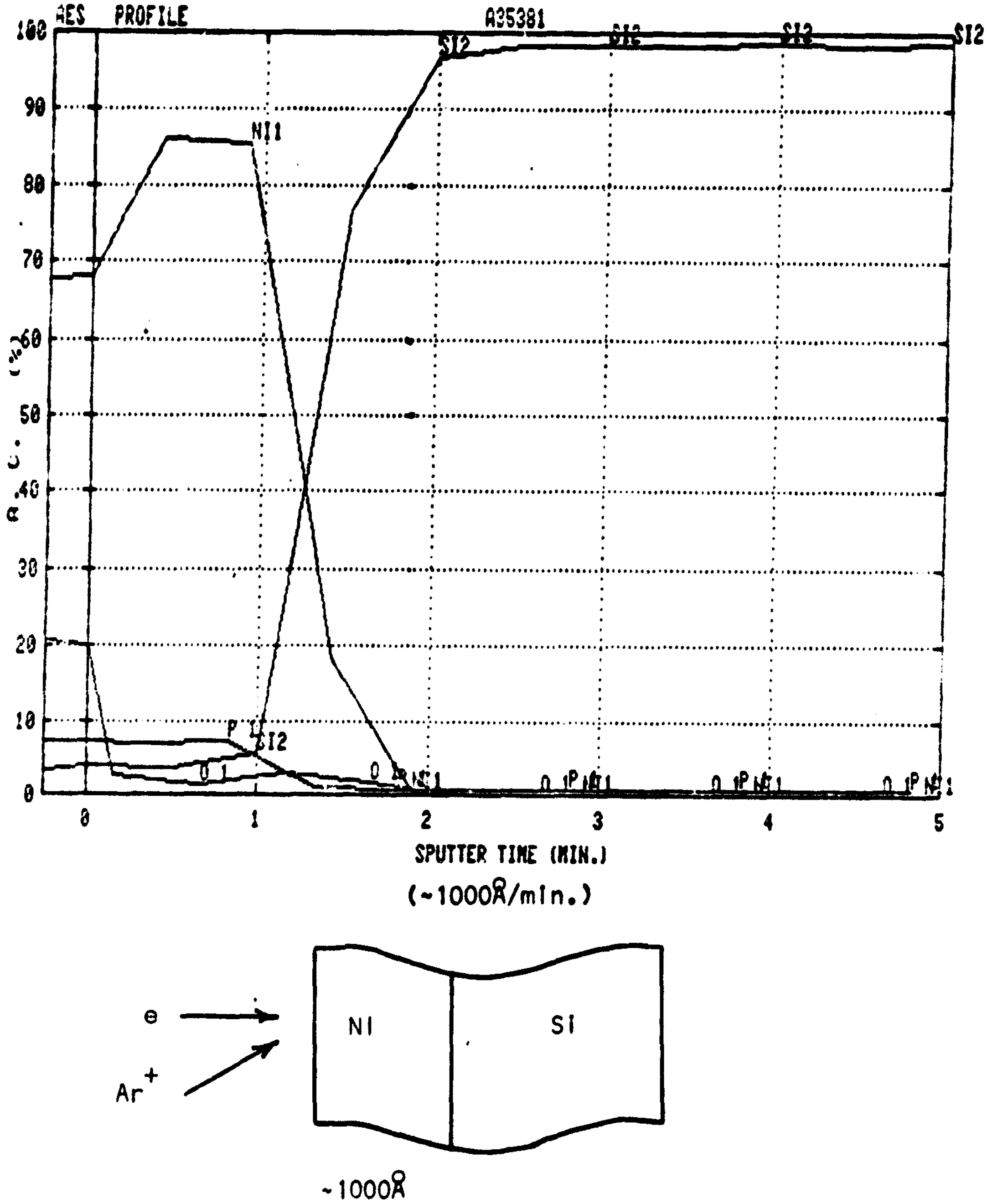

FIGURE 3.1: SCANNING AUGER MICROANALYSIS DEPTH PROFILE OF AS-PLATED NICKEL ON POLISHED SILICON SUBSTRATE.

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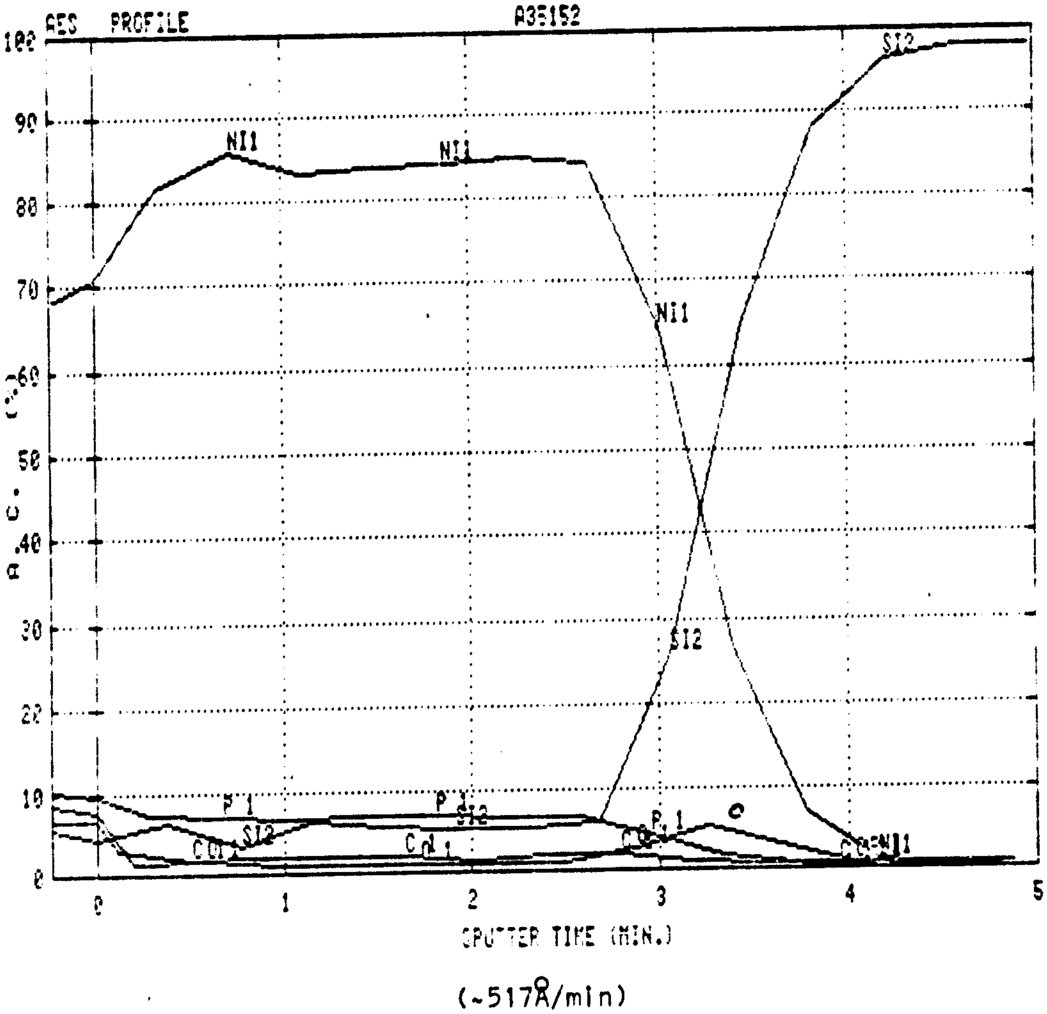

FIGURE 3.2: SCANNING AUGER MICROANALYSIS DEPTH PROFILE OF AS-PLATED NICKEL CONTACT ON SILICON SOLAR CELL FRONT GRID LINE.

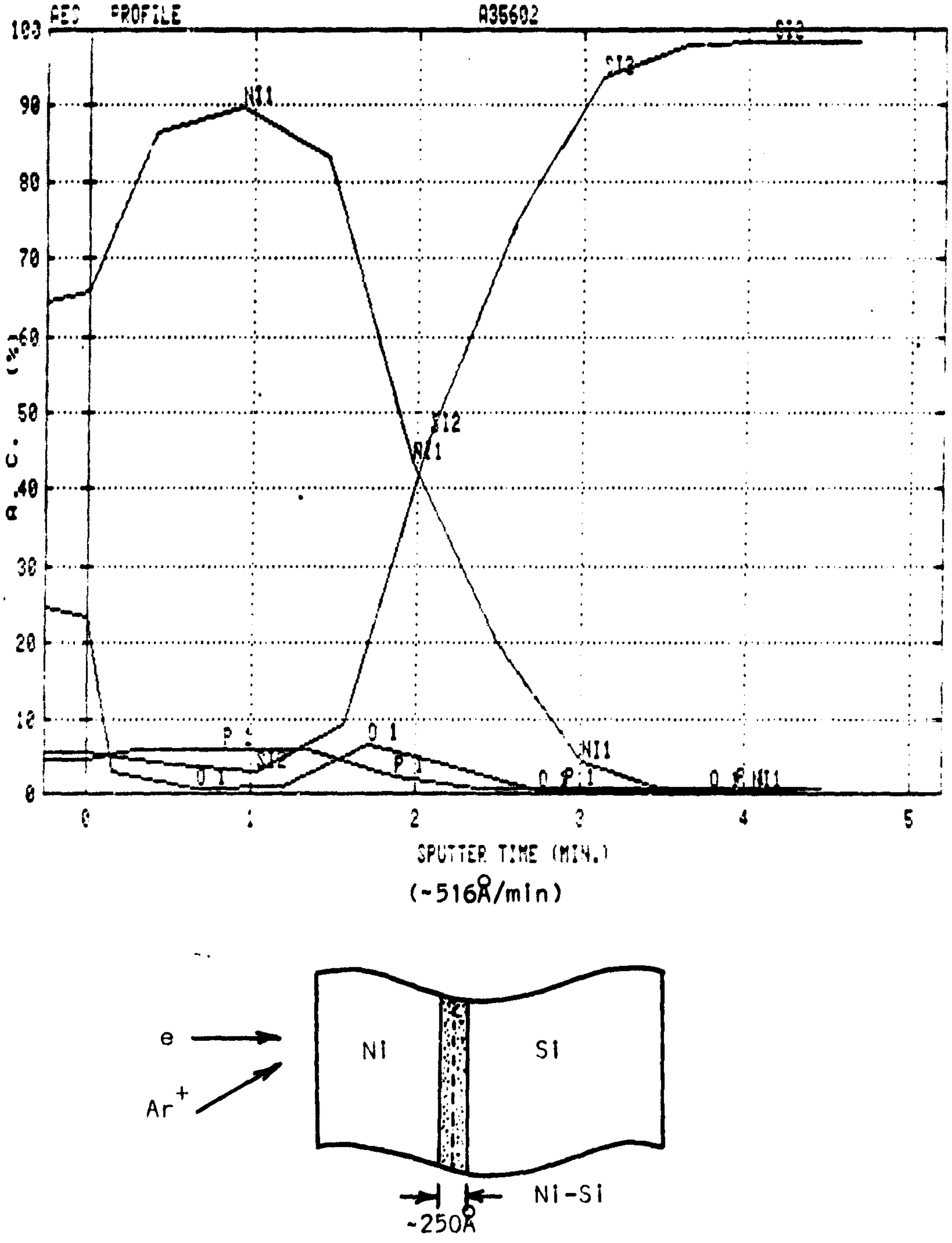

FIGURE 3.3: SCANNING AUGER MICROANALYSIS DEPTH PROFILE OF SINTERED NICKEL LAYER ON POLISHED SILICON SUBSTRATE.

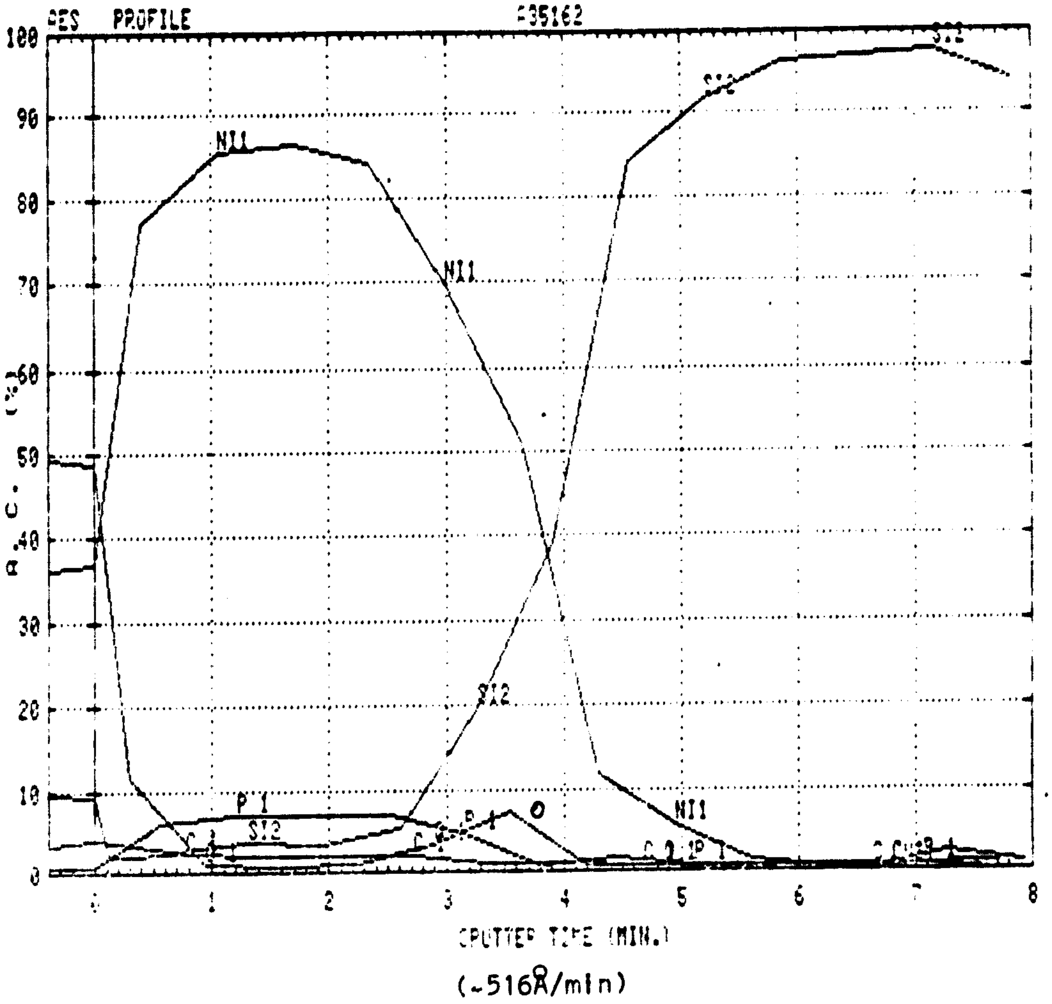

FIGURE 3.4: SCANNING AUGER MICROANALYSIS DEPTH PROFILE OF SINTERED NICKEL CONTACT ON SILICON SOLAR CELL FRONT GRID LINE.

The depth profiles after sintering definitely show atomic mixing or nickel silicide formation. Evaluation of these profiles along with Auger peak-to-peak intensity data plots indicates approximately 250Å of nickel silicide formation resulting from the 300°C, 30 min sinter. This compares reasonably well with published data when allowances are made for such factors as actual temperature and time during a furnace cycle (thermal inertia).

3.3.3 THERMAL STRESS STUDIES

Another crucial area of study for metallization of non-Cz substrates is to establish the effects generated by heat treatment of the metal contacts. Because of the multicrystalline nature of such substrates, metal diffusion and solar cell junction degradation may occur more readily than for Cz wafers. Samples were prepared to establish a time-temperature matrix for sintering the nickel contact layer on both non-Cz diodes and diodes on Cz wafers. Substrates with standard solar cell junctions were plated with metal over the entire front surface (to accentuate any degradation effects) and then sintered for various times and temperatures to characterize the onset of degradation of junction current-voltage characteristics.

Besides polished <100>, Cz wafers used as controls, nickel plated diodes were analyzed on ribbon-to-ribbon (RTR) laser regrown substrates (Motorola), dendritic web ribbon material (Westinghouse), and sliced polycrystalline, cast silicon substrates (Wacker-Silso). After the substrates had a 0.4μm deep phosphorus diffusion at 900°C, aluminum was deposited on the back and alloyed through the diffused region at 800°C for a back contact. Approximately 1000Å of electroless nickel was plated directly on the sbustrates using the nickel sulfate bath described above. The samples were then laser scribed on the backs and broken into 1 to 2 cm^2 size diodes. The final structure is illustrated in Figure 3.5. The electrical characteristics -- current at voltage -- were

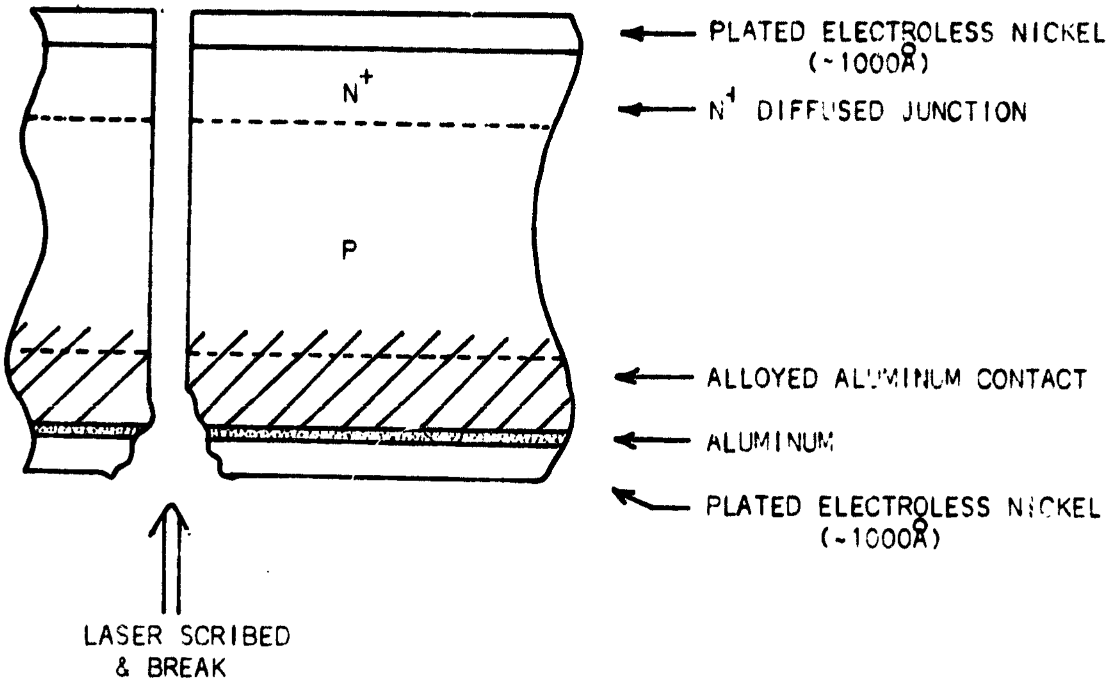

FIGURE 3.5: DIODE STRUCTURE USED TO EVALUATE ELECTROLESS NICKEL CONTACTS.

measured before and after heat treatment. A matrix of various times and temperatures is shown in Table 3.1, and the resulting log current versus voltage data (log I-V) are plotted for each sample of the matrix in figures 3.6 to 3.37.

The data presented in the I-V plots confirm, in general, that direct plated electroless nickel contacts can be used for non-Cz type solar cells without any electrical deterioration after an acceptable processing thermal cycle. The I-V plots indicate very good (~ideal) diode properties for the particular RTR and web samples compared to the particular single crystal samples of this matrix. Good contact can be made at low temperatures, 250° - 300°C, as shown by a contact improvement on those diodes which showed some initial contact problems. There is a gradual junction deterioriation with increased time at temperature, but the time at temperature required before any significant solar cell degradation appears to be well within any reasonable thermal processing cycle.

It can be noted that a consistent threshold mechanism occurs at 350°C, where very little or no diode degradation appears at short sinter times but marked degradation occurs for long sinter times. From the time-at-temperature results of lower temperature trials, it could be projected that short times at 350°C would show more degradation than observed. This discrepancy may be a result of reported phase reaction changes where NiSi formation becomes predominant (instead of Ni_2Si) at temperatures of 350°C and greater.

The dendritic web substrate samples do not show degradation as rapid as the other samples of the matrix. There are at least two explanations for this. Since the web material is higher resistivity (4-8 Ω-cm instead of 1 Ω-cm as used for the Cz and RTR samples), the same phosphorus diffusion cycle will result in a junction which is slightly deeper (because of the lower background doping concentration.) Of more importance, nickel silicide formation rates (Ni_2Si) have been reported to be more than twice as slow for <111> silicon substrates as for <100> silicon. The web material is of <111> orientation.

TABLE 3.1: NICKEL CONTACT TIME-TEMPERATURE SINTER MATRIX FOR VARIOUS SUBSTRATE MATERIALS.

TEMPERATURE (°C)	TIME (min)	SUBSTRATE			
		Cz	RTR	WEB	POLY
250	15	X			
250	30	X	X	X	X
250	60	X	X	X	X
250	120	X			
300	15	X			
300	30	X	X	X	X
300	60	X	X	X	X
300	120	X			
350	30	X	X	X	X
350	60	X	X	X	X
400	15	X	X	X	X

Each X designates a test sample.

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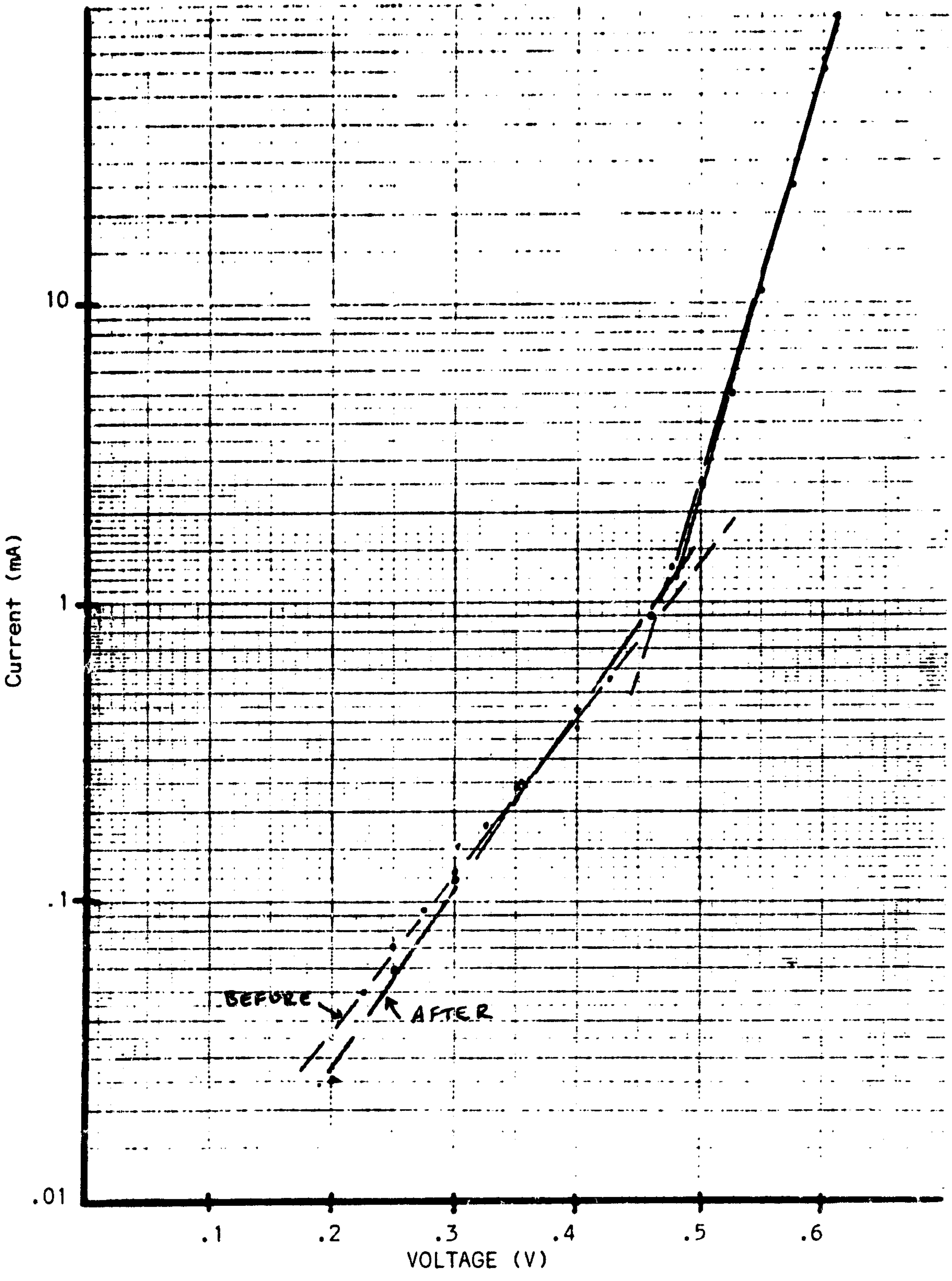

FIGURE 3.6 Nickel plated and sintered diode, <100> Cz substrate, 250°C for 15 min., 1.9 cm^2 junction area.

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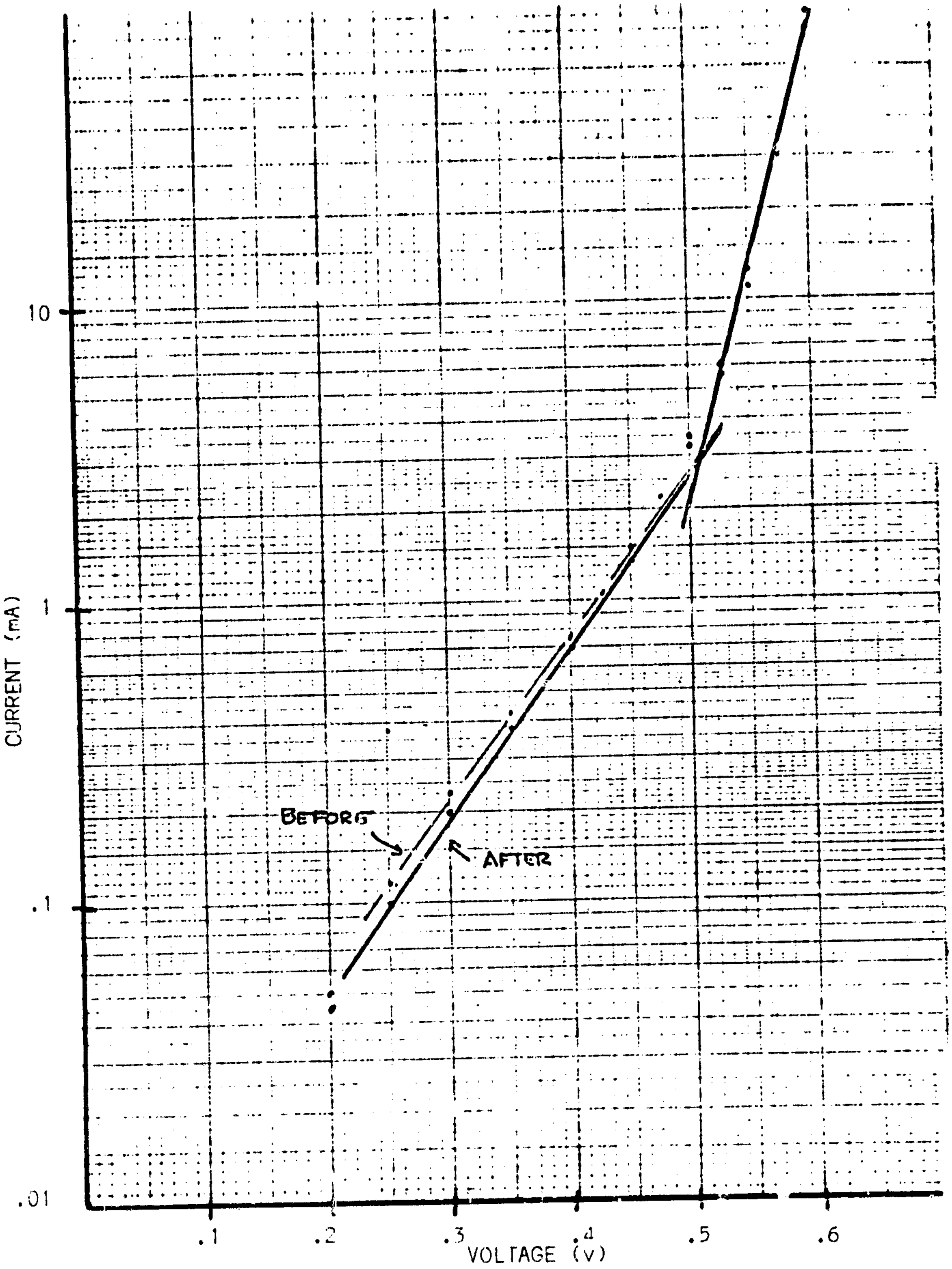

FIGURE 3.7 Nickel plated and sintered diode, <100> Cz substrate, 250°C for 30 minute, 2.5 cm² junction area.

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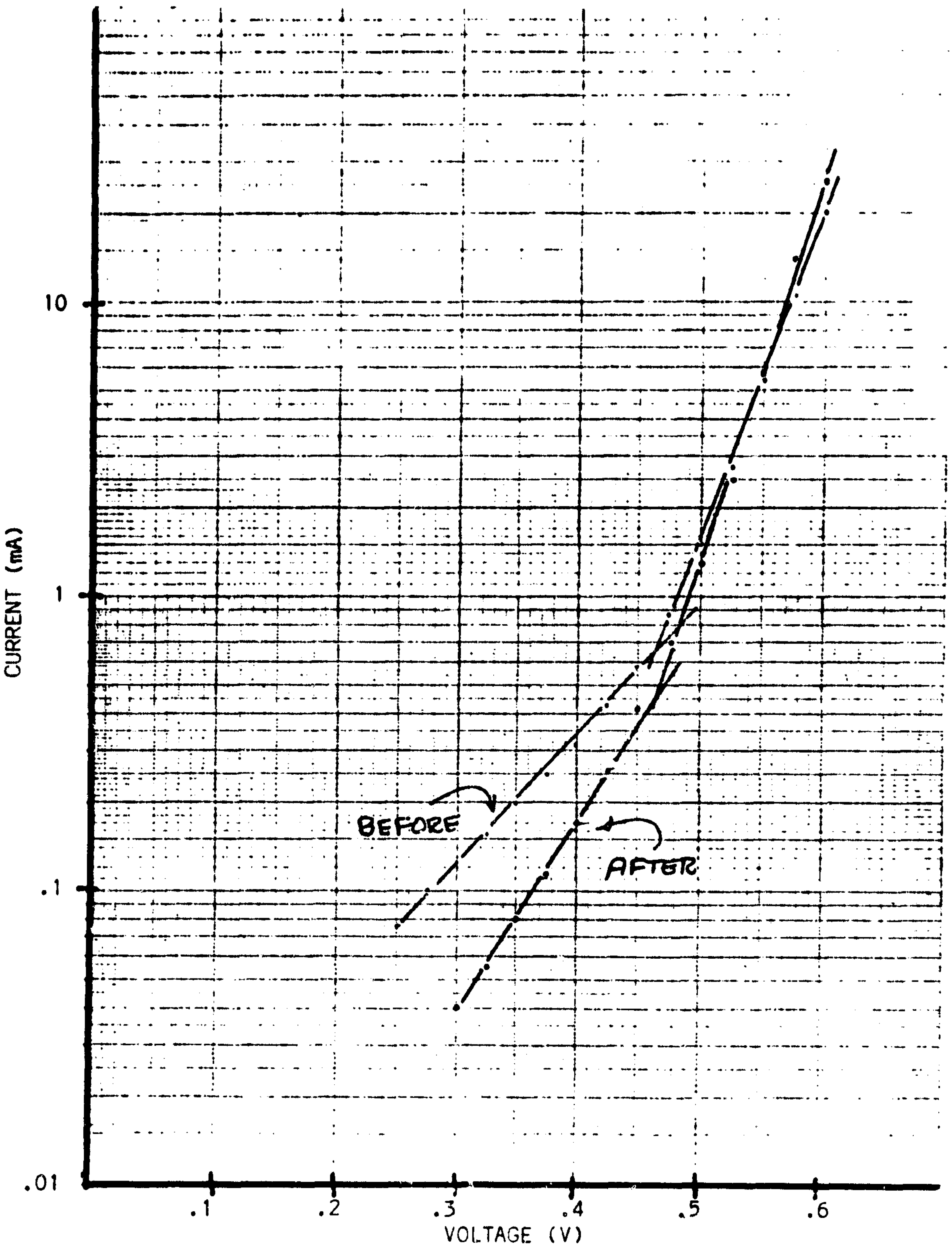

FIGURE 3.8: Nickel plated and sintered diode, <100>, Cz substrate, 250° for 60 min., 1.1 cm^2 junction area.

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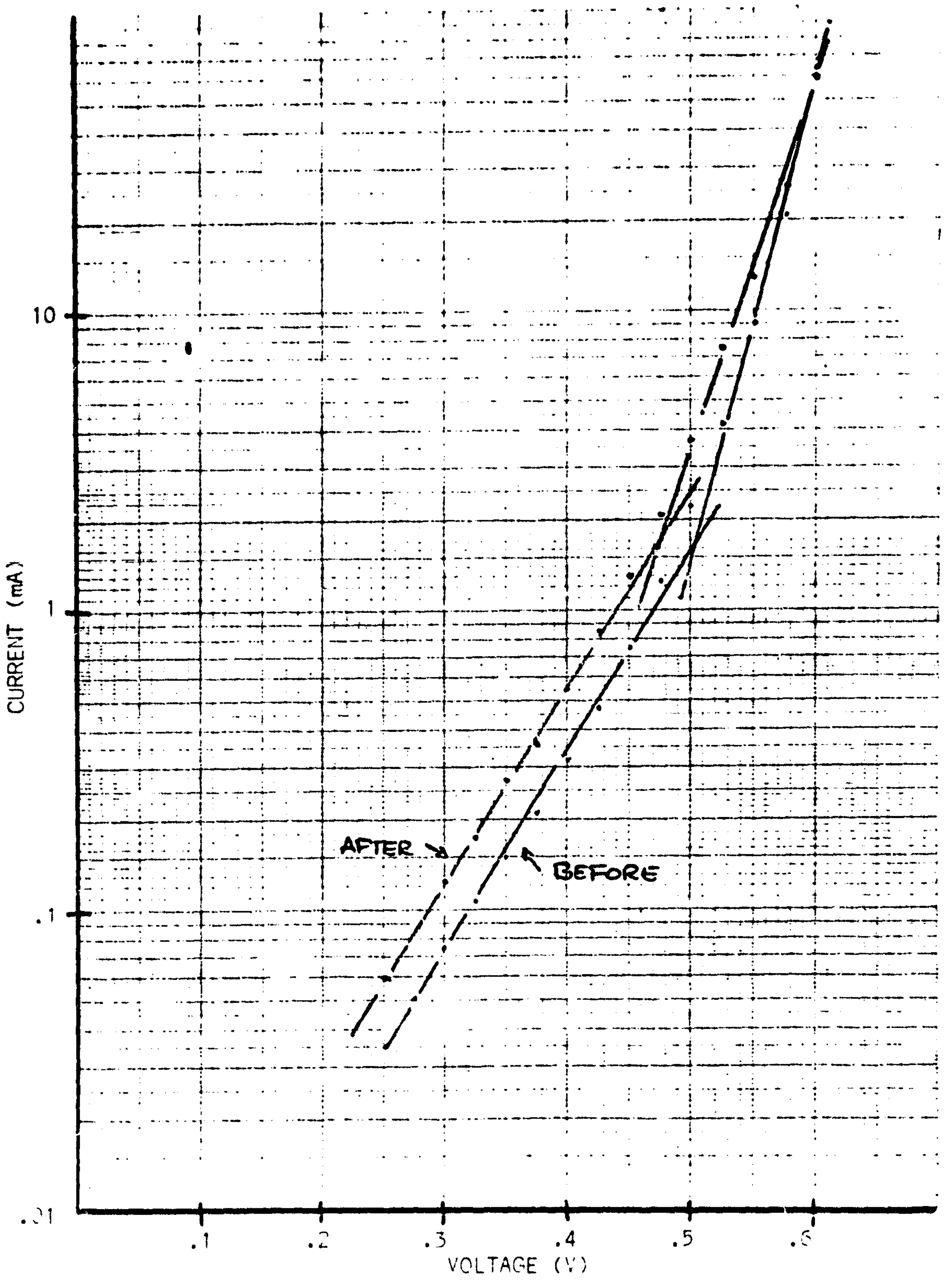

FIGURE 3.9: Nickel plated and sintered diode, <100> Cz substrate, 250°C for 120 min., 1.5 cm^2 junction area.

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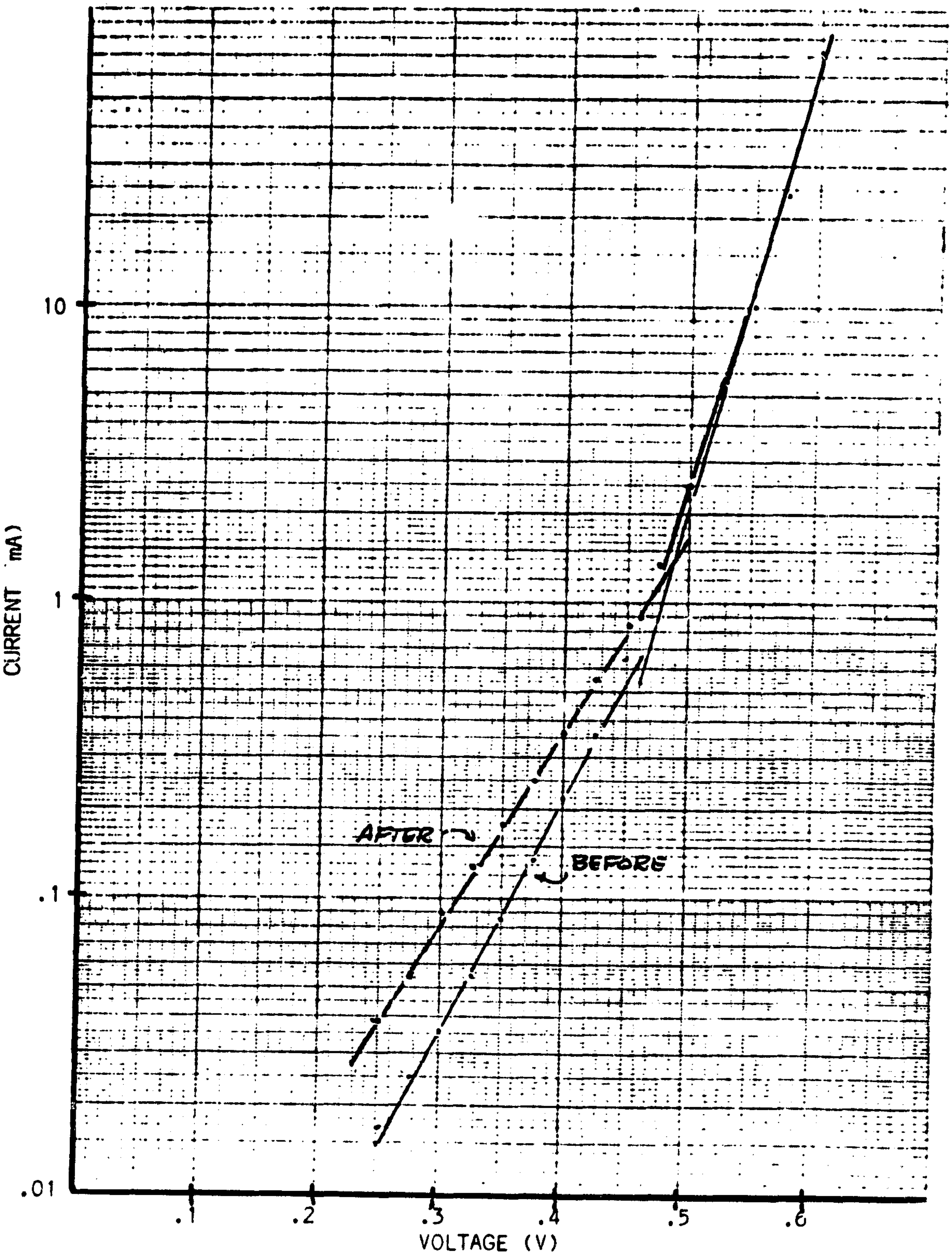

FIGURE 3.10: Nickel plated and sintered diode, <100> Cz substrate, 300°C for 1[illegible] min., 2.0 cm^2. junction area.

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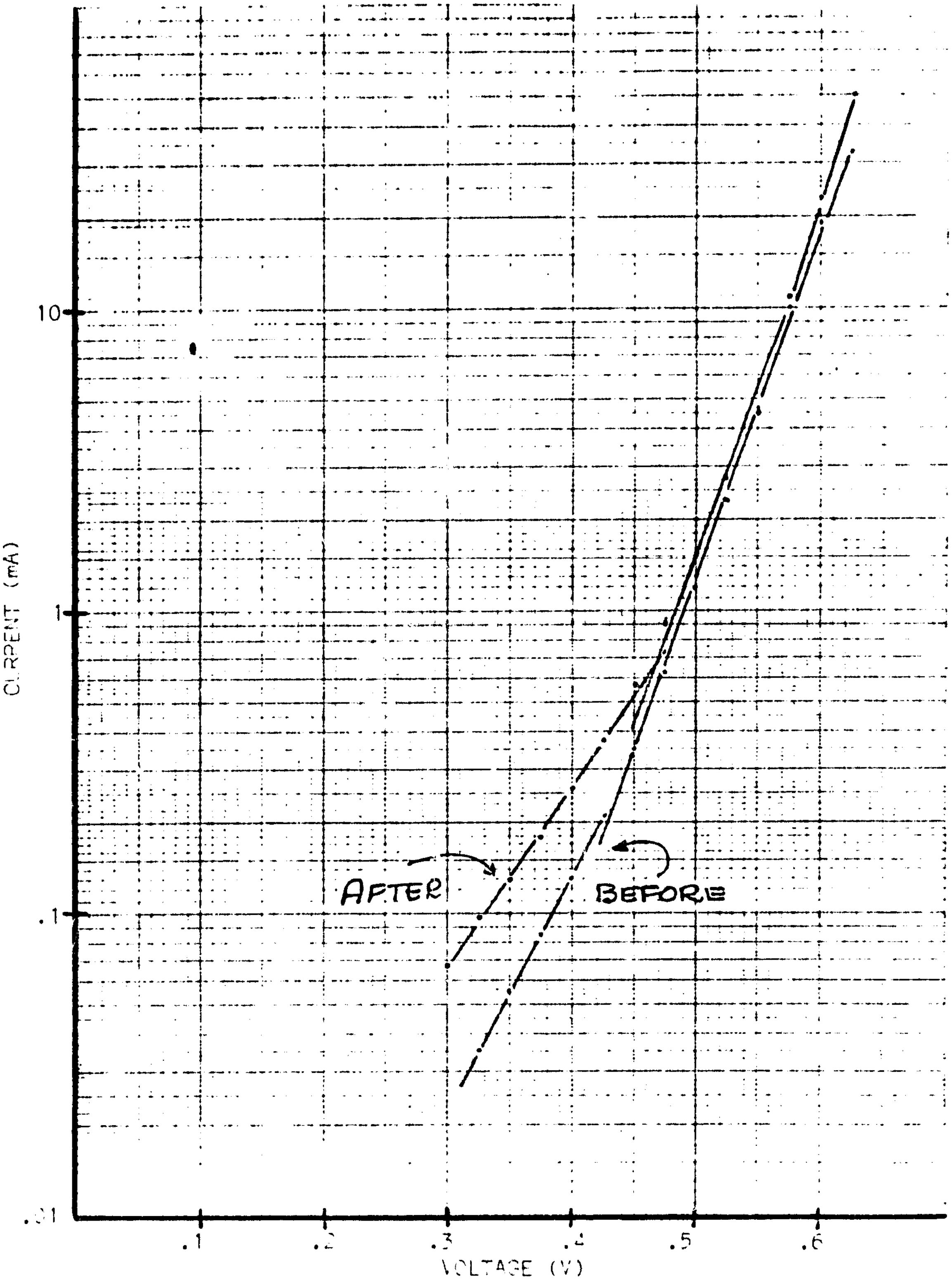

FIGURE 3.11: Nickel plated and sintered diode, <100> Cz substrate, 300°C for 30 min, 1.9 cm^2. junction area.

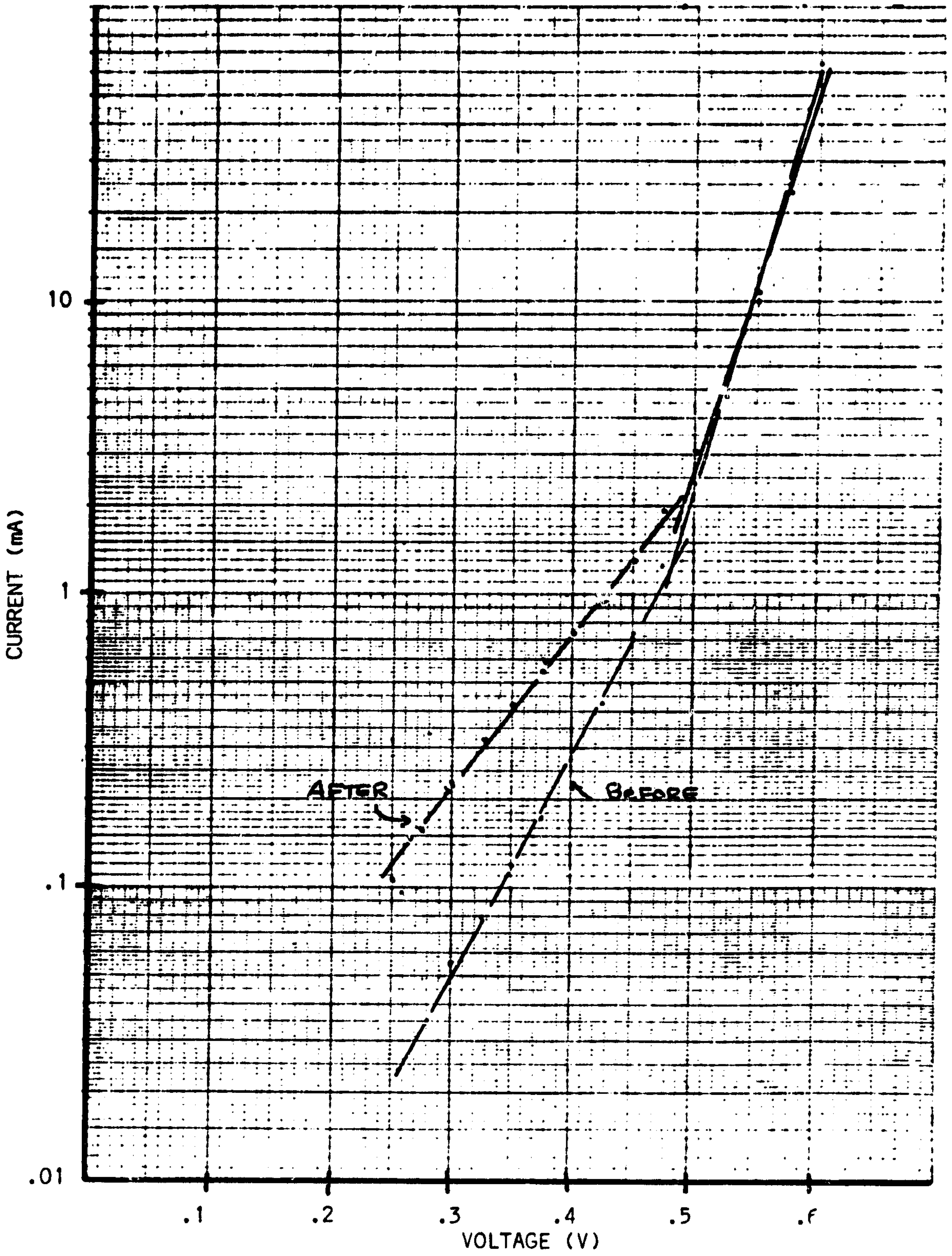

FIGURE 3.12: Nickel plated and sintered diode, <100> Cz substrate, 300°C for 60 min, 1.9 cm^2. junction area.

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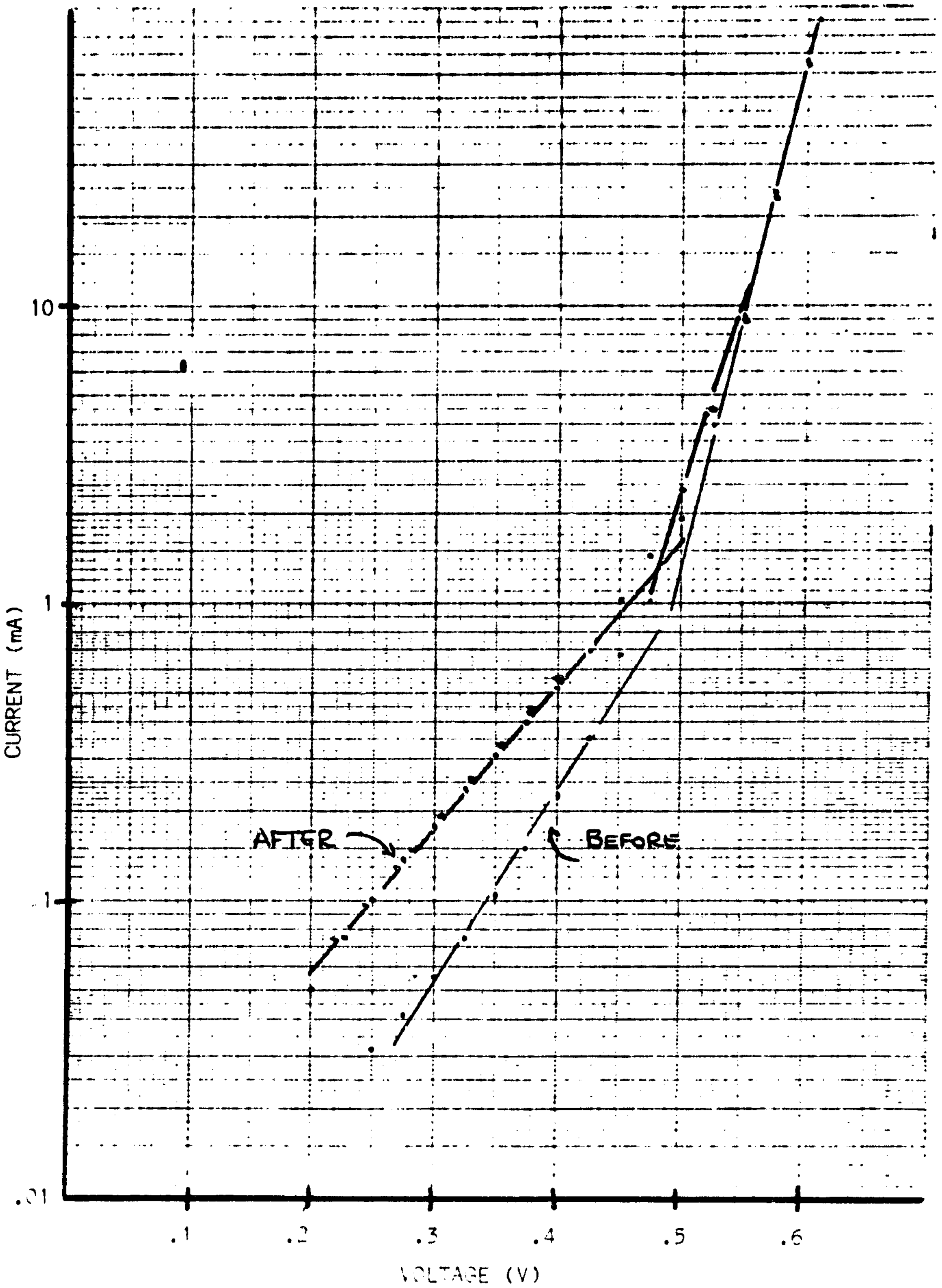

FIGURE 3.13: Nickel plated and sinter diode <100> Cz substrate, 300°C for 120 min., 2.1 cm^2 junction area.

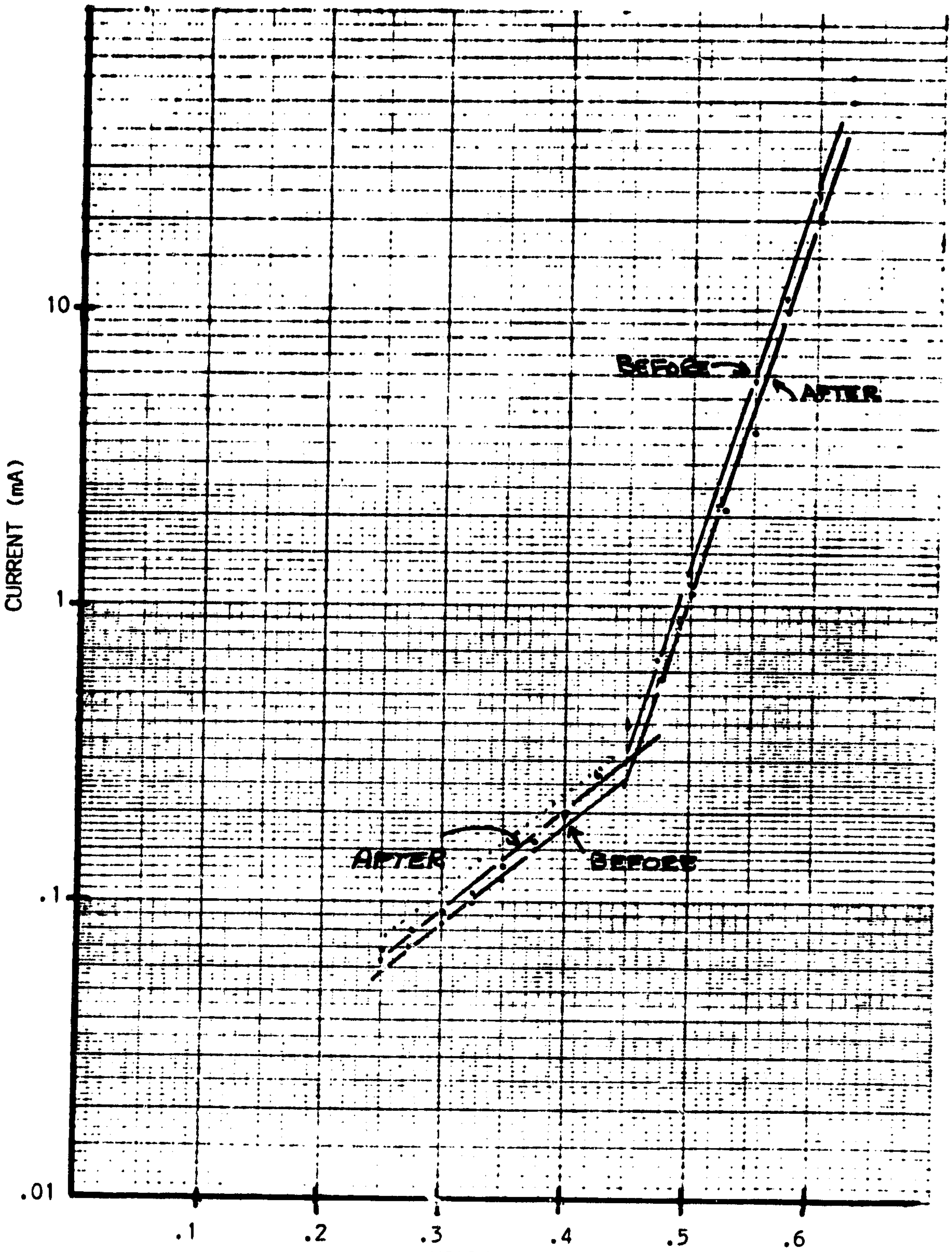

FIGURE 3.14: Nickel plated and sintered diode, <100> Cz substrate, 350°C for 30 min, 1.1 cm^2. junction area.

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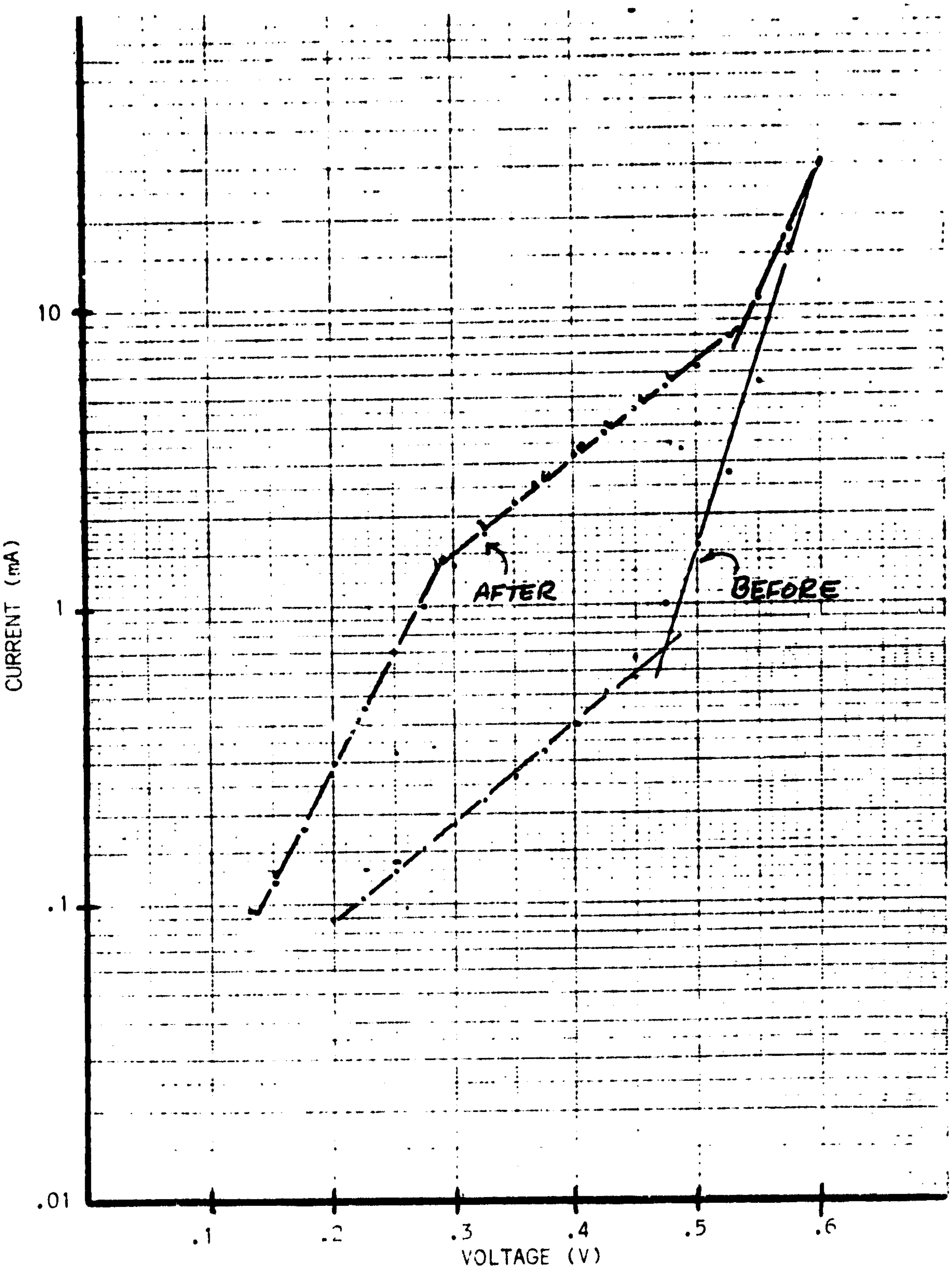

FIGURE 3.15: Nickel plated and sintered diode, <100> Cz substrate, 350°C for 60 min., 1 cm². junction area.

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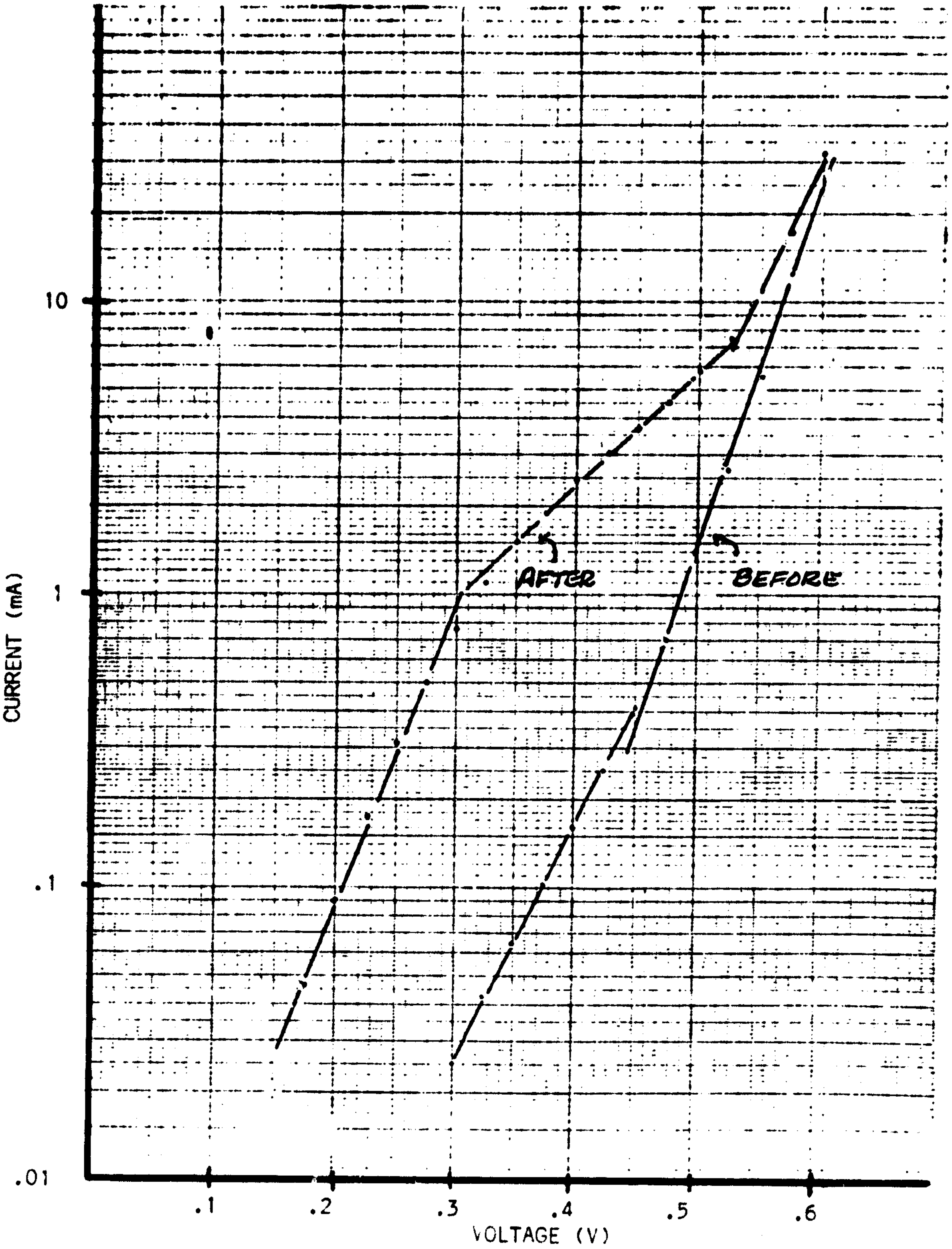

FIGURE 3.16: Nickel plated and sintered diode, <100> Cz substrate, 400°C for 15 min., 1.2 cm^2. junction area.

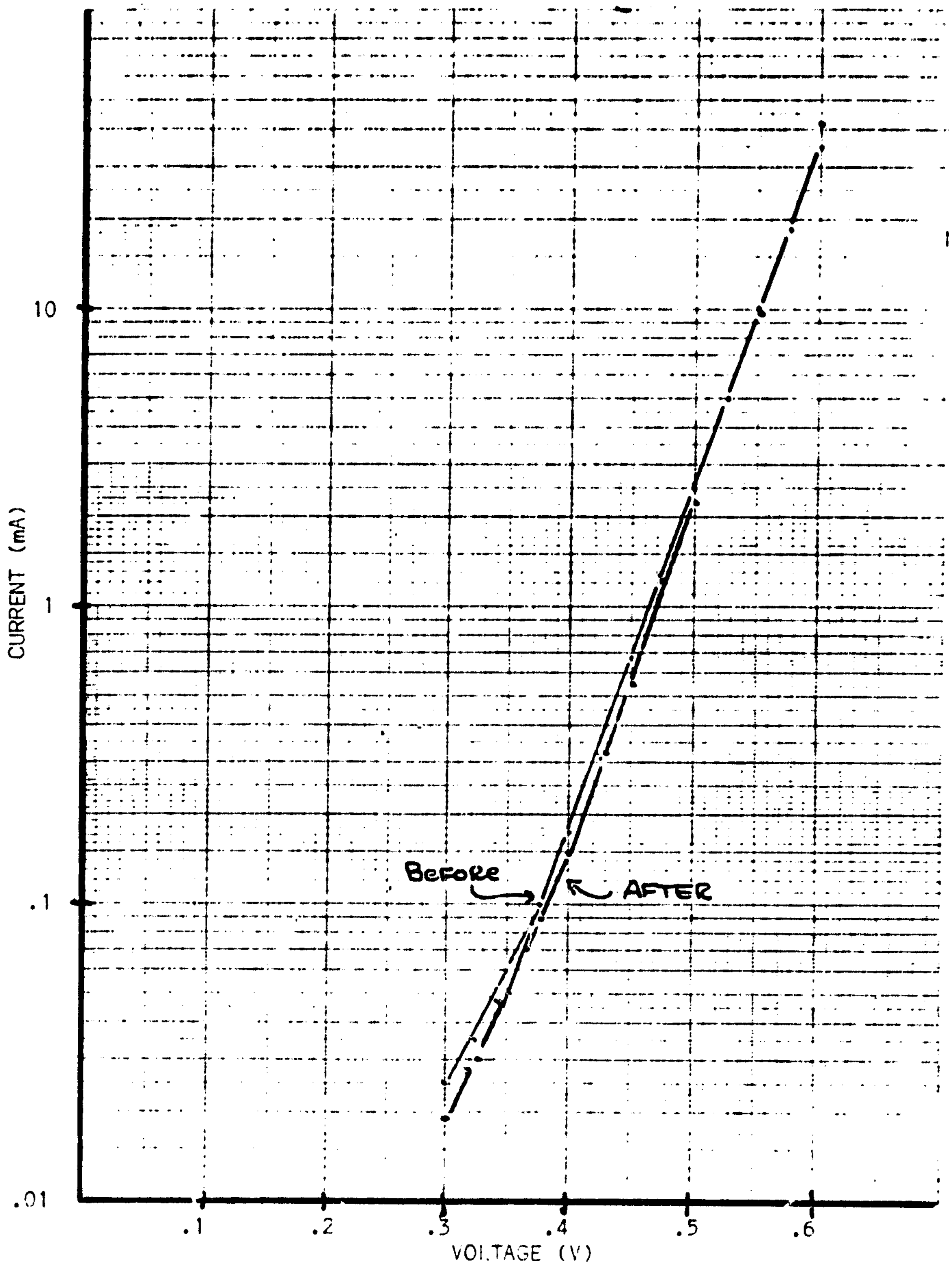

FIGURE 5.17: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) material, 250°C for 30 min., 1.0 cm^2 junction area.

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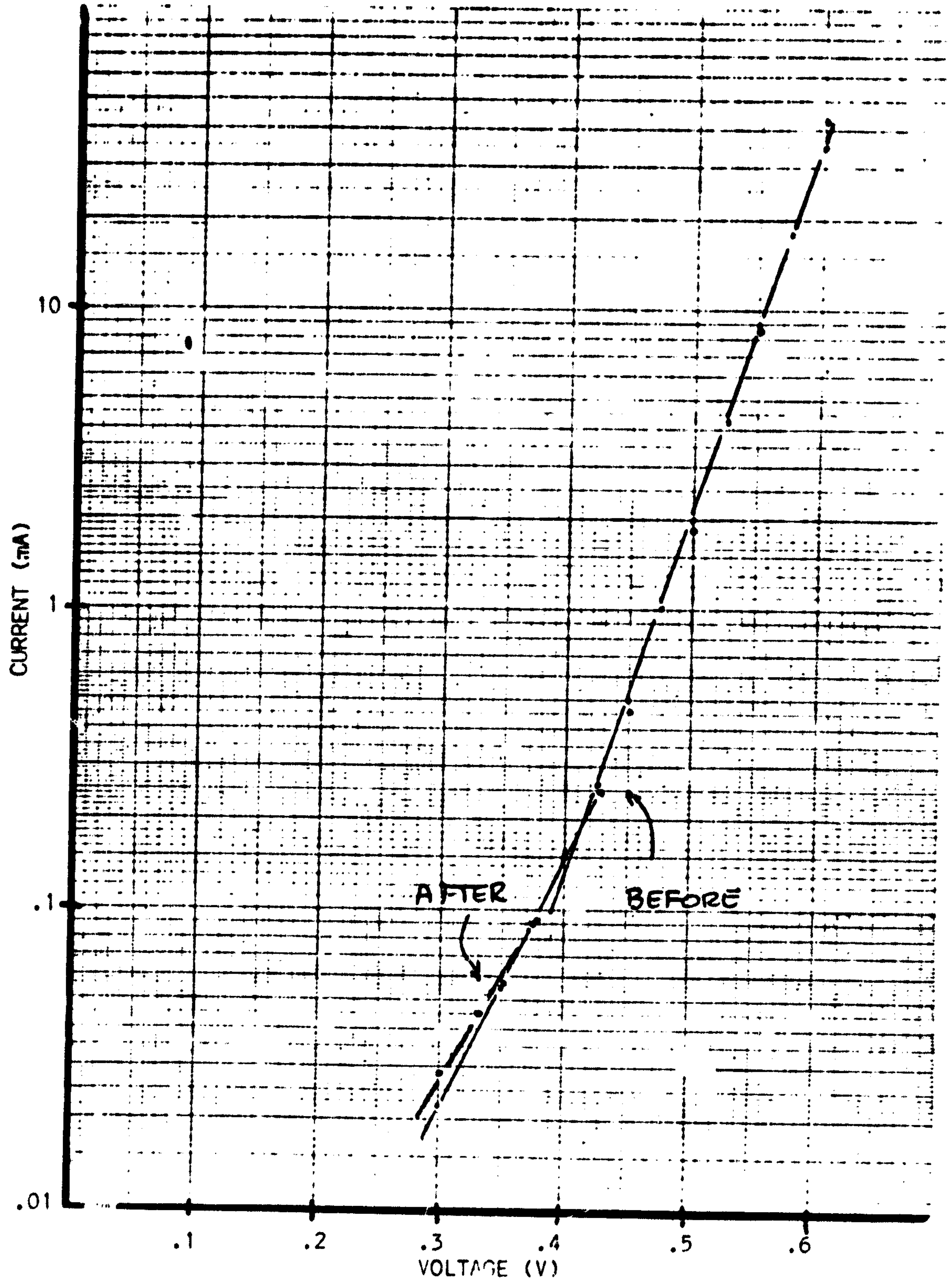

FIGURE 3.18: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) material, 250°C for 60 min., 0.8 cm^2 junction area.

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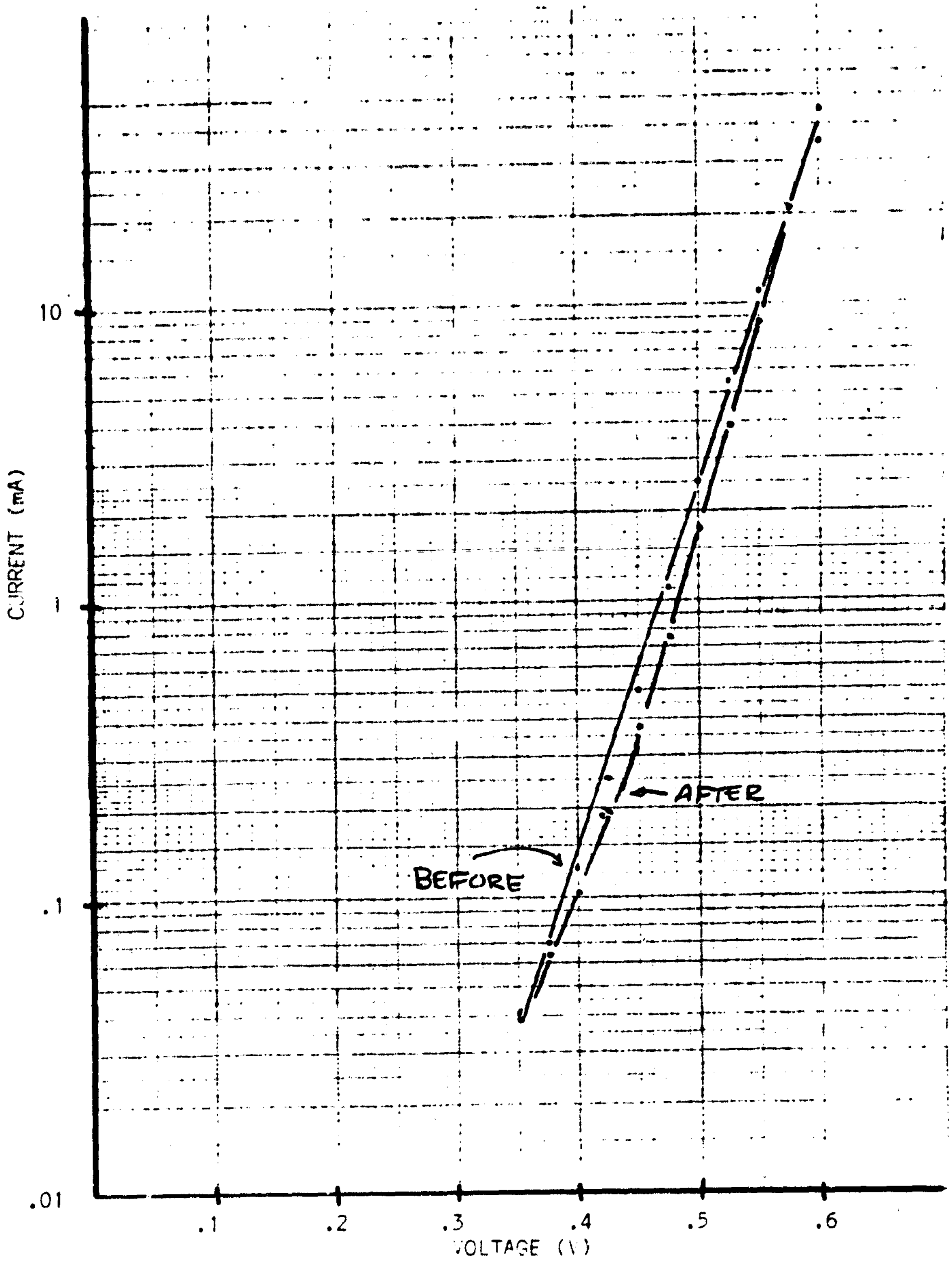

FIGURE 3.19: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) material, 300°C for 30 min., 0.9 cm^2 junction area.

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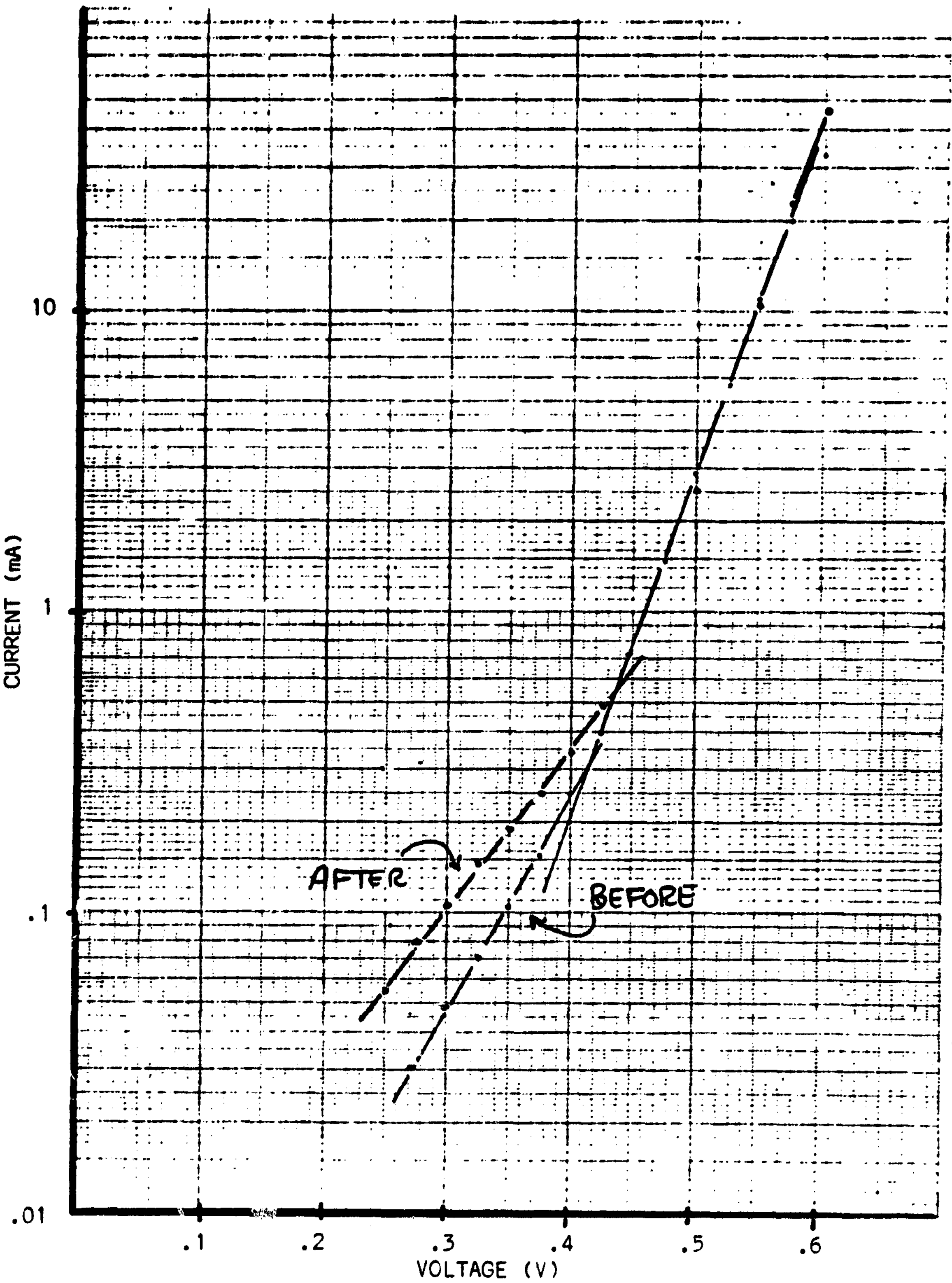

FIGURE 3.20: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) material, 300°C for 60 min., $1.1\ cm^2$ junction area.

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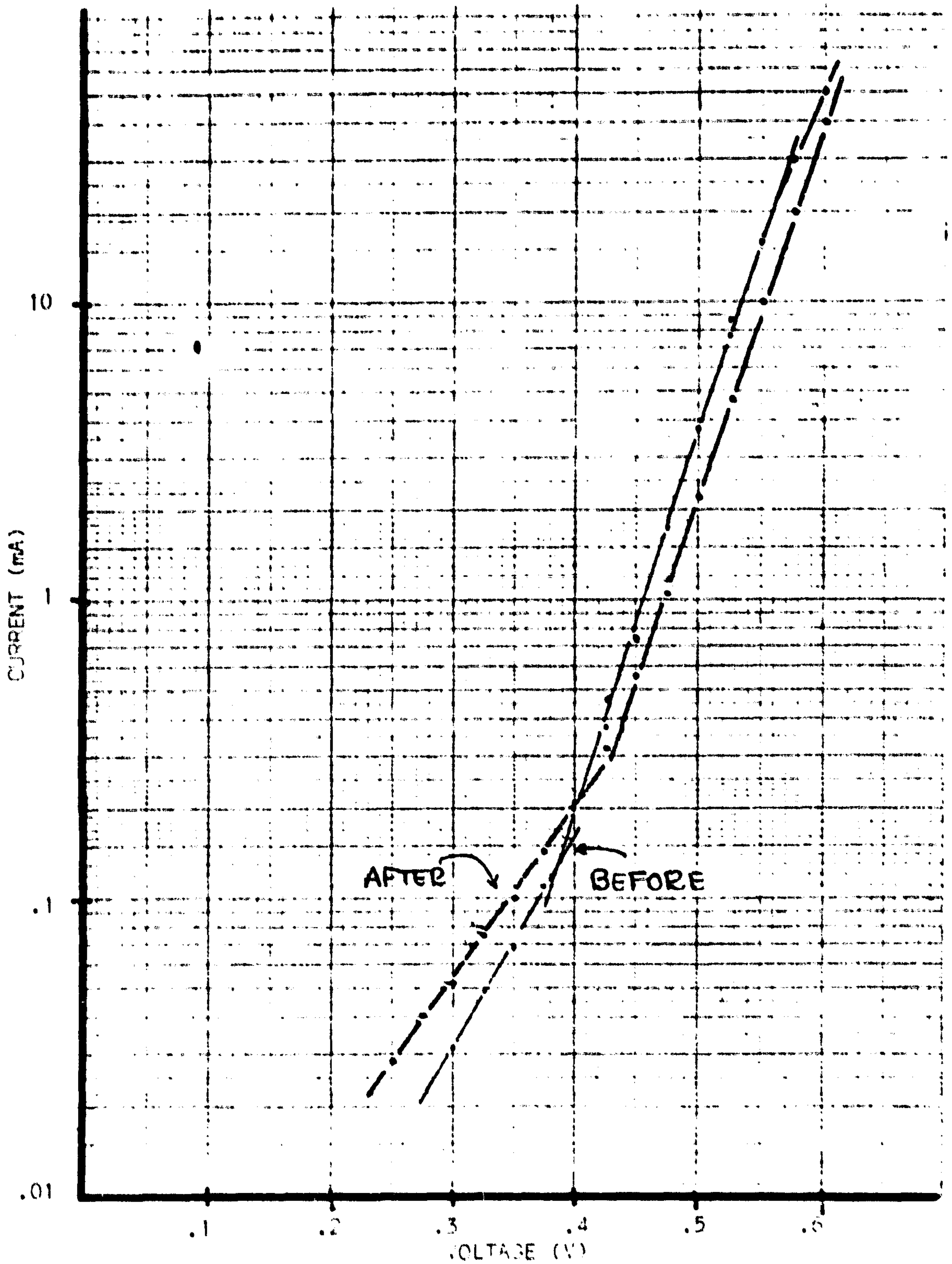

FIGURE 3.31: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) Material, 350°C for 30 min., 0.9 cm² junction area.

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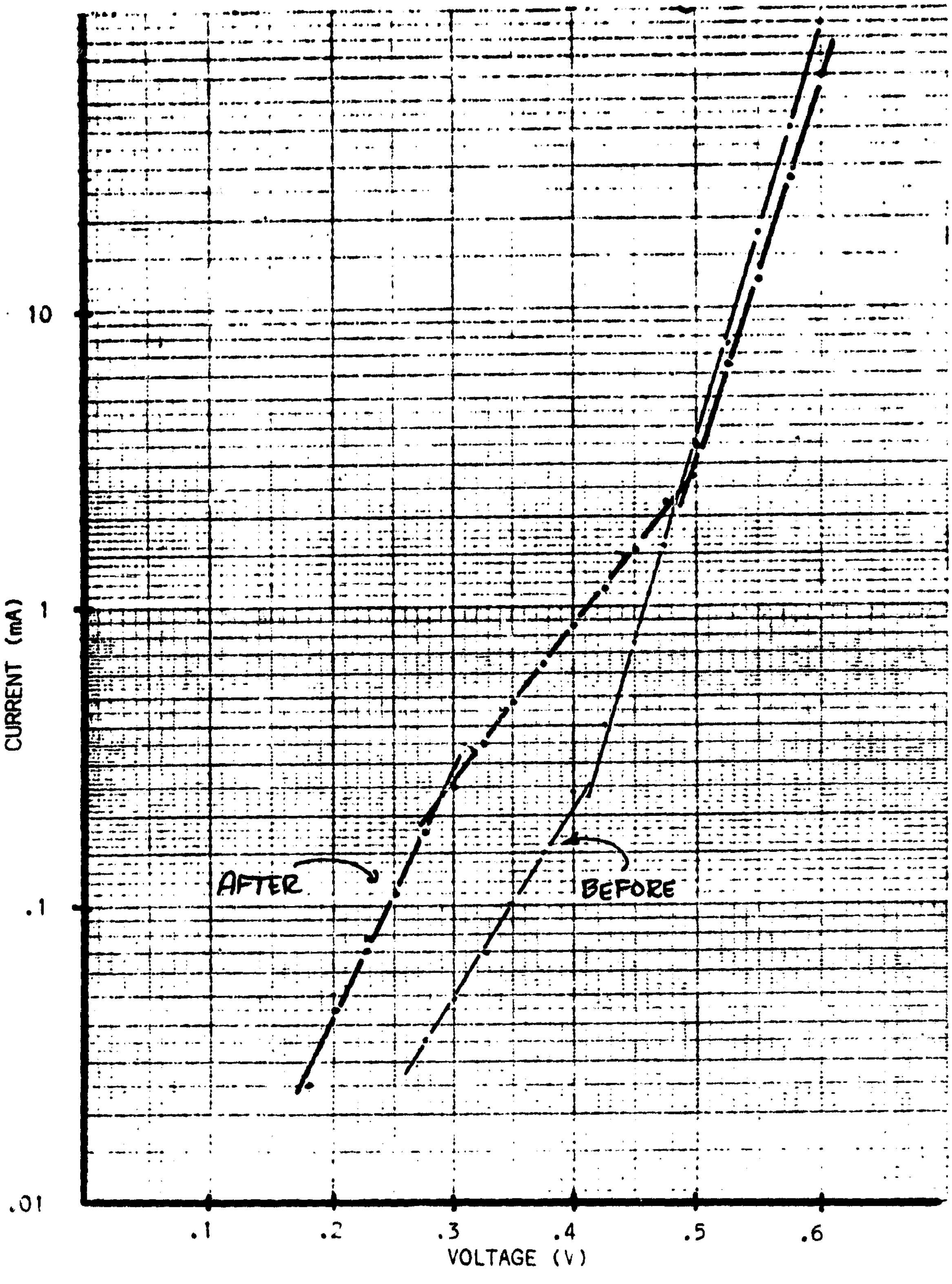

FIGURE 3.22: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) Material, 350°C for 60 min., 1.0 cm^2 junction area.

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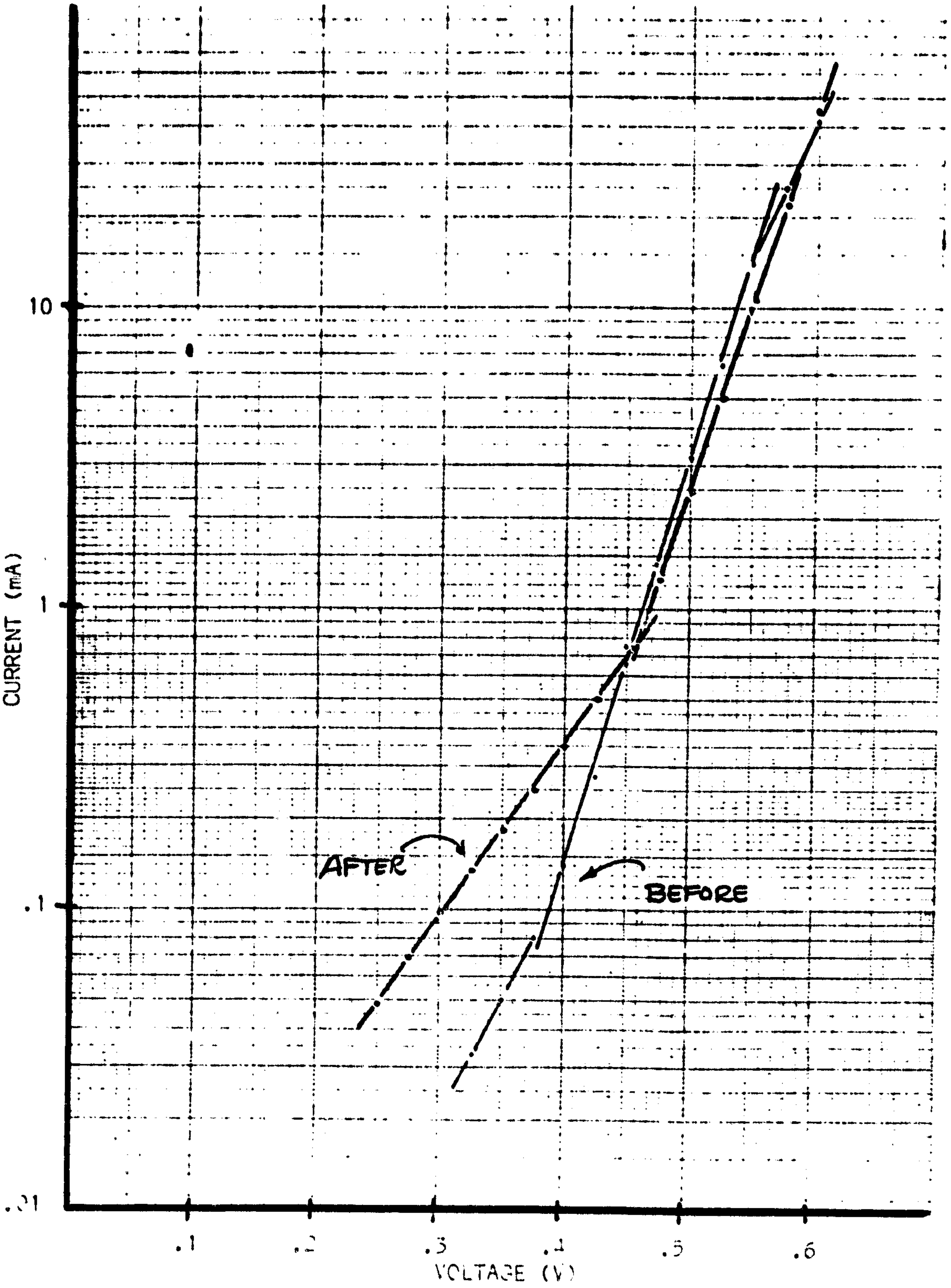

FIGURE 3.23: Nickel plated and sintered diode, Ribbon-to-Ribbon (RTR) material, 400°C for 15 min., 1.1 cm^2 junction area.

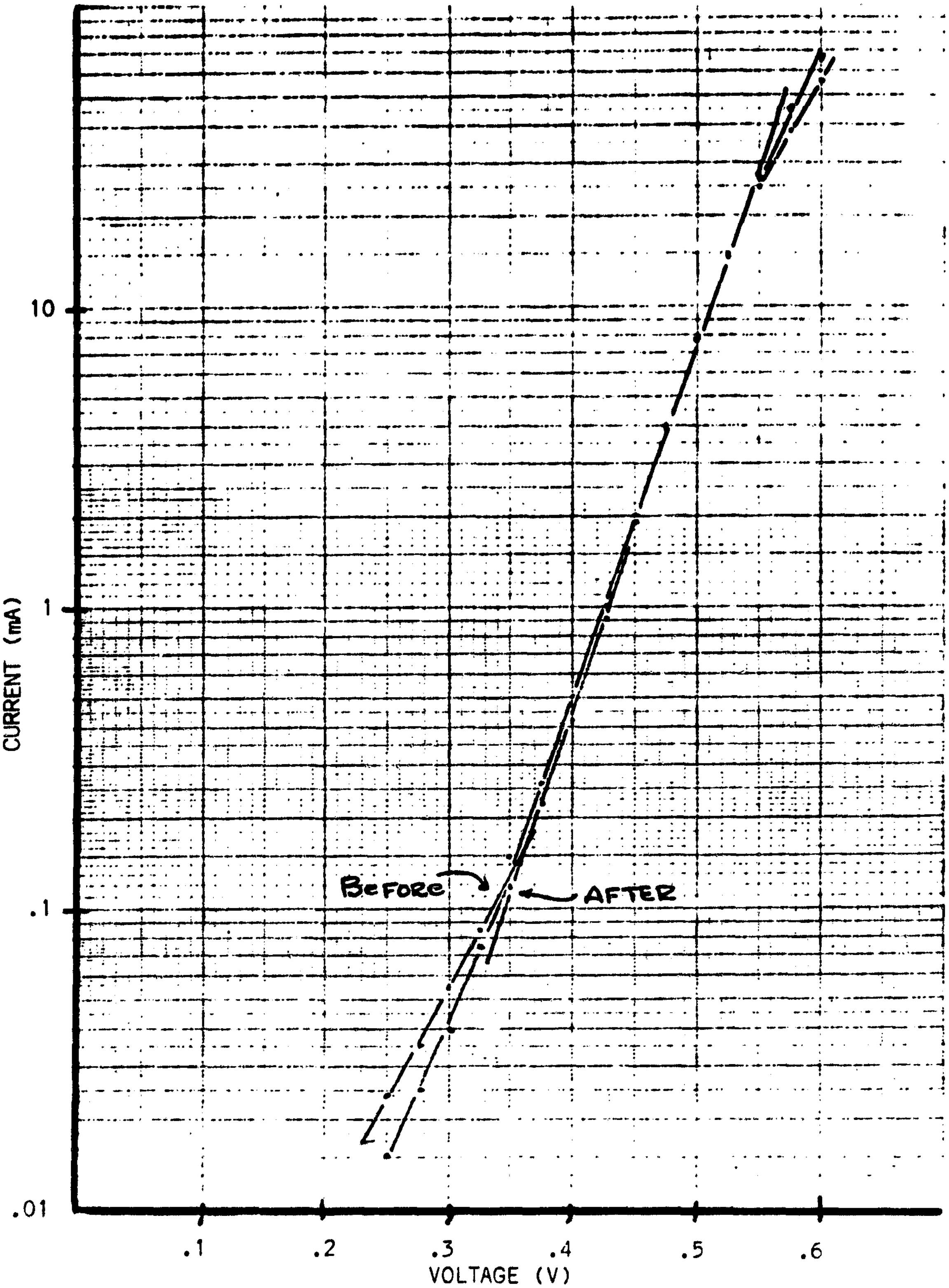

FIGURE 3.24: Nickel plated and sintered diode, dendritic web substrate, 250°C for 30 min., 1.2 cm^2 junction area.

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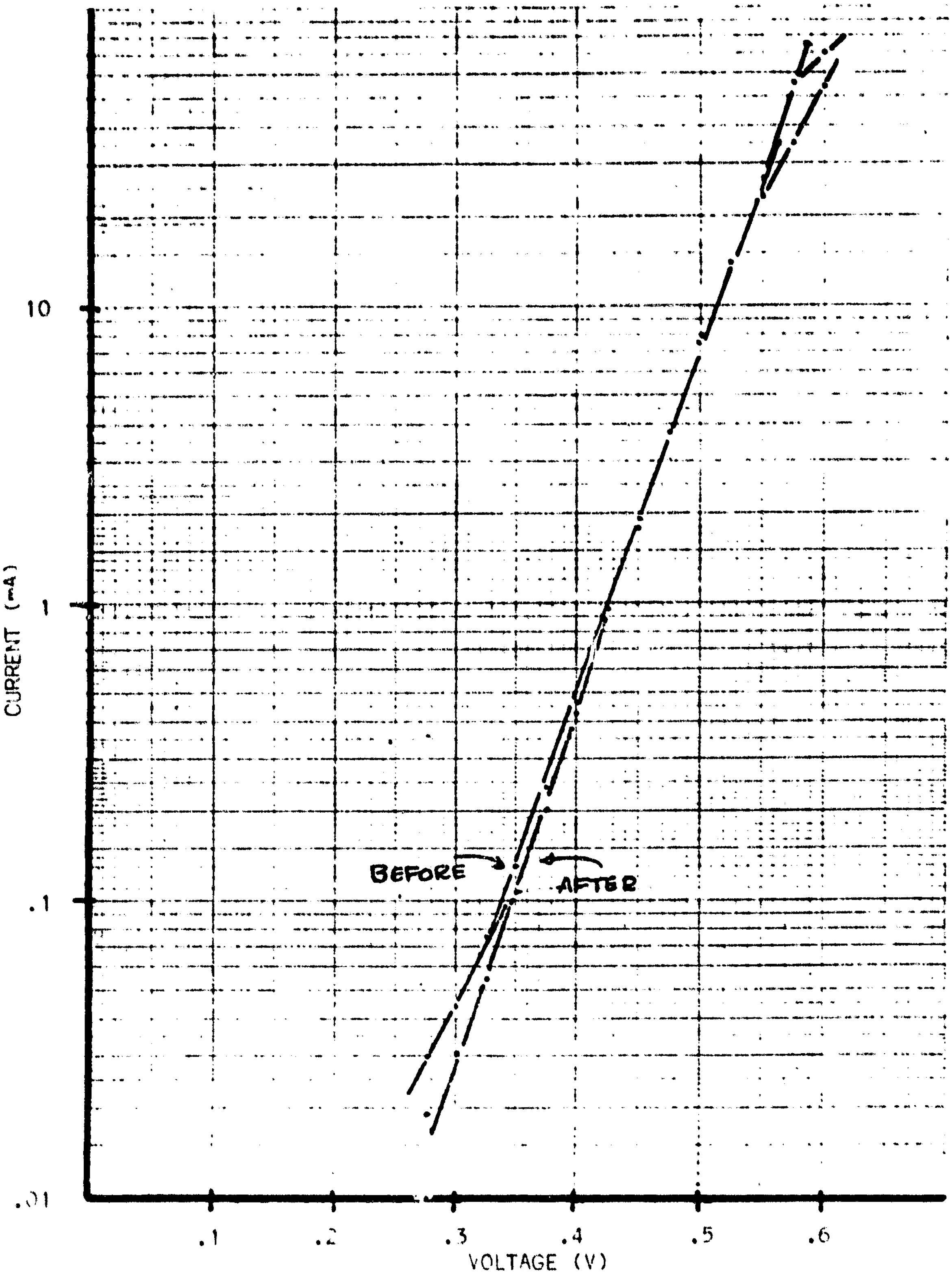

FIGURE 5.25: Nickel plated and sintered diode, dendritic web substrate, 250°C for 60 min., 1.2 cm² junction area.

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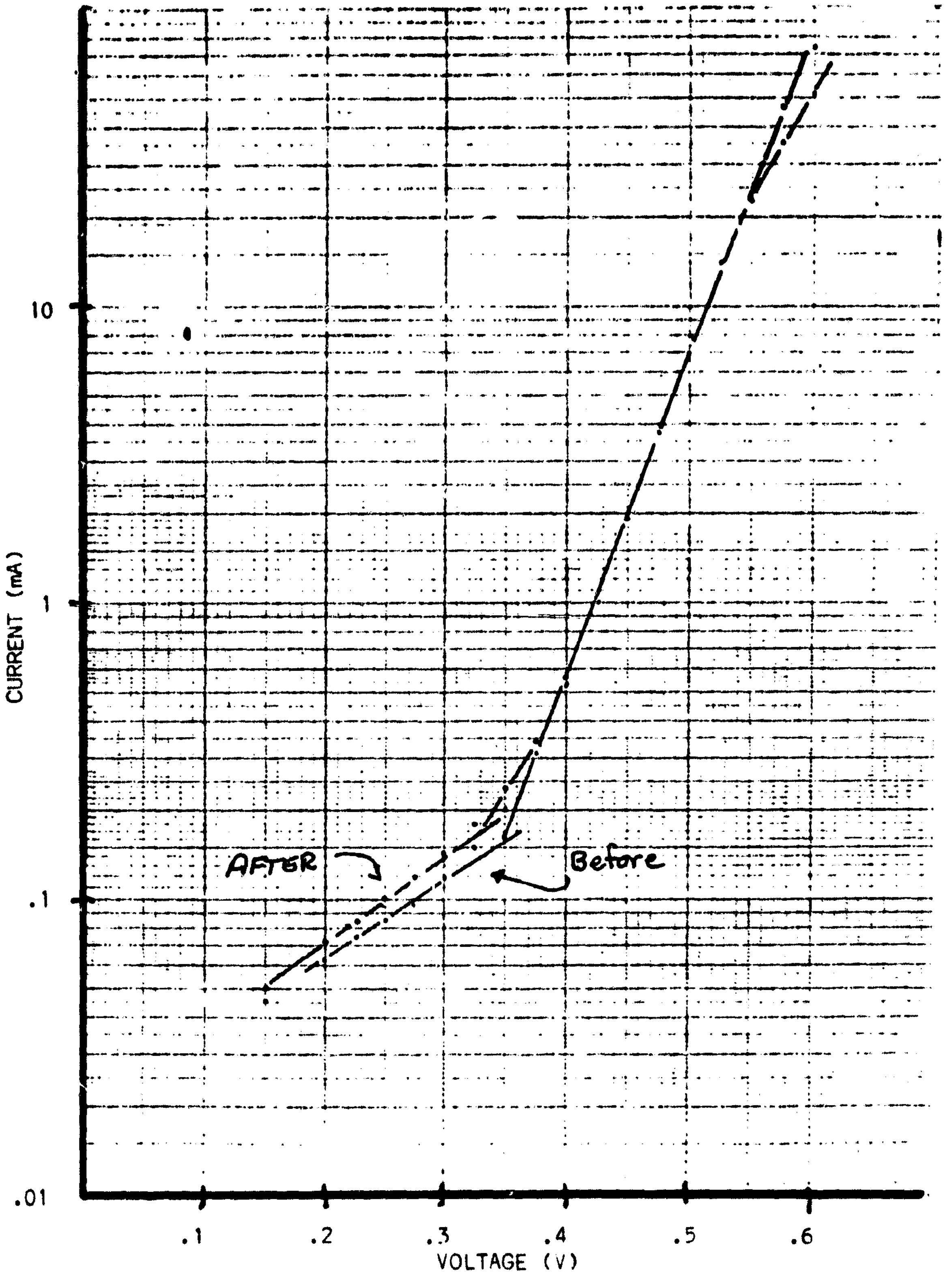

FIGURE 3.26: Nickel plated and sintered diode, dendritic web substrate, 300°C for 30 min., 1.1 cm^2 junction area.

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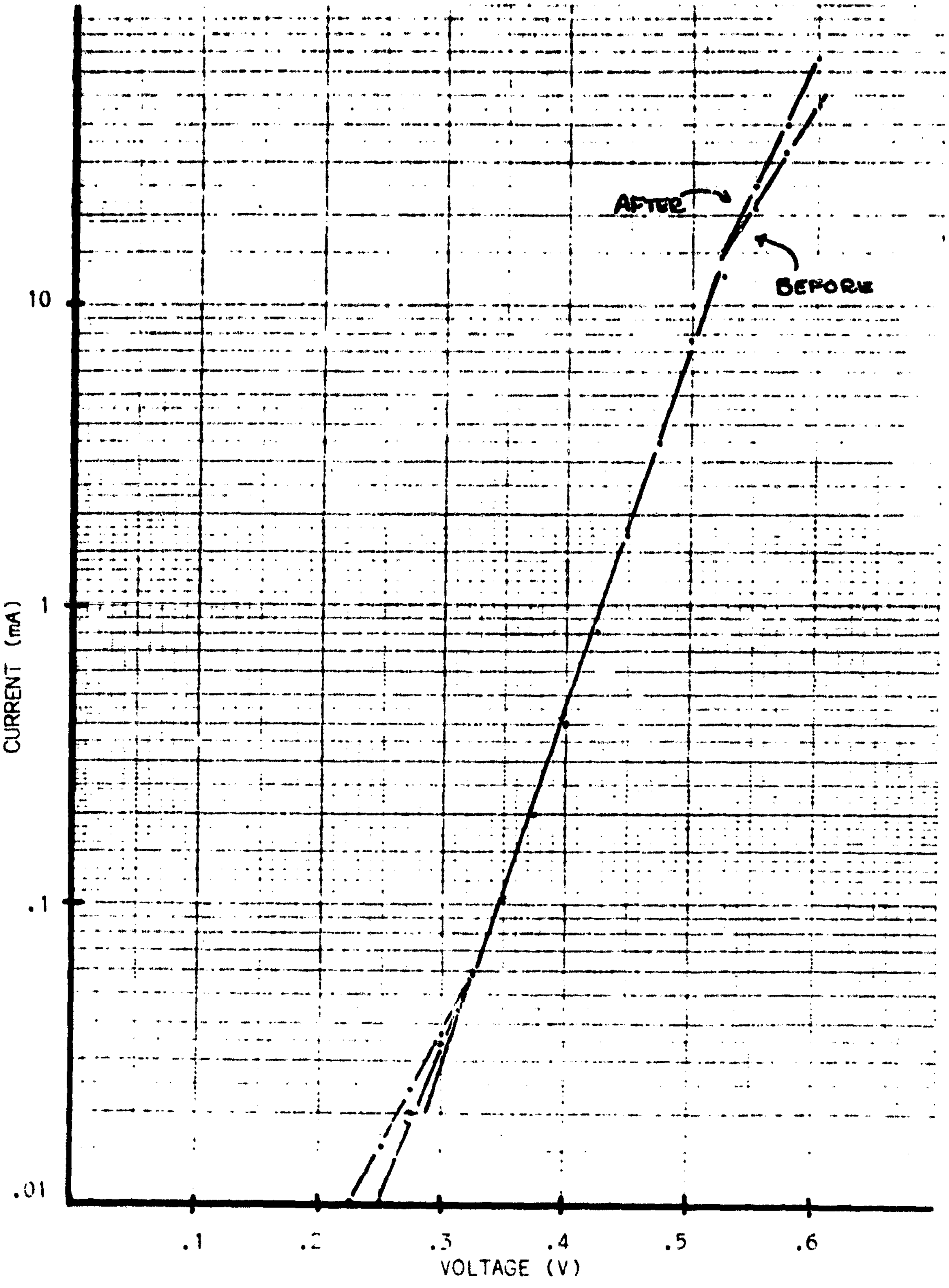

FIGURE 3.27: Nickel plated and sintered diode, dendritic web substrate, 300°C for 60 min., 1.0 cm² junction area.

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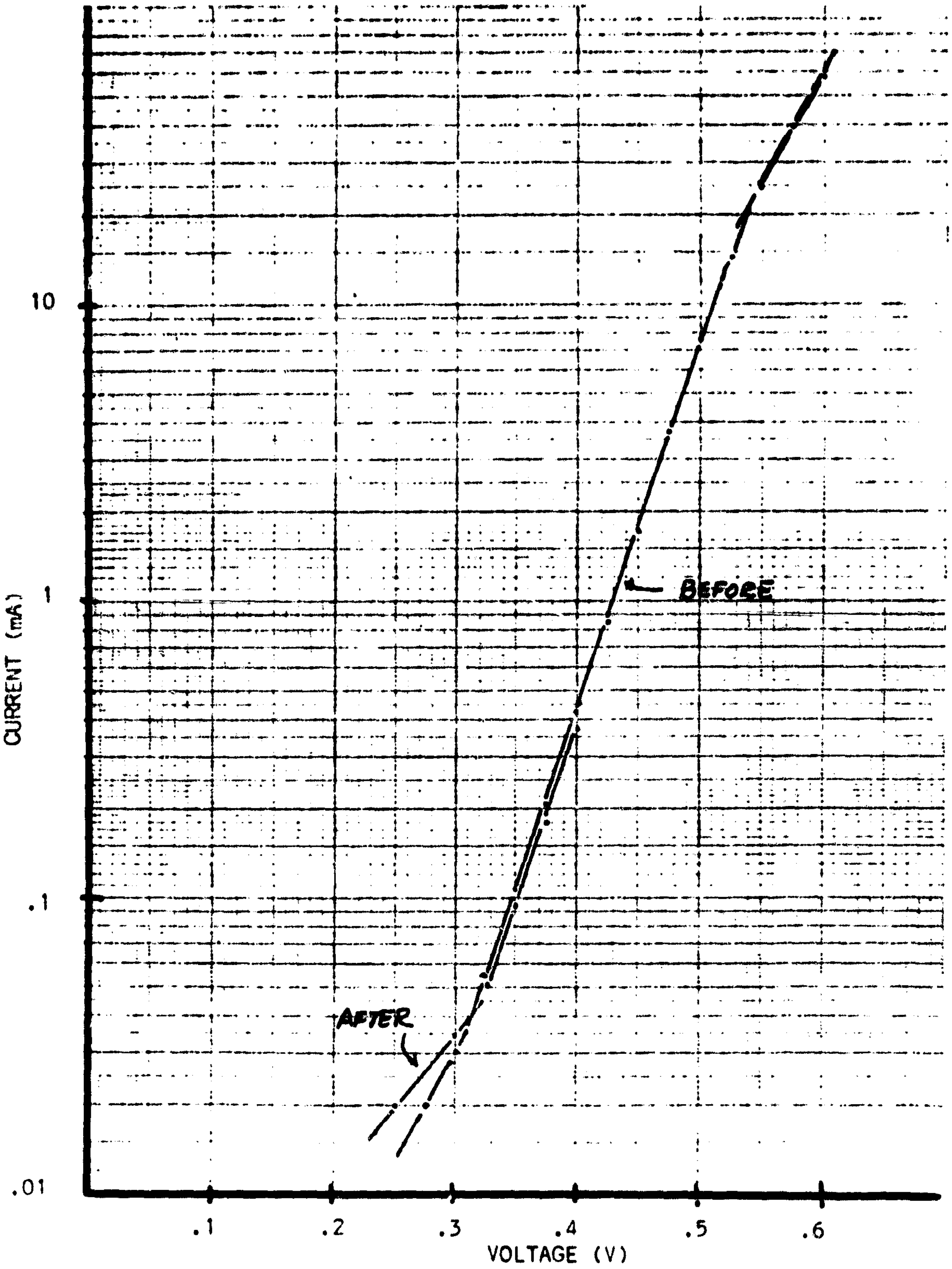

FIGURE 3.28: Nickel plated and sintered diode, dendritic web substrate, 350°C for 30 min., 1.1 cm^2 junction area.

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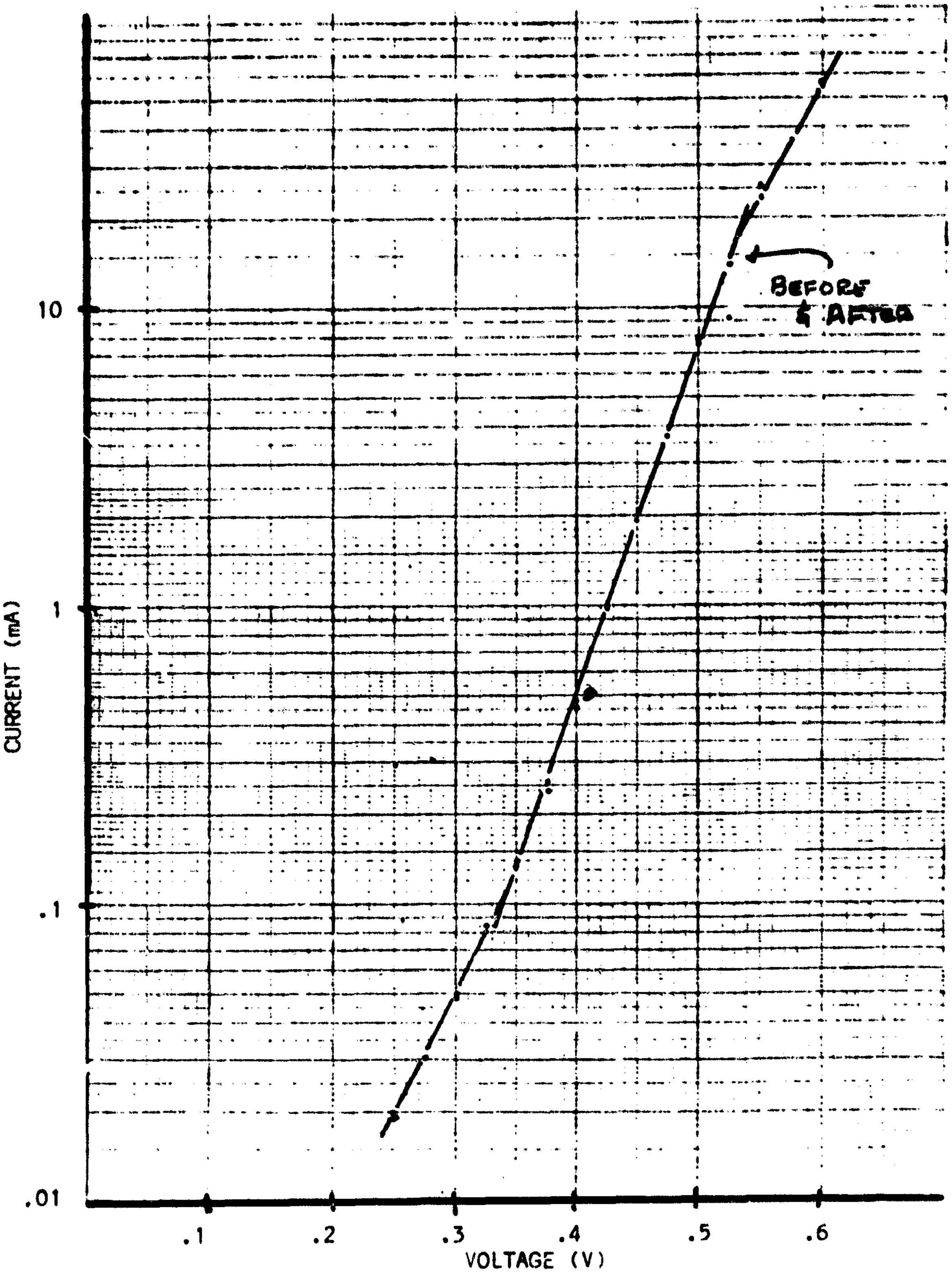

FIGURE 3.29: Nickel plated and sintered diode, dendritic web substrate, 350°C for 60 min., 1.1 cm^2 junction area.

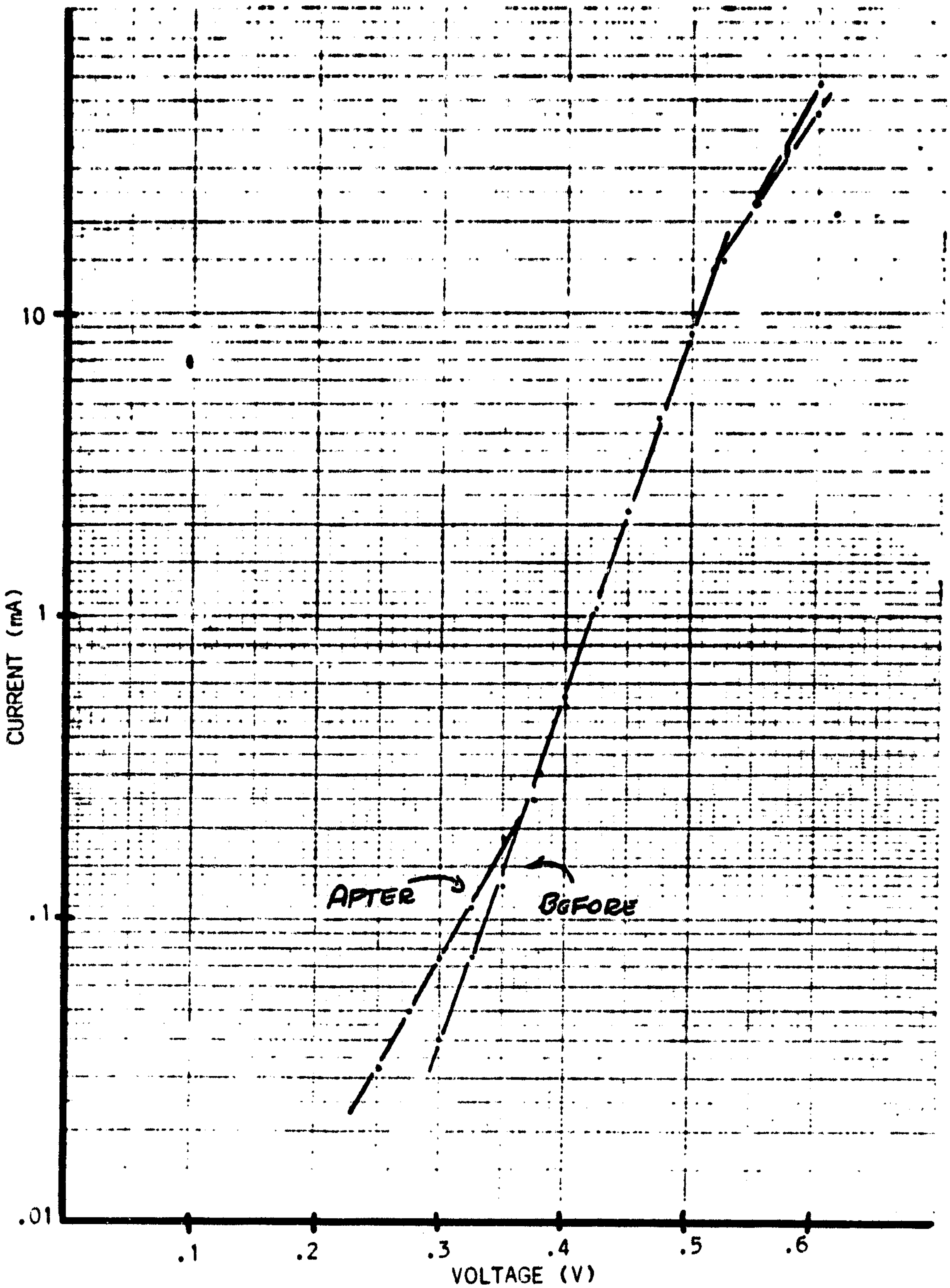

FIGURE 3.30: Nickel plated and sintered diode, dendritic web substrate, 400°C for 15 min., 1.0 cm^2 junction area.

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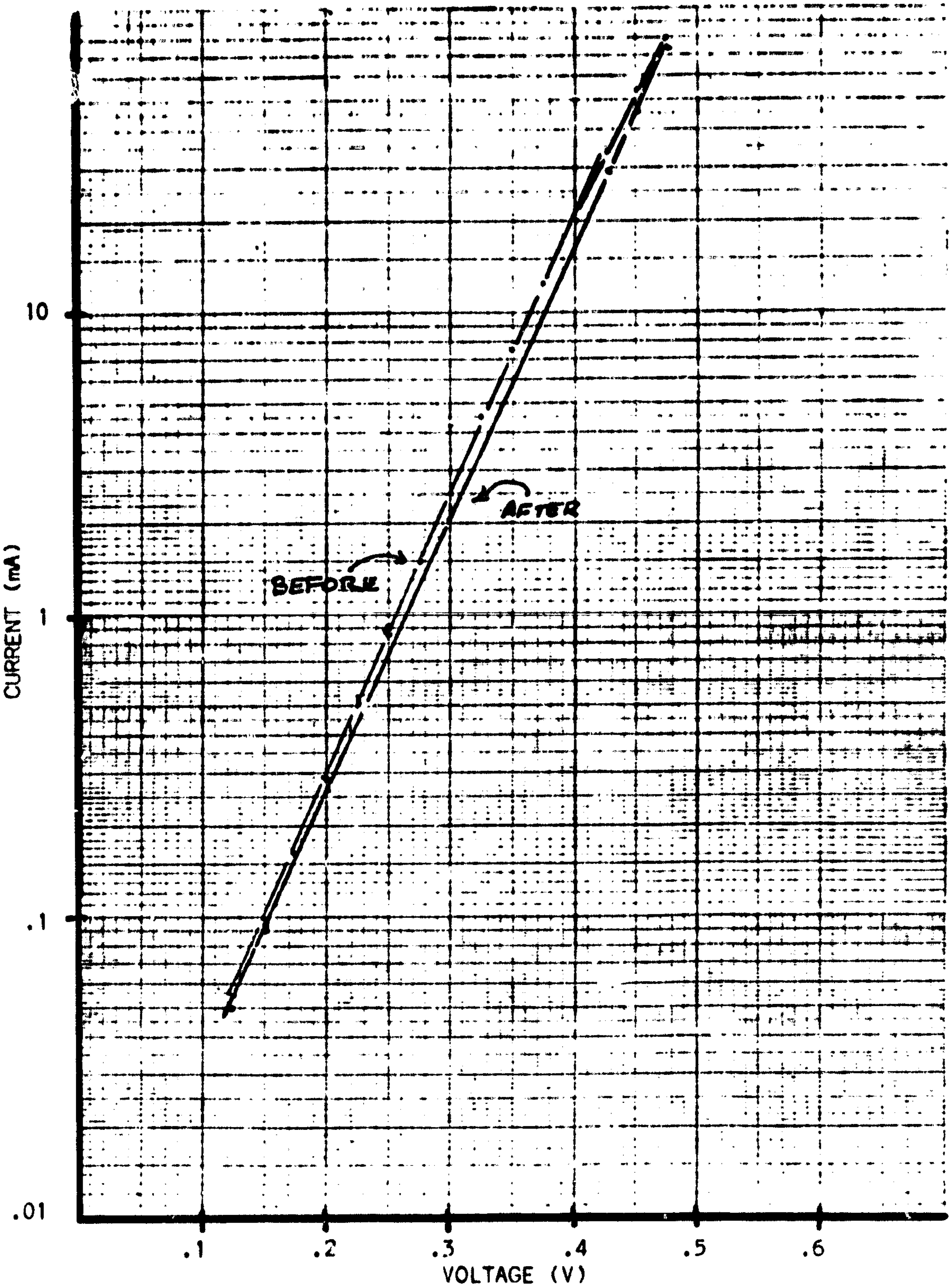

FIGURE 3.31: Nickel plated and sintered diode, polycrystalline cast substrate, 250°C for 30 min., 1.0 cm^2 junction area.

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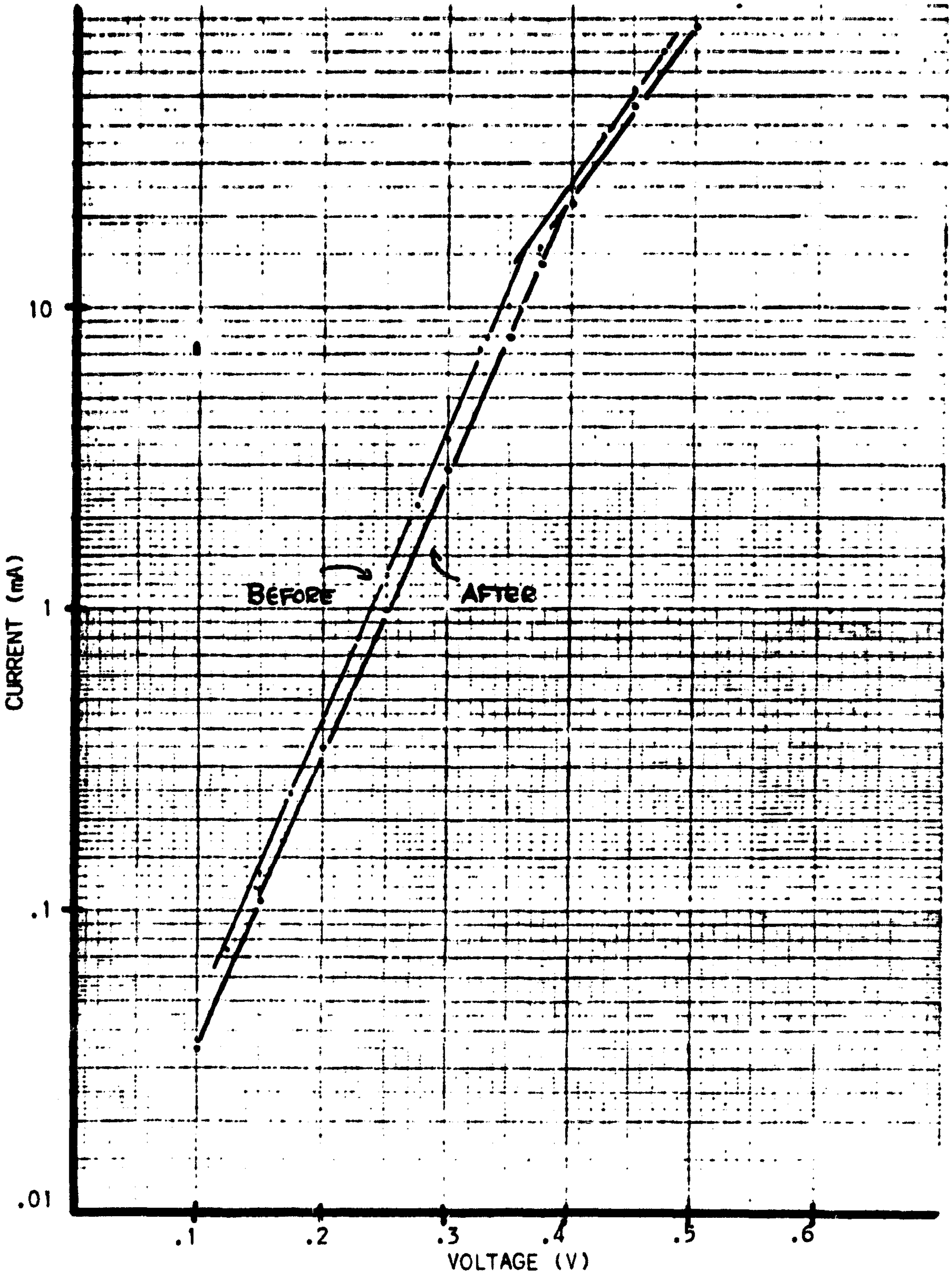

FIGURE 3.32: Nickel plated and sintered diode, polycrystalline cast substrate, 250°C for 60 min., 1.1 cm^2 junction area.

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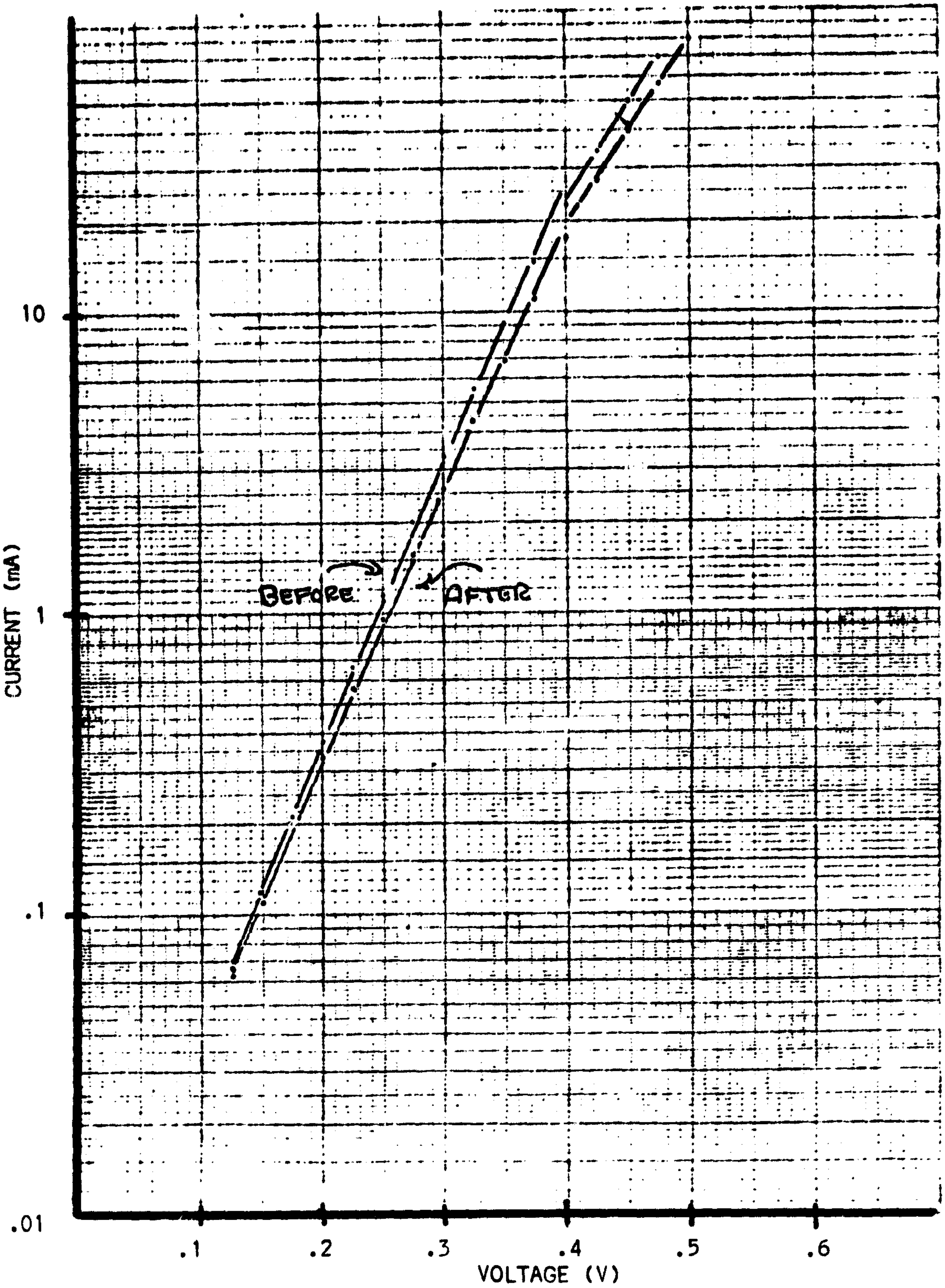

FIGURE 3.33: Nickel plated and sintered diode, polycrystalline cast substrate, 300°C for 30 min., 0.9 cm^2 junction area.

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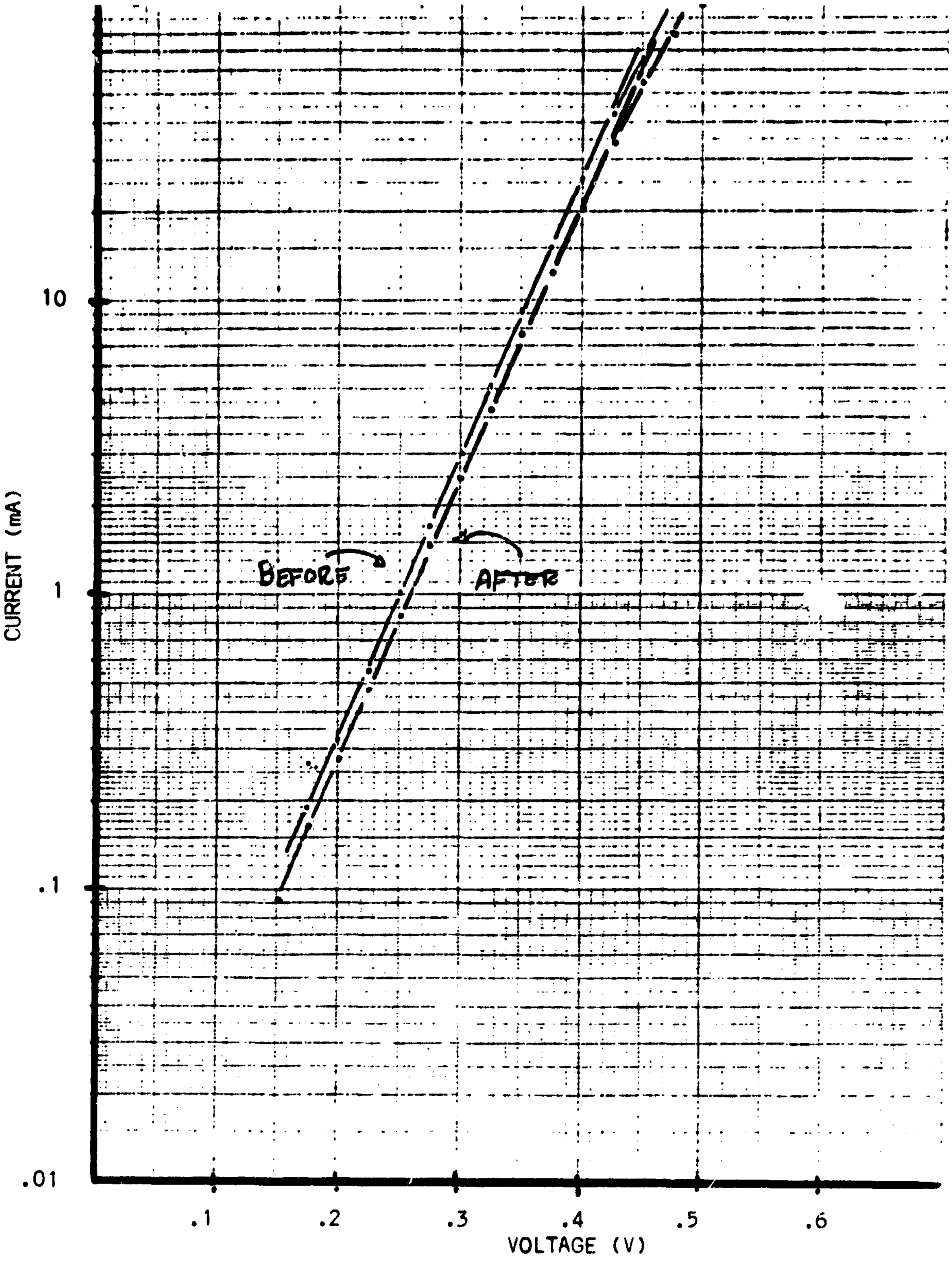

FIGURE 3.34: Nickel plated and sintered diode, polycrystalline cast substrate, 300°C for 60 min., 1 cm^2 junction area.

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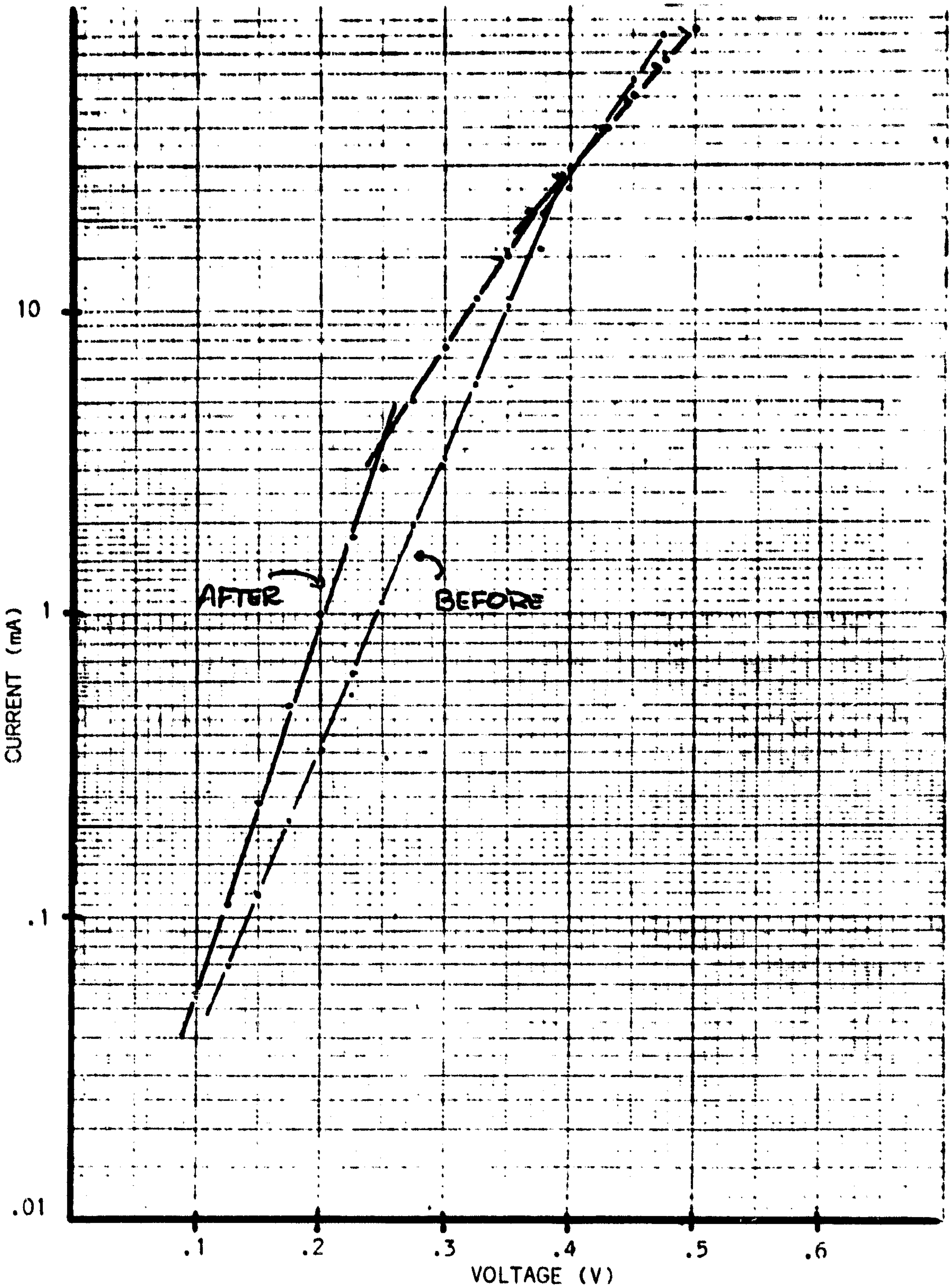

FIGURE 3.35: Nickel plated and sintered diode, polycrystalline cast substrate, 350°C for 30 min., 1 cm^2 junction area.

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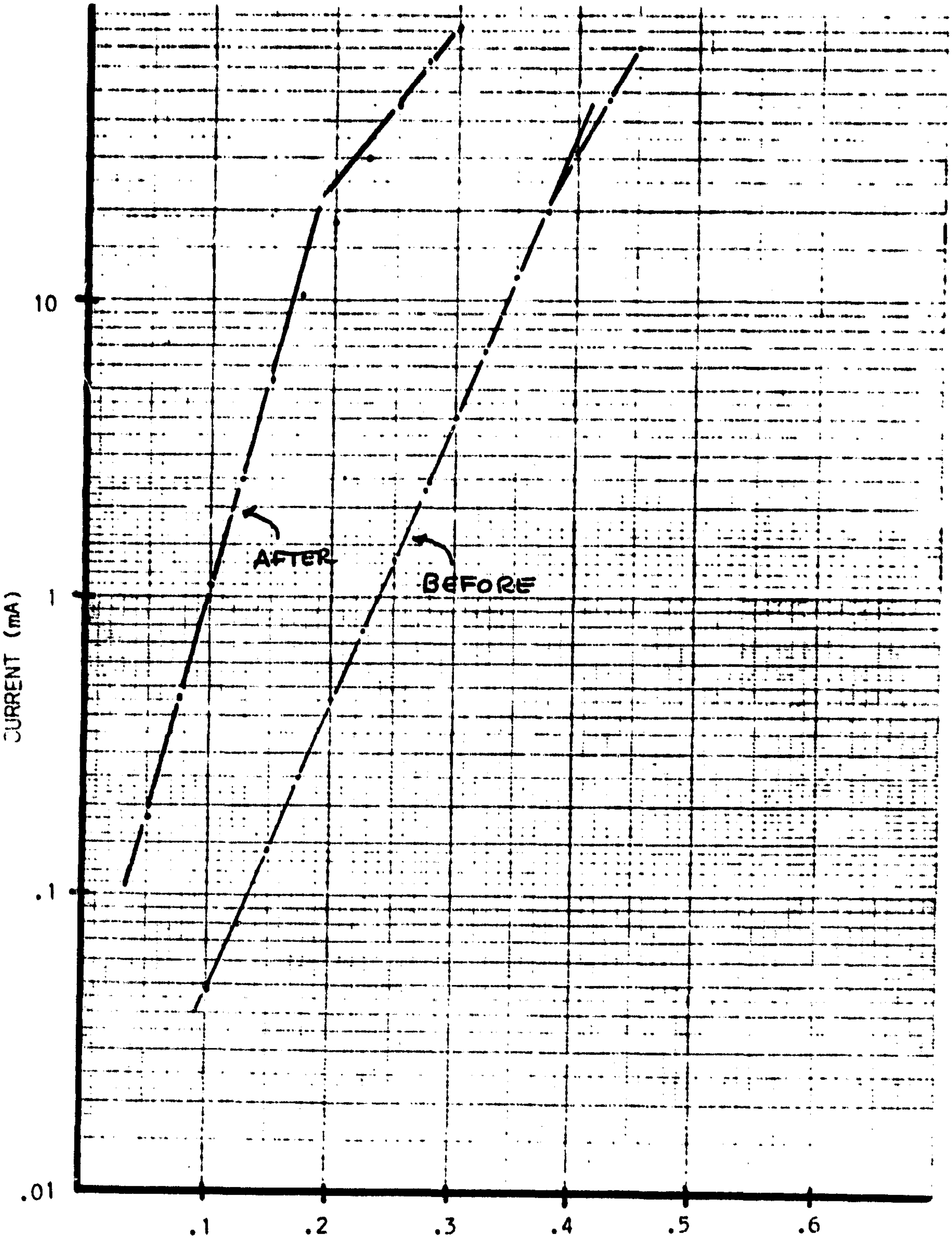

FIGURE 3.36: Nickel plated and sintered diode, polycrystalline cast substrate, 350°C for 60 min., 1.1 cm² junction area.

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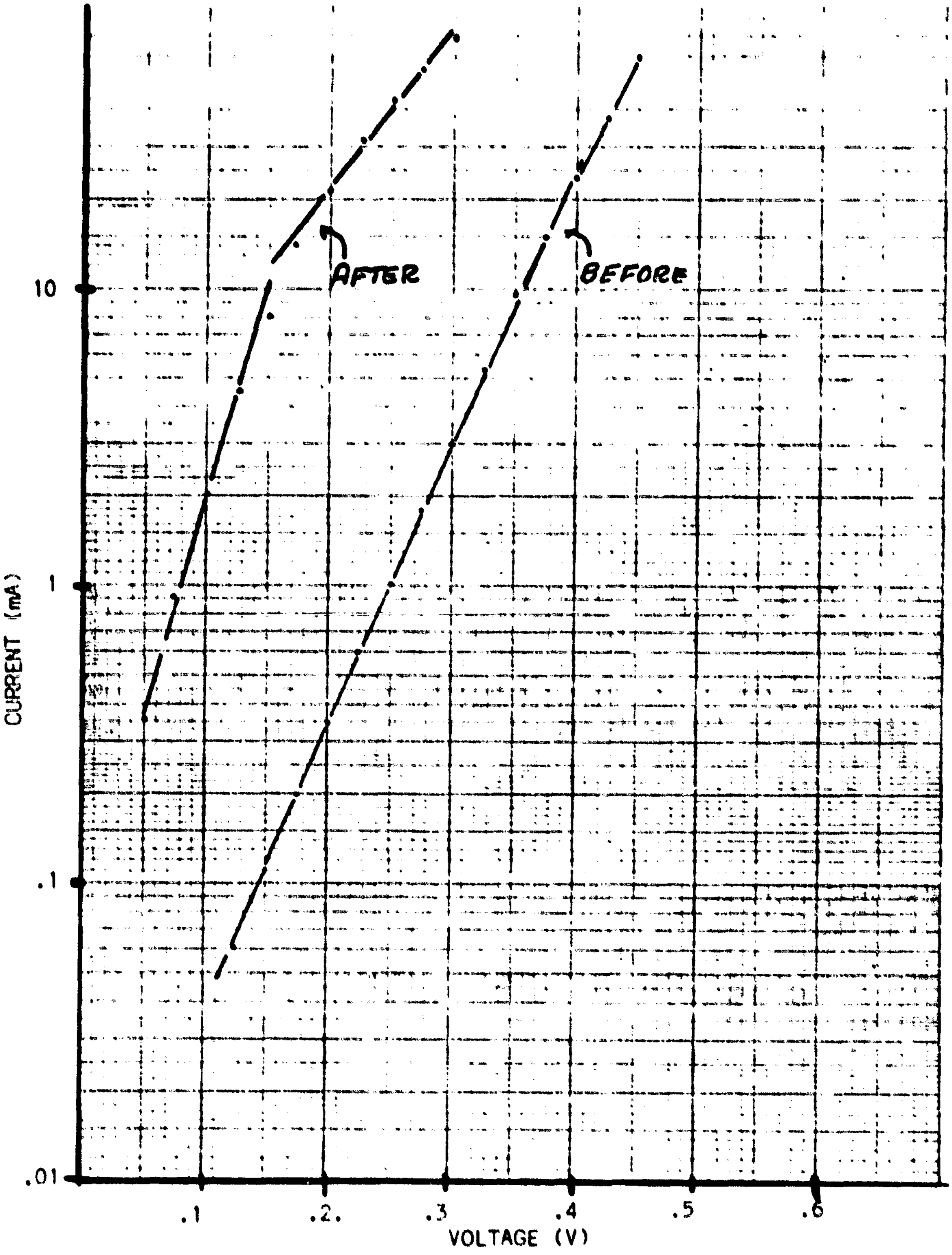

FIGURE 3.37: Nickel plated and sintered diode, polycrystalline cast substrate, 400°C for 15 min., 1.1 cm^2 junction area.

Good electrical contacts were made to the cast polycrystalline substrate diodes and it does not apper that the thermal stress cycles introduced degradation of these diodes any more rapidly than for the other substrate samples. However, it must be noted that even before sintering the cast poly diodes had significantly poorer I-V characteristics compared to the other samples. This is presumably a result of excess recombination currents at grain boundaries.

In summary, the direct plated electroless nickel contact system provides a cost effective ohmic contact for solar cells on non-Cz substrates as well as Cz substrates. The nickel contact can withstand thermal processes which are adequate for processing and assembling solar cells without introducing any significant solar cell performance degradation.

3.3.4 ELECTROLESS COPPER PLATING

Feasibility of using a copper conductor layer applied to the nickel contact layer by an electroless deposition process has been established. Desired copper thicknesses have been plated with no apparent stress problems using a commercial electroless copper plating solution, Metex Additive Electroless Copper Solution No. 9620, from MacDermid Incorporated of Waterbury, Connecticut. This solution is operated at 60°C and used in accordance with published MacDermid Technical data sheets.

Best results were obtained when samples were plated with a thick (3000Å-5000Å) second nickel barrier lyaer immediately prior to electroless copper plating. This ensured a fresh, reactive nickel surface to initiate the electroless copper deposition. Copper plating times ranging from 5 minutes to 60 minutes have been investigated. A time on the order of 35-45 min. appears to provide satisfactory copper thickness for one-sun operation.

Satisfactory operation of an electroless copper plating system in a production environment demands automatic bath control and replenishment. These aspects were not investigated; however, commercial replenishment units are available. Nevertheless, an electroless copper process appear to be a controllable and cost effective means of applying a copper conductor layer to a solar cell metallization system. Further development work in this area is both warranted and recommended.

3.4 COST ANALYSIS

A narrative description of the methodology for the Motorola costing program has been prepared. It details all of the assumptions used to develop a costing procedure and to formalize that procedure into a computer program. All required inputs for the program are defined and described. Examples of computer files used as inputs are presented.

A description of the simulation output reports or data tables is also presented along with actual examples of cost analysis outputs.

A description of the computer program software and comparisons of the Motorola costing technique and the JPL SAMIS technique have been prepared.

3.4.1 INTRODUCTION TO MOTOROLA COSTING PROGRAM

In 1976, Motorola initiated work on a method for evaluating solar cell and module manufacturing process steps and sequences. Much of this early work was performed as a part of Phase I of the Automated Array Assembly Task of the Low Cost Silicon Solar Array Project. The first discussion of the costing method was in an Annual Technical Report for JPL Contract No. 954363 dated February 1977. As a tool for accomplishing the requirements of that contract and subsequent contracts, as well as for providing an in-house costing capability, a computer program was written in FORTRAN IV, to apply the previously hand calculated costing methodology. This computer program has evolved into the present day Motorola solar cell/module costing program.

3.4.2 COST CALCULATION METHODOLOGY

Motorola uses a "bottom up" approach in its computerized costing of solar cells and modules. An attempt is made to identify each item that is required for a stand alone factory which manufactures a single photovoltaic product. A fundamental building block of this approach is the process step. In the current program, 68 individual process steps have been identified. For each of these process steps, 15 required inputs have been established which identify all of the costs attributable to that process step. Separate input tables must be made for different substrate sizes and geometries since many of the 15 assumptions will depend on substrate shape. Table 4.1 lists each of the process steps that have been studied with the Motorola program thus far. Table 4.2 shows a combination of this list of steps and the 15 specific inputs for each step for a 10 x 10 cm substrate.

Each of the 15 required input categories is identified and defined in the following paragraphs.

1) Process Yield: This figure represents the expected output, in percent, of a particular process step. Yield losses include an estimate for all forms of lost product; catastrophic as well as parametric. The yield of a process sequence is the product of each of these values for all of the process steps within the sequence.

2) Machine Efficiency: Machine efficiency is defined as the fractional period of time that a particular piece of equipment is operational during normal work hours. This figure includes scheduled and unscheduled maintenance and down time due to loss of facilities such as electricity, water, or process gases.

TABLE 4.1

CURRENT LIST OF PROCESS STEPS

```
 1 =     1.000 CRYSTAL GROWTH
 2 =     2.000 CRYSTAL GRIND
 3 =     3.000 CRYSTAL CROPPING
 4 =     4.000 CRYSTAL SAW
 5 =     5.000 CLEAN-ETCH
 6 =     6.000 CENTRIFUGE
 7 =     7.000 TEXTURE ETCH
 8 =     8.000 COAT-BAKE
 9 =     9.000 ALIGN-EXPOSE
10 =    10.000 DEVELOP-BAKE
11 =    11.000 ETCH STOP APPLY
12 =    12.000 BORON DIFFUSION
13 =    13.000 PHOSPHORUS DIFF.
14 =    14.000 IMPLANT ANNEAL
15 =    15.000 HI I IMPLANT N&P
16 =    16.000 ION IMPL-ADV N
17 =    17.000 SILICON NITRIDE
18 =    18.000 HI PRESS. SCRUB
19 =    19.000 PLASMA CLEAN
20 =    20.000 MESA ETCH 1
21 =    21.000 MESA ETCH 2
22 =    22.000 RINSE-DRY
23 =    23.000 DIELECTRIC ETCH
24 =    24.000 PLATING ETCH
25 =    25.000 PD PLATE
26 =    26.000 NI PLATE
27 =    27.000 SINTER
28 =    28.000 ELECTROLESS CU
29 =    29.000 SOLDER COAT
30 =    30.000 CELL TEST
31 =    31.000 CELL ATTACH
32 =    32.000 MODULE CLEAN
33 =    33.000 MODULE ASSEMBLY
34 =    34.000 E-BEAM RTR
35 =    35.000 CURE
36 =    36.000 MODULE TEST
37 =    37.000 ION IMPL-ADV P
38 =    38.000 ION IMPLANT P
39 =    39.000 PLASMA ETCH
40 =    40.000 WAX APPLY
41 =    41.000 WAX REMOVE
42 =    42.000 PLASMA PATTERN
43 =    43.000 METALLIZATION
44 =    44.000 ACID CLEAN
45 =    45.000 EVAP. METAL
46 =    46.000 EVAP. A.R.
47 =    47.000 IMMERSION PD A
48 =    48.000 IMMERSION PD H
49 =    49.000 ELECTROLESS PD
50 =    50.000 ELECTROLESS NI
51 =    51.000 SPIN DRY
52 =    52.000 SOLDER
53 =    53.000 ELECTROLYTIC AG
54 =    54.000 WAFER SAW
55 =    55.000 ELECTROLYTIC CU
56 =    56.000 POLY RIBBON
57 =    57.000 RIBBON ETCH
58 =    58.000 LASER RTR
59 =    59.000 SIHCL3 POLY
60 =    60.000 SICL4 POLY
61 =    61.000 SIH4 POLY
62 =    62.000 STRING ASSY/TEST
63 =    63.000 ARRAY ASSY/TEST
64 =    64.000 LAMINATION
65 =    65.000 MODULE TRIM
66 =    66.000 PVB PREP
67 =    67.000 TEDLAR PREP
68 =    68.000 GLASS PREP
```

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TABLE 4.2

INPUTS FOR EACH PROCESS STEP FOR A 10 cm x 10 cm SUBSTRATE

		1 PROCESS YIELD%	2 MACH EFFIC	3 MACH CAPAC	4 KS PER MACH	5 LABOR PER MACH	6 SCFT PER MACH	7 KW PER MACH	8 CFM PER MACH	9 GPM PER MACH	10 EXP $ PER KWFR	11 CONST EXP $/MACH	12 VAR EXP $ PER MACH	13 MAT $ PER KWFR	14 FAC REQ	15 MAINT PER MACH	
1	CRYSTAL GROWTH	90.00	.90	295	175.00	.33	60	125.0	40	.0	161.14	0	0	-1.0000	1	.1300	1
2	CRYSTAL GRIND	99.90	.90	6350	50.00	.25	90	1.5	40	.0	31.93	0	0	-1.0000	1	.2000	2
3	CRYSTAL CROPPING	99.90	.90	2440	6.00	1.00	40	6.0	100	.0	.25	0	0	-1.0000	1	.2000	3
4	CRYSTAL SAW	95.00	.90	37	35.00	.05	30	1.0	0	.0	136.00	0	0	.0000	1	.4000	4
5	CLEAN-ETCH	99.80	.90	1368	75.00	1.00	300	10.0	600	5.0	.00	5000	0	.0000	2	.2000	5
6	CENTRIFUGE	99.80	.96	400	2.50	.25	30	1.0	0	1.0	.00	250	0	.0000	1	.0052	6
7	TEXTURE ETCH	99.20	.93	3200	100.00	.50	120	3.0	1000	6.0	27.10	0	0	.0000	2	.0533	7
8	COAT-BAKE	99.40	.92	250	-1.00	.06	0	.0	0	.0	5.03	0	0	.0000	1	.0052	8
9	ALIGN-EXPOSE	99.80	.94	500	31.25	1.00	40	1.5	0	.0	.00	0	151	.0000	1	.3052	9
10	DEVELOP-BAKE	99.40	.97	250	-2.00	.00	0	.0	0	.0	4.98	0	0	.0000	1	.0052	10
11	ETCH STOP APPLY	99.00	.92	250	-1.00	.00	0	.0	0	.0	5.03	0	0	.0000	1	.0052	11
12	BORON DIFFUSION	99.00	.88	125	-4.00	.00	0	.0	0	.0	.23	760	0	.0000	2	.1300	12
13	PHOSPHORUS DIFF.	99.00	.88	125	-4.00	.06	0	.0	0	.0	5.03	760	0	.0000	2	.1500	13
14	IMPLANT ANNEAL	99.80	.96	5700	80.00	.50	203	15.0	103	.0	.57	0	0	.0000	2	.1000	14
15	HI I IMPLANT N&P	99.60	.93	1000	85.00	.50	40	13.0	40	.0	.60	410	0	.0000	1	.1000	15
16	ION IMPL-ADV N	99.80	.80	7200	250.00	2.00	400	59.0	40	.0	.04	410	2765	.0000	1	.2000	16
17	SILICON NITRIDE	99.20	.88	250	-4.00	.00	0	.0	0	.0	3.14	410	0	.0000	2	.2000	17
18	HI PRESS. SCRUB	99.60	.95	250	-3.00	.00	0	.0	0	.0	.00	0	0	.0000	1	.0052	18
19	PLASMA CLEAN	99.80	.97	600	21.00	.50	30	1.5	40	.0	.60	410	0	.0000	1	.1000	19
20	MESA ETCH 1	99.80	.93	4500	4.50	1.00	45	1.1	450	3.0	.00	2544	6457	.0000	2	.2000	20
21	MESA ETCH 2	99.80	.93	4500	4.50	1.00	45	1.1	450	3.0	.00	2544	6649	.0000	2	.2000	21
22	RINSE-DRY	99.80	.96	1200	2.50	.25	30	1.0	0	1.0	.00	250	0	.0000	1	.0052	22
23	DIELECTRIC ETCH	99.80	.93	2700	4.50	1.00	45	1.1	450	3.0	.00	2544	6000	.0000	2	.2000	23
24	PLATING ETCH	99.80	.93	1800	4.50	1.00	45	1.1	450	3.0	.93	1900	1300	.0000	2	.2000	24
25	CU PLATE	99.00	.88	1200	4.50	1.00	45	1.1	450	2.0	10.36	2544	0	50.7703	2	.2000	25
26	[illegible] PLATE	99.00	.88	600	4.50	1.00	45	1.1	650	2.0	1.00	5444	0	.0620	2	.2000	26
27	[illegible]	99.80	.94	1500	100.50	.50	156	2.0	800	.0	.00	0	0	.0000	2	.1000	27
28	ELECTROLESS CU	99.80	.90	2800	80.00	.50	132	15.0	100	2.5	1.10	0	0	9.8500	2	.1000	28
29	SOLDER COAT	99.80	.88	2200	50.00	1.00	100	15.0	4000	10.0	6.00	0	0	37.0400	1	.2000	29
30	CELL TEST	95.00	.95	1200	45.00	1.00	90	1.5	0	.0	.05	0	0	.0000	1	.1000	30
31	CELL ATTACH	99.70	.88	720	80.00	1.00	200	11.5	400	.0	.00	0	0	.0000	1	.0052	31
32	MODULE CLEAN	99.00	.88	2100	35.00	1.00	350	1.0	400	10.0	.00	0	0	.0000	1	.0052	32
33	MODULE ASSEMBLY	99.95	.88	2100	55.00	1.00	500	4.0	400	.0	.00	0	0	.0000	1	.0052	33
34	E-BEAM RTP	90.00	.92	300	130.00	1.00	135	15.0	125	.0	.30	410	0	.0000	1	.2500	34
35	C -E	99.95	.97	1728	35.00	1.00	600	10.0	200	.0	.03	0	0	.0000	1	.0052	35
36	MODULE TEST	99.50	.95	7020	165.00	1.00	250	3.0	0	.0	.91	0	0	.0000	1	.2500	36
37	ION IMPL-ADV P	99.80	.80	7200	250.00	2.00	400	50.0	40	.0	.00	410	2765	.0000	1	.2000	37
38	ION IMPLANT P	99.80	.70	150	600.00	.50	400	20.0	200	5.0	.05	410	205	.0000	1	.0052	38
39	PLASMA ETCH	99.80	.97	600	21.00	.50	30	1.5	40	.0	13.25	410	0	.0000	1	.1300	39
40	WAX APPLY	99.40	.92	250	-1.00	.00	0	.0	0	.0	.30	0	0	.0000	1	.0052	40
41	WAX REMOVE	99.60	.95	250	-3.00	.00	0	.0	0	.0	.60	0	0	.0000	1	.0052	41
42	PLASMA PATTERN	99.40	.93	300	80.00	.25	40	2.0	40	.0	.81	410	0	.0000	1	.1007	42
43	METALLIZATION	99.00	.88	800	65.00	.50	105	15.0	3200	1.5	.33	0	0	1.0163	2	.2000	43
44	ACID CLEAN	99.80	.93	600	45.00	.50	140	3.3	2800	.5	.06	6200	0	.0000	1	.2000	44
45	EVAP. METAL	.00	.00	0	.00	.00	0	.0	0	.0	.02	0	0	.0000	0	.0300	45
46	EVAP. AR.	.00	.00	0	.00	.00	0	.0	0	.0	.00	0	0	.0000	0	[illegible]	46
47	IMMERSION PD A	99.40	.93	1800	12.00	1.00	45	1.0	500	3.0	.03	260	0	.3000	2	.2000	47
48	IMMERSION PD B	99.40	.93	1800	12.00	1.00	45	1.6	500	3.0	.03	260	0	.0400	2	.2000	48
49	ELECTROLESS PD	99.40	.93	1200	12.00	1.00	45	1.6	500	3.0	.06	0	0	[illegible]	2	.2000	49
50	ELECTROLESS NI	99.40	.96	3000	88.76	1.00	100	7.0	800	2.5	.02	0	0	.4520	2	.0500	50
51	SPIN DRY	99.60	.96	400	2.50	.25	30	1.0	0	.0	.00	0	0	.0000	1	.0052	51
52	SOLDER	99.80	.88	2200	50.00	1.00	100	15.0	4000	10.0	6.00	0	0	6.7745	1	.2000	52
53	ELECTROLYTIC AG	.00	.00	0	.00	.00	0	.0	0	.0	.00	0	0	.0000	0	.0000	53
54	WAFER SAW	99.80	.96	60	30.00	.50	40	1.0	0	.0	100.00	0	0	.0700	1	.0700	54
55	ELECTROLYTIC CU	99.80	.93	400	30.00	1.00	45	2.0	500	1.0	.00	0	0	.0700	2	.1000	55
56	POLY [illegible]	95.00	.80	720	62.50	.33	240	20.0	100	2.0	42.07	120	0	.0000	2	.0533	56
57	RIBBON ETCH	99.80	.90	972	75.00	1.00	360	10.0	600	.0	2.21	0	0	.0000	1	.2500	57
58	LASER RTP	99.00	.90	600	100.00	1.00	320	25.0	40	.0	.00	0	0	.0000	1	.2500	58
59	SIHCL3 POLY	99.00	.98	900	165.00	2.00	275	250.0	125	.0	73.65	500	0	-1.0000	2	.1000	59
60	SICL4 POLY	99.00	.98	900	250.00	1.00	275	250.0	125	.0	67.00	0	0	-1.0000	2	.1000	60
61	SIH4 POLY	99.00	.98	900	90.00	1.00	275	140.0	125	.0	73.00	500	0	-1.0000	2	.1000	61
62	STRING ASSY/TEST	99.00	.90	900	50.00	.33	40	1.0	20	.0	.02	0	0	2.3520	2	.0500	62
63	ARRAY ASSY/TEST	99.80	.97	600	20.00	1.00	150	1.5	80	.0	.00	0	0	165.2200	2	.1000	63
64	LAMINATION	99.80	.95	330	25.00	.20	135	6.0	80	.0	.00	410	0	.0000	1	.0500	64
65	MODULE TRIM	99.95	.99	5200	1.00	1.00	40	.5	0	.0	1.52	0	0	.0000	1	.0000	65
66	PVB PREP	99.90	.99	9000	25.00	1.00	290	1.0	0	.0	.02	0	0	.0000	1	.0100	66
67	TEDLAR PREP	99.99	.99	16500	20.00	1.00	100	.5	0	.0	.00	0	0	.0000	1	.0100	67
68	GLASS PREP	99.99	.98	8250	16.00	1.00	65	5.0	600	4.0	.00	0	0	.0000	1	.0100	68

__3) Machine Capacity:__ This figure is an estimate of the maximum hourly output of each piece of equipment. It assumes that the equipment operates 100% of the time and has no yield loss.

__4) K$ Per Machine:__ The purchase price of all capital equipment required for a specific process step is given in thousands of dollars. As can be seen in Table 4.2, this figure is sometimes listed as a coded negative number. This is done to identify pieces of equipment in which the number of subsystems (tracks or tubes) used for a particular step may vary depending on production volume. For example, use of the code (-1) in this column represents a photoresist coating machine which is capable of containing four independent tracks. In this case, a four track cabinet is used, and only the number of tracks required to achieve a specific manufacturing volume will be installed in the cabinet(s). The price of the cabinet and each individual track are contained within the main computer program. This same approach is utilized for photoresist development and high pressure scrubber equipment which are identified by (-2) and (-3), respectively. These different numbers simply extract different equipment cost figures from the program. The (-4) code represents a hot wall diffusion furnace. In this case, it is assumed that every diffusion furnace will contain eight tubes, which must be paid for whether each is used or not. In the computer program, all of the individual tubes required for each process identified by a (-4) in the fourth column are totaled, and this total is divided by eight in order to determine the actual number of eight tube diffusion units required for the entire process sequence. The cost allocated to the particular process step using a diffusion furnace is, thus, the cost of each tube used plus a fractional share of any unused tubes.

For equipment containing a negative number in the fourth column, the inputs in the next 5 columns are listed as zeros in Table 4.2. The actual figures are for labor, floor space, electrical power, exhaust, and de-ionized water are contained in the main program and are entered in terms of a complete piece of equipment rather than a single track or tube. The remaining values, however, do represent the single track or tube data. For example, the machine capacity of a phosphorus diffusion furnace is assumed to be 125 substrates per hour per tube.

5) Labor Per Machine: This figure represents the number of direct labor personnel required to operate a specific piece of equipment, assuming the equipment is utilized 100% of the normal work hours.

6) Square Feet Per Machine: The figure entered in column six represents the total floor space that is required for each piece of equipment. Included in this number is the actual space occupied by the machine plus operator work space and the area required for facilities connections and maintenance access.

7) KW Per Machine: The electrical power requirements for each machine is entered in column seven of Table 4.2. The figure used here is the "nameplate" power requirement for the machine and contributes to two separate electrical needs; actual machine usage and the consequent excess air conditioning load. Actual machine electrical power requirements are assumed to be half of the nameplate power figure and the heat load is assumed to be 5% of the nameplate power figure. Additionally, the power used by the machine is further determined by whether the machine operates 100% of the time (8766 hours per year) or only during operational demand. Column 14 of Table 4.2 determines the facilities need of each piece of equipment; a (1) meaning that facilities are required on demand and a (2) indicating that facilities are required at all times whether product is being processed or not.

8) CFM Per Machine: Column eight of Table 4.2 lists the exhaust requirements of each piece of equipment in terms of cubic feed per minute.

This exhaust air flow rate is used to calculate the electrical power required to achieve the necessary exhaust and the power required for air conditioning the additional make-up air needed because of the exhaust. These values are assumed to be 460W per 1000 CFM for creating the exhaust plus 6 KW per 1000 CFM for air conditioning the make-up air. It is assumed that all exhaust needs are required 8766 hours per year.

9) GPM Per Machine: A commonly used commodity in solar cell fabrication processes is deionized water. Column nine of Table 4.2 lists the estimated need for deionized water in terms of gallons per minute for each process step in which it is used. Annual usage of deionized water is based on a 3 shift operation totalling 5400 hours per year (324,000 min. per year). The actual annual water usage is somewhat less than a simple 324,000 minutes times the total gallons per minute for a process sequence. Equipment down time and equipment demand are also considered when calculating deionized water needs.

10) Expenses Per Thousand Wafers: This figure represents the aggragate direct expenses in dollars per 1000 substrates associated with performing a particular process step, excluding expenses related only to machines. Expenses are defined as those commodities which are required to produce a solar cell or module, but which do not appear in the finished product. Examples of this include process gases, chemicals, and waste products. If the waste products have salvage value, the expense number is reduced by the salvagable income.

11) Constant Expense Dollars Per Machine: The figure listed in column 11 of Table 4.2 represents an estimate of annualized costs associated with operating a particular machine, independent of the actual number of hours the machine is operated. For example, vacuum pump oil may be changed at regular intervals during the year resulting in a fixed annual cost for that commodity.

12) <u>Variable Expense Dollars Per Machine</u>: This figure is similar to that listed in column 11; however, in this case, use of a particular machine related commodity is based on operation hours rather than calendar hours. An example of this would be replacement of an ion implanter source filament after some specified number of operational hours.

13) <u>Material Dollars Per Thousand Wafers</u>: Material commodities are defined as those items which are used to manufacture solar cells and modules and can be idenfitied in the final product. Examples include silicon substrates, metallization, and module parts. Column 13 identifies the cost of these commodities in terms of dollars per thousand wafers or wafer equivalent. In Table 4.2, the figure listed is sometimes (-1). This represents a process step in which the silicon substrate is being manufactured. In these steps, a separate file is read into the computer program which establishes the masses of both expense and material silicon consumed in the step. These values, in conjunction with the thickness of the manufactured substrate and the cost of the starting silicon material are used to calculate the material and expense costs of silicon in that particular process step. Substrate thickness and the cost of polysilicon or the chemicals used to obtain polysilicon are variables which are input at the beginning of the program. These inputs and the form of the additional input data table will be discussed in detail later in this report.

14) <u>Facilities Requirement</u>: As has previously been discussed, this figure determine whether a particular piece of equipment requires consumption of plant facilities 100% of the time (2) or only when the product is being produced (1).

15) <u>Maintenance Per Machine</u>: The final column of figures in Table 4.2 represents an estimate of the number of maintenance technicians that are necessary to assure continued operation of a single piece of equipment identified in the

process step. These technicians will be considered an indirect requirement but are listed in this file due to their close relationship to the type and amount of equipment used.

The inputs contained in Table 4.2 can be changed quite easily. Simple editing commands can be used to modify either the name of the process step or any of the 15 assumptions associated with that name. Additional process steps can be added to the list; however, this would require a modification to the main program since the list is currently dimensioned to a 68 x 15 matrix array.

Having established a list of process steps, it is necessary to order the desired processes into a process seqeunce. This is accomplished by creating a file which contains this and other information. The example in Table 4.3 is labeled COMPARE1.

In the file COMPARE1, a number of lines of information are required. The first line contains a name which is printed at the top of each simulation table to identify the process being used. In this case the process was named "MEPSDU", however, any name up to 16 characters can be used. The second line must contain the number of process steps contained in the process sequence. This example contains 20 process steps. Line three contains the order in which the process steps are used in the process sequence. The numbers used here correspond to the process step numbers as listed in the left and right margins of Table 4.2. In this sequence, for example, process step 60, $SiCl_4$ Poly, is the first step, and process step 36, Module Test, is the 20th and final step. Process steps may be entered in any order and used as many times as necessary in the process sequence.

In the semiconductor industry, which solar cell manufacturing is a part of, it is customary to have a number of similar or related process steps operating in

TABLE 4.3

PROCESS SEQUENCE FILE

```
  COMPARE1
1.000 MEPSDU
2.000 20
3.000 60 57 34 7 15 14 17 42 50 27 28 30 62 66 67 68 63 64 65 36
4.000 1 1 4 1
5.000 5 5 7 1
6.000 5 8 12 1
7.000 7 13 20 1
```

TABLE 4.4

CELL DIMENSION FILE FOR SHEET SILICON TECHNOLOGY

```
  POLY1
1.000 10CM
2.000 .1
3.000 10CM
4.000 0
5.000 0
6.000 100
```

TABLE 4.5

CELL DIMENSION FILE FOR INGOT TECHNOLOGY

```
  FLAT1
1.000 10CM
2.000 .04869
3.000 10CM
4.000 .02032
5.000 17.114
6.000 3
7.000 2.153
```

the same physical area. A benefit of this approach is that personnel can be more effectively used. For example, in a diffusion area, where substrates are cleaned and furnaces are operated, it may be determined that the furnace operator is only required to work 60% of the time in order to produce the desired volume of product. The operator cleaning substrates, however, may be required to spend 110% of the available time in order to accomplish the job. By grouping these related functions, the diffusion operator would assist the substrate cleaner and avoid the need for an additional substrate cleaner. In the computer program there are seven such process groups identified. They are:

1. Crystal Growth
2. Wafer Preparation
3. Photolithography
4. Surface Preparation
5. Junction and Dielectric Formation
6. Metallization
7. Assembly

The number preceding each of the categories listed above is used to identify that manufacturing area. In Table 4.3, four lines of information are used to divide the processing steps into four manufacturing categories. Each of these lines contains four numbers, the first of which identifies the manufacturing area. The second and third numbers in each of these entries identifies the first and last process step of the sequence that is contained within the process category. In the example shown in Table 4.3, the fourth line contains the numbers 1, 1, 4, 1. Therefore, the first process category that will be defined in a simulation will be (1) Crystal Growth and the first through the fourth process steps listed in the process sequence (60, 57, 34, 7) will be included in this process category. Similarly, the second process category will be (5) Junction and Dielectric Formation and will contain the fifth through seventh process steps listed in the process sequence (15, 14, 17).

In the example used here, each of the process steps contained within a particular process category happens to fall in sequential order in the process sequence. A process sequence may, however, have process steps that would be contained in a single process category but are separated by other category process steps in the process sequence. For example, a process sequence may contain a diffusion step followed by a photoresist operation and then another diffusion step. To clarify this example, the following mini-process is described.

Mini-process process steps list:

1.	(12)	Boron Diffusion
2.	(8)	Coat-Bake
3.	(9)	Align-Expose
4.	(10)	Develop-Bake
5.	(23)	Dielectric Etch
6.	(22)	Rinse-Dry
7.	(19)	Plasma Clean
8.	(13)	Phosphorus Diffusion

The file that would be written for this example would look like this:

```
1.  EXAMPLE
2.  8
3.  12   8   9   10   23   22   19   13
4.  5    1   1   0
5.  0    7   8   1
6.  3    2   6   1
```

The format is identical to that which has already been described. Lines four and five, however, show some differences which should be explained. In line four, the process cateogry is listed as a (5) to define Junction and Dielectric Formation and the process steps are identified as being the first through the first step. This format is used when only one process step is contained in an individual line entry. The fourth number in line four is a zero (0) which indicates that other process steps somewhere in the process sequence should be contained in the Junction and Dielectric Formation process category. The process steps that are to be contained in this category are the seventh and eighth steps, Plasma Clean and Phosphorus Diffusion and are so identified in line five. The leading (0) in line five simply indicates that a new process category is not being printed and that the process steps contained on this line are part of the most recent process category printed. When the fourth number in the line is a one (1), it indicates that all of the process steps for that particular process category have been included and that a new process cateogry can be printed or that all of the process steps have already been assigned to a category and that the program should proceed to its next function.

The next file required by the computer program is one that identifies the size of the solar cells that will be evaluated. The file is constructed in one of two ways, depending on whether a sheet technology or an ingot technology is being simulated. Which case is being simulated is determined within the computer program by the examining which process steps are chosen from a process step file such as shown in Table 4.2. If the simulation is determined to be for a sheet process, a six statement cell dimension file is required, such as the example of Table 4.4. If it is an ingot process, a seven statement cell dimension file is required, such as the example of Table 4.5.

For the case of a sheet technology, the example file of Table 4.4 is labeled POLY1. In this file, the data listed in the first line is printed at the top of each simulation table developed by the overall program so as to identify the size of cell being evaluated. In this example, 10 cm is printed to identify a 10 cm x 10 cm solar cell. Any term may be entered in this first line up to eight characters. The second line contains a term which establishes the area of a single solar cell in cm^2 divided by 1000. This figure is entered into the program and multiplied by the cell efficiency and the concentration (1 for flat plate applications) to determine the output watts per cell. In this program, it is assumed that the insolation is 0.1 W per cm^2. Thus for a 10 cm x 10 cm cell, and a 15% cell efficiency, the calculations would be:

$$\frac{100\ cm^2}{1000} \times 15 = 1.5 \text{ W per cell}$$

The divisor of 1000 accounts for the fact that cell efficiency is entered in percent rather than decimal form and that the insolation is 0.1 W per cm^2.

The third entry in Table 4.4 identifies the process step data file that will be used. In the example presented here, the 10 cm file illustrated in Table 4.2 is used. Similar process step tables for two inch diameter substrates (5 cm), three inch diameter substrates (7 cm), and five inch diameter substrates (12 cm) have been used with this program. Any substrate size may be used as long as a data file is created which accurately reflects the process equipment assumptions for use with that particular substrate size. The process name list should remain consistent from file to file, only the 15 data entries should be different to reflect variations in machine capacity, expenses, and so forth.

When a silicon sheet process is being evaluated, zeros must be entered for the next two lines of data in the file of Table 4.4. Entries other than zero are reserved for files created for ingot processes and would provide information about additional silicon consumption associated with sliced wafer formation.

The sixth line of data in the Cell Dimension File for sheet processes restates the area (in cm^2) of a single substrate. This value (100 in the example of Table 4.4) is used by the program along with substrate thickness inputs to calculate the cost of material contained in the substrate. As discussed previously, this calculation is initiated by a (-1) code in column 13 of Table 4.2 for a process step (number 60, SICL4 POLY) required by the Process Sequence File, Table 4.3, for this sheet process simulation example.

The first 3 lines of data on the Cell Dimension File for ingot technologies (Table 4.5) have the same meaning as the first 3 lines of Table 4.4.

The next two lines of data in the file of Table 4.5 are specifically intended for calculations of silicon consumption when an ingot technology is used. For ingot technologies, the fourth line reflects the thickness of silicon lost due to sawing of the ingot into substrates. For example, if this lost silicon (kerf) due to sawing is 8 mils per substrate, then the number 0.02032 should be entered on the fourth line of data, thus, reflecting the loss of 0.02032 cm (8 mils) of silicon per substrate. The fifth line of data represents the mass (in Kilograms) of usable silicon available for slicing after the crystal growth operation. A reasonable set of assumptions is that 10% of the original silicon charge is lost due to incomplete growth from the melt. That is, for a 30 Kg polycrystalline charge, 3 Kg of silicon will be left in the crucible after crystal growth is complete. Additionally the amount of silicon available for slicing into substrates is further reduced by removal of the crystal neck and tail as well as the sawing of the crystal into usable shapes and sizes for slicing. Table 4.5 illustrates these data entries for a simulation in which a five inch diameter ingot was grown and 10 cm x 10 cm substrates with rounded corners were cut.

In Table 4.5, the entry on line five indicates that a crystal weighing 17.114 Kg is available for slicing into substrates. This figure is based upon:

Silicon into crucible	30 Kg
Silicon left in crucible (10%)	- 3 Kg
Neck Removal	-0.5 Kg
Tail Removal	-2.5 Kg
Side Slabs (to form psuodo square)	-4.733 Kg
Sawdust (removal of neck, tail and sides)	-1.47 Kg
Sawdust (sectioning into 3" lengths)	-0.683 Kg
Remaining Usable Silicon	17.114 Kg

It has been assumed that the neck, tail, and side slabs are fully recoverable for future melts and are, thus, not considered in the costing calculations. The silicon left in the crucible and sawdust is, however, not recoverable and is treated as an expense item. Notice in Table 4.5, that line two has the entry 0.09869. This figure reflects the fact that the surface area of the 10 cm x 10 cm cell is 98.69 cm^2 due to the rounded corners.

In Table 4.5, lines six and seven contain the values 3 and 2.153 respectively. The process sequence for which Table 4.5 was used contained two process steps in which a (-1) was in the thirteenth column, process step number 1, CRYSTAL GROWTH, and process step number 3, CRYSTAL CROPPING. These two data entries represent the 3 Kg of silicon left in the crucible, and the sum of 1.47 Kg and 0.683 Kg of silicon lost due to sawing of the ingot into usable sizes. As can be seen here, when an ingot technology is being evaluated, the numbers entered on lines six and beyond are done so in terms of the mass (in Kg) of silicon consumed by a process step and are entered in the order in which the process step is encountered in the process sequence.

Additional calculations occur within the program in order to determine the expense and material requirements for silicon usage, but are not necessarily associated with the inputs from the Cell Dimension File. These calculations will be discussed in detail when the body of the program is described.

The final list of information required by the program in order to perform a costing simulation is shown in Table 4.6. In Table 4.6, a number of inputs are requested by the program and are described below. The first request from the program determines whether a single set of data will be evaluated or whether a sensitivity analysis will be performed. Table 4.6 illustrates the form of requests required by the program for a single set of data. Entry of a (0) in this first line indicates that the data will be entered from the terminal. Similarily, the second line requires a response which will determine whether the results of a simulation are printed at the terminal or are routed to a file which may be sent to an offline, high speed printer. A zero (0) response will provide immediate printing of a simulation at the users terminal while a one (1) response will store the information in a file named REPORT. The third line requests the name of the file that describes the process name. The entry of "COMPARE1" in this example calls into the program the data contained in Table 4.3 which has been discussed earlier in this report. In much the same manner, the fourth request calls for the name of the file that describes the cell dimension. Table 4.4, "POLY1" contains the data required for this entry. Following these entries, each element of the costing analysis that is considered most likely to have the greatest inpact on variations in total cost are entered as a variable.

The first of these variables is associated with the annual production capacity of the factory and is entered in terms of mega-watts; 50 megawatts is entered in the example shown in Table 4.6. Cell efficiency is the second variable

TABLE 4.6
TERMINAL INPUTS

ORIGINAL PAGE IS OF POOR QUALITY

```
TERMINAL(=0),FILE(=1) =?0
PRINTER=LOCAL(0),OFFLINE(1) =?1
PROCESS NAME =?COMPARE1
CELL DIMENSION =?POLY1
ANNUAL MEGA-WATTS =?50
CELL EFFICIENCY(%)=?14
SOLAR CONSTANTS(SUNS) =?1
POLY SILICON COST($/KILO) =?.4
NUMBER OF MONTHS IN EACH PHASE(4 INPUTS) =?12 12 12 48
ANNUAL INTEREST RATE(%)=?9.25
POWER RATE(CENTS/KWH) =?4
DIRECT LABOR RATE($/HOUR)=?6
POLY SILICON THICKNESS(PRE-ETCH MICRONS)=?105
WHICH TABLE(1 TO 8, 9 FOR ALL) =?9
```

TABLE 4.7

OVERHEAD CATEGORIES

```
 1 =      1.000 DIRECT FACTORY
 2 =      2.000 ENGINEERING
 3 =      3.000 PRODUCTION CONT
 4 =      4.000 BLDG SERVICES
 5 =      5.000 MAINTENANCE
 6 =      6.000 MANAGEMENT
 7 =      7.000 MARKETING/SALES
 8 =      8.000 PURCHASING
 9 =      9.000 FINANCE
10 =     10.000 SECRETARY POOL
11 =     11.000 DATA PROCESSING
12 =     12.000 TRAINING
13 =     13.000 PERSONNEL
14 =     14.000 CAFETERIA
15 =     15.000 LEGAL
16 =     16.000 SECURITY
17 =     17.000 HEALTH
```

required by the program and is entered in percent, 14 in this example. One of the capabilities of this costing program is that concentrator solar cells can also be evaluated. The request for Solar Constants (Suns) by the program simply relates to the insolation falling on the cell where 100 mW/cm^2 = 1 and 1 W/cm^2 = 10. Any value may be entered here.

A major concern of the photovoltaic industry is associated with the cost of polycrystalline silicon. The eighth request in Table 4.6 and fourth variable evaluated addresses this concern. When ingot technology is used the entry is usually 10 (\$/Kg) reflecting DOE goals or 85 (\$/Kg) reflecting typical, current market prices. Any value, however, may be entered here. Motorola, in its process development programs, has established a procedure for forming polycrystalline silicon sheets directly from a silicon bearing chemical. Those that have been evaluated include $SiHCl_3$, $SiCl_4$, and SiH_4. For this example, the $SiCl_4$ approach has been selected and the entry of 0.4 (\$/Kg) shown in Table 4.6 reflects the cost of $SiCl_4$ per kilogram. Conversion efficiency of this and the other silicon bearing chemicals into usable silicon sheets is contained within the body of the program and will be discussed in detail later.

This program assumes a stand alone factory which does not currently exist. In order for it to exist, four separate phases of factory life have been identified, each of which requires some variable period of time to complete. These four phases reflect the following times in the life of the factory.

Phase 1 The first phase of the factory represents that time required to construct and facilitize the building. Included in this phase are site selection and preparation, environmental considerations, as well as the physical construction of the building and installation of the necessary plant services. Personnel staffing and other indirect expenses during this and subsequent phases are contained in four overhead files. These files will be discussed when the main program is described.

Phase 2 In the second phase, time is allotted for the installation of all manufacturing equipment. During this phase equipment will be turned on and de-bugged.

Phase 3 This phase is established to provide a training period for direct labor personnel. It has been assumed that during the first half of the phase, direct labor personnel will learn to operate equipment but will not manufacture product. During the second half of this phase, product will begin to be produced with full production capacity being achieved at the end of the phase. It has been assumed that the growth in production output will be linear during the second half of this phase, thus, resulting in an output of 25% of the annualized production capacity when averaged over the total length of Phase 3.

Phase 4 This final phase represents the time during which full production is achieved. Level production at the volume defined in line four of Table 4.6 is assumed throughout the remaining life of the factory. For simplicity, the factory is assumed to terminate at the end of this fourth phase; replaced by a new and different technology.

In the example shown in Table 4.6, the first three phases are assumed to each be 12 months in duration and phase four is assumed to be 96 months in duration. As with the other inputs, any values may be used.

Contained in each of these four phases is a bottom-up analysis of each of the indirect (overhead) requirements for the factory and some assumptions as to how the requirements are allocated. The list shown in Table 4.7 shows the overhead categories that have been identified in this analysis. A description of each of these overhead categories and the assumptions contained within them follows.

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 $28.3K for foreman and $22.9K for supervisors. Foreman are hired during Phase 2 and supervisors are added in Phase 3 as needed to accomodate the increasing direct labor employment level. Direct factory expense items are listed in a separate expense category.

2. ENGINEERING. The engineering area will maintain process integrity. The following engineering staff will remain constant over the range of annual production to be evaluated.

(1) Manager @ $43.3K/year
(1) Secretary @ $13K/year
(9) Engineers @ $32K/year each
(12) Technicians @ $17K/year each

Capital equipment is expected to cost $500K and will be depreciated over 8 years on a straight line basis. Associated expenses are assumed to be 1/3 of the total engineering cost, excluding depreciation. The engineering manager, secretary and all engineers will be hired in the first phase with technicians being added in Phase 2.

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	@	$32K/year
(1)	Secretary	@	$13K/year
(1)	Scheduler	@	$20K/year
(2)	Clerks	@	$10.9K/year each
(1)	Customer Service Engineer	@	$25K/year
(1)	Order Entry Clerk	@	$10.9K/year
(4)	Inventory Control	@	$13K/year each

This group will remain constant up to the 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 of $100K, depreciated on an 8 year straight line 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 3.

4. BUILDING SERVICES. This cost cagegory includes lighting and HVAC which are estimated to be 48¢/ft^2/month; taxes and insurance which are estimated to be 25.3¢/ft^2/month; and custodial services which are estimated to be 0.118 man/1000 ft^2 @ 10.4K/year. The square footage of the facility is based on the following assumptions. The total area figure (TOTAL SQ FT.) 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:

a) TOTAL SQ. FT. x 1.3 = 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.

b) DFA X 1.2 = FTL (FACTORY TOTAL)

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

c) FTL X 1.3 = TBA (TOTAL BUILDING AREA)

This additional 30% of the total factory area is utilized for all support functions. The results of this division of total building area are:

49% = direct manufacturing area
15% = hallway and storage areas within the manufacturing area
13% = warehouse area
23% - support area

Two distinct factory areas are identified in this cost analysis. The first is direct manufacutring area which is determined by adding the areas required for each piece of equipment used in the several production areas. This manufacturing area, represents 49% of the total factory area and, due to the high degree of utility facilitization, construction costs are estimated to be $\$120/\mathrm{ft}^2$. 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 $\$55/\mathrm{ft}^2$. Using these ratios of construction costs and factory utilization, an average construction cost of $\$86.85/\mathrm{ft}^2$ 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 ($86.85) 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 results in an effective construction cost of $\$177.24/\mathrm{ft}^2$ for the 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. 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 $\$1/\mathrm{ft}^2$ or $44K/acre. In order to achieve an average cost estimate for a solar cell manufacturing plan, \$1/ft^2 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 \$177.24/ft^2 of direct manufacturing space will be increased to include property by \$6.80 resulting in an effective cost of \$184.04/manufacturing ft^2. 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 2 with the employment of one person @ \$10.4K/year followed by the addition of custodial personnel in Phase 3 as per the formula.

5. MAINTENANCE. Assumptions here are that one administrator at \$32K/year (1st shift only) one supervisor at \$23K/year per shift for each 10 technicians are employed. Mechanical/electrical technicians at \$17K/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. The maintenance staff is employed in Phase 2.

6. MANAGEMENT. The management section of overhead is assumed to contain a general manager at \$52K and four staff engineers at \$43.3 each. Expenses are 20% of these salaries. The general manager is included in Phase 1, a staff member (finance manager) is added in Phase 2, and the remaining staff is added in Phase 3.

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, two salesmen, each with annual salaries of $30K, and 5 clerks at $10.9K/year. Expenses are 1/2 of these salaries and commissions are 2.4 x salesmen's salary. It is also assumed that there are no applications activities. The product marketer and one salesman will begin in Phase 2 with the remaining staff added in Phase 3.

8. PURCHASING. The purchasing function is assumed to remain constant with one purchasing agent at $28K/year and expenses of 20% of salary. This cateogry is initiated in Phase 1.

9. FINANCE. Finance Personnel include one accounts payable clerk, one accounts receivable clerk, and one payroll clerk at $10.9K/year. Expenses are 20% of salaries. The accounts payable clerk and the payroll clerk are employed in Phase 1 and the accounts receivable clerk is employed in Phase 3. This function is assumed independent of volume.

10. SECRETARY POOL. Two secretaries at $13K/year and 3 clerks at $10.9K/year are assumed for this section. Expense items are assumed to exist in the several areas win which these employees work. One secretary begins in Phase 1 with the remaining four personnel beginning in Phase 3.

11. DATA PROCESSING. This operation is constant and utilizes a leased computer and peripheral equipment. The computer will provide inventory tracking, direct labor reporting, reject analysis, and management information services. One programmer/operator at $28K is required. Expenses are assumed to be $52K per year.

12. TRAINING. Training is considered to be one of the most important functions in the overhead section. As a result, one organizer at $28K, nine trainers for crystal growth and wafer processing at $15.6K/year and three trainers for assembly at $15.6K/year will be employed in Phase 2 to become familiar with equipment and processes. In phase 3, these people perform an extensive training program for direct labor personnel. In Phase 4 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.

13. PERSONNEL. This section requires one employee in Phase 1 at $28K with an additional clerk at $10.9K/year to be added in Phase 2. Phases 3 and 4 include these two employees when volume is equal to 10 MW or less plus an additional employee at $28K/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.

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 (8 year S.L.) on the equipment will begin in Phase 3.

15. LEGAL. It is assumed that all legal matters will be performed by a contract attorney for $30K/year beginning in Phase 1. This is considered an expense item.

16. SECURITY. Security guards will be employed in Phase 3 on a two employee per shift basis at $16K/year.

17. HEALTH. Nurses will begin in Phase 3 on a one nurse per shift basis at $18K/year. Expenses are 10% of salary.

18. Q.A. The Q.A. function is initiated in Phase 3 and consists of one inspector at $12K/year for each 5 MW of annual production. Expenses are assumed to be 10% of payroll and depreciation is assumed to be $200 per person per year.

For all indirect labor employees, fringe benefits are assumed to be $3.1K/year times the number of employees regardless of salary or grade. Personnel contained in each of these categories is calculated (where appropriate) and taken to the next highest integer; thus, there are no fractional employees.

The assumptions contained in these 18 overhead categories are entered into the costing program from four files, one for each phase of factory life. Table 4.8a through 4.8d show the data format used for these inputs. As can be seen in these tables, entries may be numeric, zero, or negative integer. Numeric entries imply that the specific item identified by that entry is independent of changes in the several variables analyzed by the program. For example, engineering is assumed to remain constant within a phase regardless of other variables. Entries identified by a zero simply imply that the overhead category in question does not apply in that particular phase or sub-category. Examples are that building services are not included before the building is built and that commissions are paid on sales only. Negative number entries are codes which suggest that the overhead category or a portion of that category will vary as a

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TABLE 4.8a
OVERHEAD INPUTS, PHASE 1

FILE OD1

	CENSUS	PAYROLL	FRINGES	EXPENSE	DEPREC.	MATERIAL	COMMISSION
DIRECT FACTORY	0	.0	.0	.0	.0	0	0
ENGINEERING	11	344.3	34.1	114.8	.0	0	0
PRODUCTION CONT	0	.0	.0	.0	.0	0	0
BLDG SERVICES	0	.0	.0	.0	.0	0	0
MAINTENANCE	0	.0	.0	.0	.0	0	0
MANAGEMENT	1	52.0	3.1	10.4	.0	0	0
MARKETING/SALES	0	.0	.0	.0	.0	0	0
PURCHASING	1	28.0	3.1	5.6	.0	0	0
FINANCE	2	21.8	6.2	4.4	.0	0	0
SECRETARY POOL	1	13.0	3.1	.0	.0	0	0
DATA PROCESSING	0	.0	.0	.0	.0	0	0
TRAINING	0	.0	.0	.0	.0	0	0
PERSONNEL	1	28.0	3.1	2.8	.0	0	0
CAFETERIA	0	.0	.0	.0	.0	0	0
LEGAL	0	.0	.0	30.0	.0	0	0
SECURITY	0	.0	.0	.0	.0	0	0
HEALTH	0	.0	.0	.0	.0	0	0
N.A.	0	.0	.0	.0	.0	0	0

TABLE 4.8b
OVERHEAD INPUTS, PHASE 2

FILE OD2

	CENSUS	PAYROLL	FRINGES	EXPENSE	DEPREC.	MATERIAL	COMMISSION
DIRECT FACTORY	3	84.9	9.3	.0	.0	0	0
ENGINEERING	23	548.3	71.3	206.5	.0	0	0
PRODUCTION CONT	0	.0	.0	.0	.0	0	0
BLDG SERVICES	1	10.4	3.1	-1.0	.0	0	0
MAINTENANCE	-13	-14.0	-15.0	-16.0	.0	-17	0
MANAGEMENT	2	95.3	6.2	19.1	.0	0	0
MARKETING/SALES	2	60.0	6.2	30.0	.0	0	0
PURCHASING	1	28.0	3.1	5.6	.0	0	0
FINANCE	2	21.8	6.2	4.4	.0	0	0
SECRETARY POOL	1	13.0	3.1	.0	.0	0	0
DATA PROCESSING	0	.0	.0	.0	.0	0	0
TRAINING	13	215.2	40.3	21.5	.0	0	0
PERSONNEL	2	38.0	6.2	4.0	.0	0	0
CAFETERIA	0	.0	.0	.0	.0	0	0
LEGAL	0	.0	.0	30.0	.0	0	0
SECURITY	0	.0	.0	.0	.0	0	0
HEALTH	0	.0	.0	.0	.0	0	0
N.A.	0	.0	.0	.0	.0	0	0

TABLE 4.8c
OVERHEAD INPUTS, PHASE 3

FILE 003

	CENSUS	PAYROLL	FRINGES	EXPENSE	DEPREC.	MATERIAL	COMMISSION
DIRECT FACTORY	-2	-3.0	-4.0	.0	.0	0	0
ENGINEERING	23	548.3	71.3	206.5	62.5	0	0
PRODUCTION CONT	-5	-6.0	-7.0	-8.0	12.5	0	0
BLDG SERVICES	-9	-10.0	-11.0	-12.0	.0	0	0
MAINTENANCE	-13	-14.0	-15.0	-16.0	.0	-17	0
MANAGEMENT	5	225.2	15.5	45.0	.0	0	0
MARKETING/SALES	8	144.5	24.8	72.3	.0	0	144
PURCHASING	1	28.0	3.1	5.6	.0	0	0
FINANCE	3	32.7	9.3	6.5	.0	0	0
SECRETARY POOL	5	58.7	15.5	.0	.0	0	0
DATA PROCESSING	1	28.0	3.1	52.0	.0	0	0
TRAINING	13	215.2	40.3	21.5	.0	0	0
PERSONNEL	-18	-19.0	-20.0	-21.0	.0	0	0
CAFETERIA	0	.0	.0	7.5	.0	0	0
LEGAL	0	.0	.0	30.0	.0	0	0
SECURITY	6	96.0	18.6	.0	.0	0	0
HEALTH	3	54.0	9.3	5.4	.0	0	0
G.A.	-25	-26.0	-27.0	-28.0	-29.0	0	0

TABLE 4.8d
OVERHEAD INPUTS, PHASE 4

FILE 004

	CENSUS	PAYROLL	FRINGES	EXPENSE	DEPREC.	MATERIAL	COMMISSION
DIRECT FACTORY	-22	-23.0	-24.0	.0	.0	0	0
ENGINEERING	23	548.3	71.3	206.5	62.5	0	0
PRODUCTION CONT	-5	-6.0	-7.0	-8.0	12.5	0	0
BLDG SERVICES	-9	-10.0	-11.0	-12.0	.0	0	0
MAINTENANCE	-13	-14.0	-15.0	-16.0	.0	-17	0
MANAGEMENT	5	225.2	15.5	45.0	.0	0	0
MARKETING/SALES	8	144.5	24.8	72.3	.0	0	144
PURCHASING	1	28.0	3.1	5.6	.0	0	0
FINANCE	3	32.7	9.3	6.5	.0	0	0
SECRETARY POOL	5	58.7	15.5	.0	.0	0	0
DATA PROCESSING	1	28.0	3.1	52.0	.0	0	0
TRAINING	7	121.6	21.7	12.2	.0	0	0
PERSONNEL	-18	-19.0	-20.0	-21.0	.0	0	0
CAFETERIA	0	.0	.0	7.5	.0	0	0
LEGAL	0	.0	.0	30.0	.0	0	0
SECURITY	6	96.0	18.6	.0	.0	0	0
HEALTH	3	54.0	9.3	5.4	.0	0	0
G.A.	-25	-26.0	-27.0	-28.0	-29.0	0	0

function of some change in the several factory variables. Building services, for example, change as floorspace changes. Direct factory costs vary as a function of changes in direct labor headcount. Manufacturing volume and the number of pieces of manufacturing equipment also contribute to variations in the cost of specific overhead categories. When these negative numbers are encountered by the computer program, specific calculations occur within the program to determine the value that should be printed in a simulation. These calculations will be discussed later.

The sixth variable shown in Table 4.6 and entered into the program is the annual interest rate charged on borrowed money. In this costing approach, it has been assumed that all funds required to establish the solar factory are borrowed and accumulated as necessary and are paid for from the proceeds of sales during the last half of Phase 3 and during Phase 4.

A question often directed towards the manufacturing of solar photovoltaic modules is associated with energy payback time. The entry of the seventh variable, electrical power rate, does not specifically calculate the energy payback time, but does identify the significance of electrical energy costs with respect to the total manufacturing cost.

The eighth variable input allows the program to calculate the effect on total cost of varying direct labor personnel salaries. A significant value of this calculation is the ability to determine the allowable skill level of the direct labor work force.

One of the major cost factors that must be evaluated in the production of solar cells and modules is the effect of silicon cost and silicon consumption due to a limited supply. This problem has been addressed, in part, by the inclusion of the cost of polycrystalline silicon or the cost of silicon bearing chemicals used. The ninth variable input in Table 4.6 allows the thickness of the substrate to vary. The figure entered here is used for either sliced ingot or direct sheet growth technologies. In the example shown in Table 4 6, the value is input as 105 μm. This input is for RTR sheet which will be etched to 100 μm prior to the recrystallization process.

The final entry required in this series of inputs allows the user to select all or any individual table from the analysis. Each of the several tables that is available in this computer analysis will be discussed in detail later.

Returning to the first line of Table 4.6, note that an entry of a (1) will access inputs from a file. This approach is used when a sensitivity analysis is desired. The format of the required file is illustrated in Table 4.9. In this file, each of the variable inputs that are described above must be entered on a line of data in the same order as presented in Table 4.6. For example, lines 1-10 vary annual manufacturing volume from 0.5 MW per year to 500 MW per year while fixing cell efficiency at 14%, solar concentration at 1, polysilicon cost at $0.4 per kilogram, phase 1-4 months to 6-6-6-96 respectively, annual interest rate at 10%, electrical power rate at 4 cents per kilowatt hour, direct labor rate at $6 per hour, and substrate thickness to 200 μm. Similarily, lines 11-22 fixes each of the variable as shown and varies cell conversion efficiency from 9% to 20%. Lines 23-34 varies the solar concentration from 1-100, while lines 35-47 vary the cost of polycrystalline silicon from $0.1 per kilogram to $1.50 per kilogram. The remaining lines, 48-61 vary both cell efficiency and solar concentration in order to reflect the actual increases in cell efficiency as a function of solar concentration. As can be seen from this example, each of the variables can be adjusted over any range and the number of iterations is limited only by the length of the file created.

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TABLE 4.2
EXAMPLE OF SENSITIVITY ANALYSIS FILE

```
PVFILE

  1.000 .5    14      1   .4   5    5    5    95    10    4    5    200
  2.000 1     14      1   .4   5    5    5    95    10    4    5    200
  3.000 2.5   14      1   .4   5    5    5    95    10    4    5    200
  4.000 5     14      1   .4   5    5    5    95    10    4    5    200
  5.000 10    14      1   .4   5    5    5    95    10    4    5    200
  6.000 25    14      1   .4   5    5    5    95    10    4    5    200
  7.000 50    14      1   .4   5    5    5    95    10    4    5    200
  8.000 100   14      1   .4   5    5    5    95    10    4    5    200
  9.000 250   14      1   .4   5    5    5    95    10    4    5    200
 10.000 500   14      1   .4   5    5    5    95    10    4    5    200
 11.000 100    9      1   .4   5    5    5    95    10    4    5    200
 12.000 100   10      1   .4   5    5    5    95    10    4    5    200
 13.000 100   11      1   .4   5    5    5    95    10    4    5    200
 14.000 100   12      1   .4   5    5    5    95    10    4    5    200
 15.000 100   13      1   .4   5    5    5    95    10    4    5    200
 16.000 100   14      1   .4   5    5    5    95    10    4    5    200
 17.000 100   15      1   .4   5    5    5    95    10    4    5    200
 18.000 100   16      1   .4   5    5    5    95    10    4    5    200
 19.000 100   17      1   .4   5    5    5    95    10    4    5    200
 20.000 100   18      1   .4   5    5    5    95    10    4    5    200
 21.000 100   19      1   .4   5    5    5    95    10    4    5    200
 22.000 100   20      1   .4   5    5    5    95    10    4    5    200
 23.000 100   14      1   .4   5    5    5    95    10    4    5    200
 24.000 100   14      5   .4   5    5    5    95    10    4    5    200
 25.000 100   14     10   .4   5    5    5    95    10    4    5    200
 26.000 100   14     20   .4   5    5    5    95    10    4    5    200
 27.000 100   14     30   .4   5    5    5    95    10    4    5    200
 28.000 100   14     40   .4   5    5    5    95    10    4    5    200
 29.000 100   14     50   .4   5    5    5    95    10    4    5    200
 30.000 100   14     60   .4   5    5    5    95    10    4    5    200
 31.000 100   14     70   .4   5    5    5    95    10    4    5    200
 32.000 100   14     80   .4   5    5    5    95    10    4    5    200
 33.000 100   14     90   .4   5    5    5    95    10    4    5    200
 34.000 100   14    100   .4   5    5    5    95    10    4    5    200
 35.000 100   14      1   .1   5    5    5    95    10    4    5    200
 36.000 100   14      1   .2   5    5    5    95    10    4    5    200
 37.000 100   14      1   .3   5    5    5    95    10    4    5    200
 38.000 100   14      1   .4   5    5    5    95    10    4    5    200
 39.000 100   14      1   .5   5    5    5    95    10    4    5    200
 40.000 100   14      1   .6   5    5    5    95    10    4    5    200
 41.000 100   14      1   .7   5    5    5    95    10    4    5    200
 42.000 100   14      1   .8   5    5    5    95    10    4    5    200
 43.000 100   14      1   .9   5    5    5    95    10    4    5    200
 44.000 100   14      1 1      5    5    5    95    10    4    5    200
 45.000 100   14      1 1.2    5    5    5    95    10    4    5    200
 46.000 100   14      1 1.4    5    5    5    95    10    4    5    200
 47.000 100   14      1 1.5    5    5    5    95    10    4    5    200
 48.000 100   16      1   .4   5    5    5    95    10    4    5    200
 49.000 100   17      3   .4   5    5    5    95    10    4    5    200
 50.000 100   17.6    5   .4   5    5    5    95    10    4    5    200
 51.000 100   18      7   .4   5    5    5    95    10    4    5    200
 52.000 100   18.3 10     .4   5    5    5    95    10    4    5    200
 53.000 100   18.5 14     .4   5    5    5    95    10    4    5    200
 54.000 100   18.6 18     .4   5    5    5    95    10    4    5    200
 55.000 100   18.7 25     .4   5    5    5    95    10    4    5    200
 56.000 100   18.6 30     .4   5    5    5    95    10    4    5    200
 57.000 100   18.5 40     .4   5    5    5    95    10    4    5    200
 58.000 100   18.4 45     .4   5    5    5    95    10    4    5    200
 59.000 100   18.3 50     .4   5    5    5    95    10    4    5    200
 60.000 100   18.2 60     .4   5    5    5    95    10    4    5    200
 61.000 100   18    100   .4   5    5    5    95    10    4    5    200
```

When the sensitivity analysis approach is used, the list of terminal inputs required is not the same as Table 4.6. Only four inputs are required from the terminal. These inputs include a) the name of the file to be used such as that illustrated in Table 4.9 (PVFILE for example), b) the name of the process to be evaluated (see Table 4.3), c) the cell dimension for the particular analysis (see Table 4.4), and d) the form in which the output is to be displayed. Tables 4.10a and 4.10b illustrate the two display options.

In Table 4.10a, Analysis 1 has been selected. This analysis is used when the distribution of costs associated with the several cost categories, Materials, Expense, Labor, Overhead, Interest, and Depreciation are desired. The variables, Annual MW, Cell Efficiency, Solar Concentration, and duration of each of the four phases are also listed.

If the percentage of costs assigned to the different cost categories is not required in the print out, Analysis 2 shown in Table 4.10b should be used. In this printout, each of the input variables are listed as well as the "bottom" line manufacturing cost in $/watt.

A thoughtful approach to the accurate creation of each of the files described in this section can provide a valuable tool to critically evaluate any solar photovoltaic manufacturing process. Each of the variables directly related to a process step have been identified and included in this analysis. In the next section each of the printouts of a simulation are discussed.

TABLE 4.10a
SENSITIVITY ANALYSIS I

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```
100SOLCOST.
 TERMINAL(=0),FILE(=1) =?1
 PRINTER=LOCAL(0),OFFLINE(1) =?1
 FILENAME =?PVFILE
 PROCESS NAME =?COMPARE1
 CELL DIMENSION =?POLY.I
 WHICH ANALYSIS =?1
 *STOP* 0

      MEPSDU PROCESS                                         10CM CELL CONFIGURATION
 ANNUAL   CELL   SOLAR    PHASE MONTHS     MAT    EXP    LAB    OVR    INT    DEP      COST
   MW     EFF.   CONC.   1   2   3   4      %      %      %      %      %      %      ($/W)

     .5   14.0      1    6   6   6  96     1.6    3.4    3.1   77.4    9.1    5.4     8.7571
    1.0   14.0      1    6   6   6  96     3.1    4.3    3.8   74.7    8.8    5.2     4.5352
    2.5   14.0      1    6   6   6  96     6.8    7.3    5.2   66.1    8.9    5.7     2.1065
    5.0   14.0      1    6   6   6  96    11.4   10.7    7.1   56.2    8.0    5.6     1.2497
   10.0   14.0      1    6   6   6  96    16.5   14.5    9.4   44.4    8.5    6.8      .8597
   25.0   14.0      1    6   6   6  96    22.5   19.0   12.4   29.0    8.0    7.8      .6388
   50.0   14.0      1    6   6   6  96    25.4   21.4   13.7   22.8    8.5    8.2      .5588
  100.0   14.0      1    6   6   6  96    27.2   22.7   14.7   18.4    8.6    8.5      .5220
  250.0   14.0      1    6   6   6  96    28.7   23.8   15.2   15.6    8.0    8.7      .5084
  500.0   14.0      1    6   6   6  96    28.8   24.0   15.4   14.6    8.9    8.7      .4050
  100.0    9.0      1    6   6   6  96    27.9   23.4   15.1   16.2    8.7    8.7      .7880
  100.0   10.0      1    6   6   6  96    27.7   23.3   15.0   16.5    8.7    8.7      .7137
  100.0   11.0      1    6   6   6  96    27.7   23.1   14.9   17.0    8.6    8.6      .6530
  100.0   12.0      1    6   6   6  96    27.5   22.9   14.8   17.6    8.6    8.6      .5850
  100.0   13.0      1    6   6   6  96    27.4   22.8   14.7   18.0    8.6    8.5      .5500
  100.0   14.0      1    6   6   6  96    27.2   22.7   14.7   18.4    8.6    8.5      .5220
  100.0   15.0      1    6   6   6  96    26.9   22.6   14.5   18.9    8.6    8.5      .4924
  100.0   16.0      1    6   6   6  96    26.8   22.4   14.4   19.4    8.6    8.4      .4645
  100.0   17.0      1    6   6   6  96    26.5   22.2   14.4   20.0    8.6    8.4      .4418
  100.0   18.0      1    6   6   6  96    26.4   22.1   14.3   20.4    8.5    8.3      .4186
  100.0   19.0      1    6   6   6  96    26.3   21.9   14.1   20.5    8.5    8.4      .3981
  100.0   20.0      1    6   6   6  96    26.1   21.7   14.1   21.1    8.5    8.3      .3805
  100.0   14.0      1    6   6   6  96    27.2   22.7   14.7   18.4    8.6    8.5      .5220
  100.0   14.0      5    6   6   6  96    19.5   16.7   11.5   37.7    8.1    6.6      .1454
  100.0   14.0     10    6   6   6  96    14.0   12.8    8.5   50.7    7.8    5.8      .0972
  100.0   14.0     20    6   6   6  96     9.6    9.0    6.0   62.7    7.5    5.0      .0741
  100.0   14.0     30    6   6   6  96     7.1    7.0    4.6   69.3    7.5    4.5      .0666
  100.0   14.0     40    6   6   6  96     5.5    6.2    4.3   71.8    7.7    4.7      .0642
  100.0   14.0     50    6   6   6  96     4.7    4.9    3.9   75.5    7.4    4.1      .0624
  100.0   14.0     60    6   6   6  96     4.0    4.4    3.0   77.5    7.5    4.0      .0590
  100.0   14.0     70    6   6   6  96     3.5    4.1    3.0   77.9    7.5    4.1      .0581
  100.0   14.0     80    6   6   6  96     3.0    3.8    3.0   78.5    7.5    4.1      .0576
  100.0   14.0     90    6   6   6  96     2.8    3.6    3.0   79.0    7.6    4.1      .0573
  100.0   14.0    100    6   6   6  96     2.5    3.4    3.0   79.4    7.7    4.1      .0570
  100.0   14.0      1    6   6   6  96    26.1   23.1   14.9   18.6    8.7    8.6      .5147
  100.0   14.0      1    6   6   6  96    26.4   23.0   14.8   18.5    8.7    8.6      .5174
  100.0   14.0      1    6   6   6  96    26.8   22.8   14.7   18.5    8.6    8.5      .5201
  100.0   14.0      1    6   6   6  96    27.2   22.7   14.7   18.4    8.6    8.5      .5229
  100.0   14.0      1    6   6   6  96    27.5   22.6   14.6   18.3    8.6    8.5      .5256
  100.0   14.0      1    6   6   6  96    27.9   22.5   14.5   18.2    8.5    8.4      .5283
  100.0   14.0      1    6   6   6  96    28.3   22.4   14.4   18.1    8.5    8.4      .5310
  100.0   14.0      1    6   6   6  96    28.6   22.4   14.4   18.0    8.5    8.4      .5337
  100.0   14.0      1    6   6   6  96    29.0   22.3   14.3   17.9    8.4    8.3      .5364
  100.0   14.0      1    6   6   6  96    29.3   22.2   14.2   17.8    8.4    8.3      .5391
  100.0   14.0      1    6   6   6  96    29.7   22.1   14.1   17.7    8.4    8.3      .5418
  100.0   14.0      1    6   6   6  96    30.0   22.0   14.0   17.6    8.3    8.2      .5445
  100.0   14.0      1    6   6   6  96    30.4   21.8   14.0   17.5    8.3    8.2      .5472
  100.0   14.0      1    6   6   6  96    30.7   21.6   13.9   17.4    8.2    8.1      .5499
  100.0   14.0      1    6   6   6  96    31.0   21.4   13.9   17.4    8.2    8.0      .5527
  100.0   16.0      1    6   6   6  96    26.8   22.4   14.4   19.4    8.6    8.4      .4645
  100.0   17.0      3    6   6   6  96    20.6   18.5   11.9   32.7    8.2    7.4      .1805
  100.0   17.6      5    6   6   6  96    18.1   15.5   10.2   41.7    8.0    6.5      .1240
  100.0   18.0      7    6   6   6  96    15.5   13.2    9.4   48.3    7.7    5.8      .1019
  100.0   18.3     10    6   6   6  96    12.0   11.4    7.5   55.7    7.7    5.4      .0865
  100.0   18.5     14    6   6   6  96    10.1    9.4    6.3   61.5    7.9    5.0      .0757
  100.0   18.7     18    6   6   6  96     8.5    7.8    4.9   66.5    7.5    4.7      .0696
  100.0   18.7     25    6   6   6  96     6.5    6.6    4.7   70.1    7.9    4.6      .0657
  100.0   18.6     30    6   6   6  96     5.6    6.0    4.3   71.0    7.7    4.7      .0642
  100.0   18.5     40    6   6   6  96     4.5    4.7    3.9   76.0    7.3    4.3      .0598
  100.0   18.4     45    6   6   6  96     4.1    4.4    3.6   77.1    7.4    4.3      .0587
  100.0   18.3     50    6   6   6  96     3.7    4.2    3.5   77.6    7.4    4.1      .0583
  100.0   18.2 [illegible] 6 6   6  96     3.2    3.8    3.0   78.4    7.5    4.1      .0577
  100.0   18.0    100    6   6   6  96     2.0    3.1    2.5   80.0    7.7    4.2      .0561
```

TABLE 4.10b
SENSITIVITY ANALYSIS 2

```
!00SOLCOST.
 TERMINAL(=0),FILE(=1) =?1
 PRINTER=LOCAL(0),OFFLINE(1) =?1
 FILENAME =?PVFILE
 PROCESS NAME =?COMPARE1
 CELL DIMENSION =?POLY1
 WHICH ANALYSIS =?2
 *STOP* 0

     MEPSOU PROCESS                                     10CM CELL CONFIGURATION
 ANNUAL  CELL  SOLAR  POLY       PHASE        INT.    PWR.   LAB.    POLY      COST
   MW    EFF.  CONC.  COST      MONTHS        RATE    RATE   RATE   MICRON    ($/W)
     .5  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200     8.7571
    1.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200     4.5552
    2.5  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200     2.1025
    5.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200     1.2477
   10.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .6597
   25.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .6508
   50.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5548
  100.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5229
  250.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5084
  500.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5050
  100.0   9.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .7806
  100.0  10.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .7137
  100.0  11.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .6530
  100.0  12.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .6036
  100.0  13.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5590
  100.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5229
  100.0  15.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .4854
  100.0  16.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .4645
  100.0  17.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .4413
  100.0  18.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .4188
  100.0  19.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .3961
  100.0  20.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .3805
  100.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5229
  100.0  14.0     5     .4    6   6   6  96  10.00    4.0   6.00    200      .1654
  100.0  14.0    10     .4    6   6   6  96  10.00    4.0   6.00    200      .0972
  100.0  14.0    20     .4    6   6   6  96  10.00    4.0   6.00    200      .0741
  100.0  14.0    30     .4    6   6   6  96  10.00    4.0   6.00    200      .0600
  100.0  14.0    40     .4    6   6   6  96  10.00    4.0   6.00    200      .0642
  100.0  14.0    50     .4    6   6   6  96  10.00    4.0   6.00    200      .0600
  100.0  14.0    60     .4    6   6   6  96  10.00    4.0   6.00    200      .0586
  100.0  14.0    70     .4    6   6   6  96  10.00    4.0   6.00    200      .0581
  100.0  14.0    80     .4    6   6   6  96  10.00    4.0   6.00    200      .0576
  100.0  14.0    90     .4    6   6   6  96  10.00    4.0   6.00    200      .0573
  100.0  14.0   100     .4    6   6   6  96  10.00    4.0   6.00    200      .0570
  100.0  14.0     1     .1    6   6   6  96  10.00    4.0   6.00    200      .5147
  100.0  14.0     1     .2    6   6   6  96  10.00    4.0   6.00    200      .5174
  100.0  14.0     1     .3    6   6   6  96  10.00    4.0   6.00    200      .5201
  100.0  14.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .5229
  100.0  14.0     1     .5    6   6   6  96  10.00    4.0   6.00    200      .5256
  100.0  14.0     1     .6    6   6   6  96  10.00    4.0   6.00    200      .5283
  100.0  14.0     1     .7    6   6   6  96  10.00    4.0   6.00    200      .5310
  100.0  14.0     1     .8    6   6   6  96  10.00    4.0   6.00    200      .5337
  100.0  14.0     1     .9    6   6   6  96  10.00    4.0   6.00    200      .5364
  100.0  14.0     1    1.0    6   6   6  96  10.00    4.0   6.00    200      .5391
  100.0  14.0     1    1.2    6   6   6  96  10.00    4.0   6.00    200      .5445
  100.0  14.0     1    1.4    6   6   6  96  10.00    4.0   6.00    200      .5500
  100.0  14.0     1    1.5    6   6   6  96  10.00    4.0   6.00    200      .5527
  100.0  16.0     1     .4    6   6   6  96  10.00    4.0   6.00    200      .4645
  100.0  17.0     3     .4    6   6   6  96  10.00    4.0   6.00    200      .1805
  100.0  17.6     5     .4    6   6   6  96  10.00    4.0   6.00    200      .1246
  100.0  18.0     7     .4    6   6   6  96  10.00    4.0   6.00    200      .1019
  100.0  18.3    10     .4    6   6   6  96  10.00    4.0   6.00    200      .0865
  100.0  18.5    14     .4    6   6   6  96  10.00    4.0   6.00    200      .0757
  100.0  18.6    18     .4    6   6   6  96  10.00    4.0   6.00    200      .0690
  100.0  18.7    25     .4    6   6   6  96  10.00    4.0   6.00    200      .0657
  100.0  18.6    30     .4    6   6   6  96  10.00    4.0   6.00    200      .0642
  100.0  18.5    40     .4    6   6   6  96  10.00    4.0   6.00    200      .0595
  100.0  18.4    45     .4    6   6   6  96  10.00    4.0   6.00    200      .0587
  100.0  18.3    50     .4    6   6   6  96  10.00    4.0   6.00    200      .0583
  100.0  18.2    60     .4    6   6   6  96  10.00    4.0   6.00    200      .0577
  100.0  18.0   100     .4    6   6   6  96  10.00    4.0   6.00    200      .0561
```

3.4.3 DESCRIPTION OF SIMULATION OUTPUT REPORTS

The Motorola solar photovoltaic computerized costing method contains seven individual output reports which may be accessed individually or as a group. Each of these reports is preceded by a heading which contains the name of the process being evaluated, the cell configuration, annual production volume, cell efficiency, solar concentration, substrate thickness, and direct labor rate. Each of these inputs have been entered at the terminal and were described in the preceding section. Some of the information contained in the reports is read directly from one of the several files that are used by the program while other information is the result of costing calculations. Each row and column of figures contained in the several reports generated by Motorola's photovoltaic costing program are described in this section.

The first report generated by the Motorola costing program is shown in Table 4.11. This and subsequent report tables contain the standard heading as is shown in the example of Table 4.11. On the left side of this table is a list of each of the process steps used. The order in which this list is presented is the order of the process sequence. The first column on this table depicts the estimate yield in percent of each process step. These values are read from the table of process step assumptions illustrated in Table 4.2 and described in the previous section.

The second column of figures represents the product of each of the process step yield numbers, starting from the last step of the process sequence and working toward the first step. In this example, the overall process sequence yield is 76.8%. Once these yield figures are known, the number of substrates or substrate equivalents required at each process step can be calculated. This calculation is based upon the inputs of total watts produced each year, the cell efficiency, solar

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TABLE 4.11

MEPSDU PROCESS 10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION 14.00 % CELL EFFICIENCY
SOLAR CONCENTRATION = 1 SOLAR CONSTANTS
SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
DIRECT LABOR RATE = $ 6.00/HOUR

PROCESS STEP	STEP YLD(%)	CUM YLD(%)	WAFERS PER HR	MACH EFF	MACH CAP	YIELD CAP
SICL4 POLY	96.0	76.8	8617	.94	857	806
RIBBON ETCH	99.8	79.9	8273	.90	972	875
E-BEAM RTR	90.0	80.1	8256	.92	360	331
TEXTURE ETCH	99.2	89.0	7930	.93	3200	2976
HI I IMPLANT N&P	99.8	89.7	7371	.90	1000	900
IMPLANT ANNEAL	99.4	89.9	7356	.96	5760	5530
SILICON NITRIDE	99.2	90.5	7312	.88	250	220
PLASMA PATTERN	99.4	91.2	7254	.93	300	279
ELECTROLESS NI	99.4	91.7	7210	.96	3000	2874
SINTER	99.8	92.3	7167	.94	1500	1410
ELECTROLESS CU	99.8	92.5	7152	.96	2880	2765
CELL TEST	95.0	92.7	7138	.95	1200	1140
STRING ASSY/TEST	99.0	97.5	6781	.90	900	810
PVB PREP	100.0	98.5	6713	.99	9900	9801
TEDLAR PREP	100.0	98.5	6712	.99	16500	16335
GLASS PREP	100.0	98.5	6711	.98	8250	8085
ARRAY ASSY/TEST	99.0	98.6	6711	.97	660	640
LAMINATION	99.8	99.6	6644	.95	330	313
MODULE TRIM	99.9	99.8	6630	.99	5200	5148
MODULE TEST	99.8	99.8	6627	.95	7920	7524
FINISHED PRODUCT	100.0	100.0	6613			
COLUMN NUMBER:	(1)	(2)	(3)	(4)	(5)	(6)

concentration, and cell size (to determine the peak power generating capacity of a single solar cell), and the total number of manufacturing hours in a year (5400 is assumed) which is contained in the body of the computer program. As can be seen in Table 4.11, 8617 substrate equivalents must be manufactured each hour in the SICL4 POLY step in order to achieve an output of 6613 finished, encapsulated solar cells per hour, the number required to produce 50 MW of peak power generating capacity in one year.

Columns four and five of Table 4.11 are read from the process step assumptions (Table 4.2) and represent the expected fraction of operating time compared to the total number of work hours, and the maximum output of each piece of equipment respectively. Column six is simply the product of columns four and five and is intended to represent the actual, yielded capacity of each piece of equipment.

Table 4.12 continues to evaluate each process step within the process sequence. For the purpose of maintaining continuity with the discussion on the several tables described in this section, and the detailed discussion on the computer program to be presented later, the first column in Table 4.12 will be referred to as the seventh column of the analysis. In this seventh column, the decimal number of machines is calculated. Those figures are the result of dividing the yielded hourly capacity of each particular piece of manufacturing equipment into the required hourly rate for each process step. For example, in the Plasma Patterning process step shown in Table 4.11, 7254 substrates must be processed each hour by pieces of equipment capable of producing 279 substrates per hour. Therefore, 26 pieces of equipment are required to perform this function. As can be seen in column seven, fractional pieces of equipment are usually required. Since smaller machines will not be obtained to perform this lower production requirement, the value in column seven

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TABLE 4.12

MEPSDU PROCESS 10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION 14.00 % CELL EFFICIENCY
SOLAR CONCENTRATION = 1 SOLAR CONSTANTS
SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
DIRECT LABOR RATE = $ 6.00/HOUR

PROCESS STEP	#MACH (DEC)	#MACH (ACT)	K$ MACH	TOTAL K$	LABOR MACH	TOTAL DL	SQFT MACH	TOTAL SQFT
SICL3 POLY	10.69	11	250.0	2750	1.00	11	525	5775
RIBBON ETCH	9.45	10	75.0	750	1.00	10	360	3600
E-BEAM RTR	24.94	25	130.0	3250	1.00	25	135	3375
TEXTURE ETCH	2.50	3	100.0	300	.50	2	120	360
HI I IMPLANT N&P	8.19	9	45.0	705	.50	5	40	360
IMPLANT ANNEAL	1.33	2	80.0	160	.50	1	200	400
SILICON NITRIDE	33.28	34	320.0	16[illegible]	.12	5	275	1375
PLASMA PATTERN	26.00	26	80.0	2080	.25	7	48	1248
ELECTROLESS NI	2.51	3	88.8	266	1.00	3	104	312
SINTER	5.08	6	100.5	603	.50	3	156	936
ELECTROLESS CU	2.59	3	60.0	180	.50	2	132	396
CELL TEST	6.26	7	46.0	322	1.00	7	60	420
STRING ASSY/TEST	8.57	9	50.0	450	.33	3	80	720
PVB PREP	.63	1	25.0	25	1.00	1	290	290
TEDLAR PREP	.41	1	20.0	20	1.00	1	10[illegible]	1[illegible]
GLASS PREP	.83	1	16.0	16	1.00	1	65	65
ARRAY ASSY/TEST	10.49	11	20.0	220	1.00	11	15	165
LAMINATION	21.23	22	25.0	550	.20	5	135	2970
MODULE TRIM	1.29	2	1.0	2	1.00	2	40	80
MODULE TEST	.88	1	165.0	165	1.00	1	250	250
TOTAL				14470		106		24692
COLUMN NUMBER:	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)

is raised to the next highest integer when fractional needs are present. Column eight reflects this increase in equipment requirements and is identified as the actual number of machines required. Notice that in the case of the Plasma Pattern process step, that exactly 26 machines are required, thus, there is no increase in the actual machine requirement category.

In column nine, the capital cost of a single piece of equipment is entered from Table 4.2. These figures in column nine are multiplied times the corresponding figures in column eight in order to determine the total equipment capital dollar requirement for each process step. Column ten contains these total equipment capital figures for each process step as well as a total capital dollar cost for the entire manufacturing process sequence. The one anomaly to this set of calculations is associated with the Silicon Nitride process step. As was explained in the previous section, when a diffusion furnace operation is used, the equipment is obtained in an integral unit containing eight individual tubes. Table 4.12 shows the need for 34 such tubes in the Silicon Nitride process step. Five, eight-tube units are required (since fractional machines are not obtained) at a cost of $320K per eight-tube unit. Thus, there is a requirement for a total of 1.6 million dollars for this particular process step.

Column eleven in the analysis shows the estimated direct labor requirement for a single piece of equipment for each process step. These figures are multiplied times the actual number of machines required for their corresponding step to obtain the total direct labor requirement (rounded up to whole people) for each step and for the process sequence.

The final two columns in Table 4.12 (columns thirteen and fourteen of the analysis) are associated with the floor space requirements within the manufacturing area. Column thirteen of the analysis contains the floor space, as defined in the previous section, for a single piece of equipment. Column fourteen represents the total floor space requirements for each process step and for the process sequence. The value represented here as total manufacturing area (TSQFT in the previous section) is assumed to be 49% of the total factory floor space. The remaining 51% of total factory floor space is consumed by indirect functions such as offices, restrooms, corridors and the like.

In Table 4.13, process steps are grouped into categories, each of which contain similar or related processing functions. Those process categories that are included in this example include CRYSTAL GROWTH, JUNCTION and DIELECTRIC FORMATION, METALLIZATION, and ASSEMBLY. The first column on this table (column fifteen of the analysis) shows how effectively each piece of manufacturing equipment is used. These values are simply the decimal number of machines required (from column seven) divided by the actual number of machines (column eight). A review of these values can be used to evaluate the basic equipment assumptions. For example, in the case of TEDLAP PREP, where the equipment is utilized less than half of the time, it may be desirable to define and use a lower cost, more fully utilized, piece of equipment.

Column sixteen performs a similar calculation to determine how effectively labor is being utilized for each process step. As can be seen in Table 4.13, labor utilization and equipment utilization are for the most part identical. In some of the process steps, however, the labor utilization is less than the equipment utilization. These occurrances are due to the fact that the labor value printed in column twelve has been integerized to the next highest value when fractional labor was calculated for a particular step. For example, if seven pieces of equipment were required and each direct labor equipment operator could run two of them, then 3.5 operators would be required. Column twelve would, however, show a requirement for four operators. As a result, since labor utilization is

TABLE 4.13

MEPSDU PROCESS
10CM CELL CONFIGURATION
14.00 % CELL EFFICIENCY
50.0 MEGA WATT ANNUAL PRODUCTION
SOLAR CONCENTRATION = 1 SOLAR CONSTANTS
SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
DIRECT LABOR RATE = $ 6.00/HOUR

PROCESS GROUPING

PROCESS STEP	EQPT UTL(%)	LABOR UTL(%)	LABOR /STEP	LABOR (DEC)	LABOR (ACT)
CRYSTAL GROWTH					
SICL4 POLY	97.2	97.6	11	10.7	
RIBBON ETCH	94.5	94.5	10	9.5	
E-BEAM RTR	99.8	99.8	25	24.9	
TEXTURE ETCH	83.2	62.4	2	1.2	
TOTAL			48	46.3	49
JCT/DIELECT FORM					
HI I IMPLANT NBP	91.6	91.9	5	4.1	
IMPLANT ANNEAL	66.5	66.5	1	.7	
SILICON NITRIDE	83.1	70.6	5	3.5	
TOTAL			11	8.3	9
METALLIZATION					
PLASMA PATTERN	100.0	92.9	7	6.5	
ELECTROLESS NI	83.9	83.9	3	2.5	
SINTER	84.7	84.7	3	2.5	
ELECTROLESS CU	86.2	64.7	2	1.3	
CELL TEST	89.4	89.4	7	6.3	
TOTAL			22	19.1	21
ASSEMBLY					
STRING ASSY/TEST	93.0	92.9	3	2.8	
EVA PREP	68.5	68.5	1	.7	
TEDLAR PREP	41.1	41.1	1	.4	
GLASS PREP	83.0	83.0	1	.8	
ARRAY ASSY/TEST	95.3	95.3	11	10.5	
LAMINATION	96.5	84.8	5	4.2	
MODULE TRIM	64.4	64.4	2	1.5	
MODULE TEST	88.1	88.1	1	.9	
TOTAL			25	21.6	23
PROCESS TOTAL					102
COLUMN NUMBER:	(15)	(16)	(17)	(18)	(19)

calculated by multiplying the fractional time the equipment is utilized (EQUIPMENT UTILIZATION), times the number of whole machines, times the labor requirement per machine, divided by the total integer labor requirement for all machines in a process step, then labor utilization may be less than equipment utilization. Using the sample above,

$$\frac{\text{7 whole machines X 0.5 operators per machine}}{\text{4 operators}} = 0.875$$

Thus, labor utilization would equal equipment utilization times 0.875.

In order to obtain a realistic direct labor value, the labor utilization factor in column sixteen is multiplied times the integerized labor value in column seventeen to obtain the fractional labor requirement shown in column eighteen. The values contained in column seventeen are identical to those in column twelve, Table 4.12. Within each process category, the fractional values of labor in each process step are totalled and multiplied times 1.05 (to account for absenteeism and turnover) to acquire an actual labor requirement for each process category. These values contained in column nineteen are the next highest integer value for labor requirements within a process cagegory. By example, the Crystal Growth process category requires:

36.4 X 1.05 = 38.22 → 39 direct labor personnel.

The values for each process category are totalled to reflect the total direct labor requirements for the entire process sequence. Had the total labor requirement of 96 at the bottom of column twelve, Table 4.12, been multiplied times 1.05 and integerized upward, 101 direct labor personnel would be required. Using the technique of process categorization, as shown in this example, results in a direct labor reduction of approximately 8% over that which would otherwise be required.

The next report produced by the costing program, Table 4.14, addresses the process requirement for major factory facilities and services. Included are electrical power, fume exhaust, and deionized water requirements. Column twenty represents the actual or estimated name plate power requirement in kilowatts for each individual piece of equipment of a process step (where multiple pieces of equipment may be used.) Columns 21 and 22 represent the fume exhaust requirements (VENT) in cubic feet per minute and the deionized water consumption in gallons per minute respectively. Each of these three requirements are read directly from the process step assumption table that was illustrated in Table 4.2 and described in the previous section. The values contained in column 23 are identical to those in column eight, Table 4.12. This and the several other columns which have been printed on more than one report table are done so when the figures contained in them effect the calculations on that particular report. For example, in Table 4.14, columns 23, 27, and 28 are each contained in other tables. They are on this table as well because they are used to calculate the values contained in columns 24, 25, and 26.

Column 24 is arrived at in a number of ways. In order to determine the way in which the calculation occurs, it must be determined whether the equipment operates continuously or only upon demand. The process by which this determination is made is described in the previous chapter in the section describing column 14 of Table 4.2. If it is determined that a particular piece of equipment operates continuously, then the value printed in column 24 is the product of the number of machines used in the process step (column 23), the name plate power rating for a single piece of equipment (column 20), and the machine efficiency (column 27). It is assumed that power is not consumed during maintenance and other non-productive times. If this type of equipment is capable of producing product but is not required to do so because of a lower than 100% demand, power is assumed

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TABLE 4.14

MEPSDN PROCESS 10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION 14.00 % CELL EFFICIENCY
SOLAR CONCENTRATION = 1 SOLAR CONSTANTS
SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
DIRECT LABOR RATE = $ 6.00/HOUR

	IND. EQPT FACILITY REQ				PROCESS STEP FACILITY REQ				
PROCESS STEP	PWR KW	VENT CFM	WTR GPM	# MACH	PWR KW	VENT CFM	WTR GPM	MACH EFF	EQPT UTLX
SICL4 POLY	236	125	.0	11	2440	1292	0	.94	97.2
RIBBON ETCH	14	600	.0	10	52	5399	0	.90	94.5
E-BEAM RTR	15	125	.0	25	212	2875	0	.92	99.8
TEXTURE ETCH	3	1000	6.0	3	8	2790	16	.93	83.2
HI I IMPLANT N&P	1[illegible]	40	.0	9	45	323	0	.90	91.0
IMPLANT ANNEAL	15	100	.0	2	28	191	0	.96	66.5
SILICON NITRIDE	140	125	.0	34	615	549	0	.88	97.8
PLASMA PATTERN	2	40	.0	20	29	967	0	.93	100.0
ELECTROLESS NI	7	800	2.5	3	20	2299	7	.96	83.6
SINTER	2	800	.0	2	11	4511	0	.94	84.7
ELECTROLESS CU	15	100	2.5	3	43	287	7	.96	86.2
CELL TEST	1	0	.0	7	5	0	0	.95	89.4
STRING ASSY/TEST	1	60	.0	9	10	485	0	.90	93.[illegible]
PVB PREP	1	0	.0	1	0	0	0	.99	68.5
TEDLAR PREP	0	0	.0	1	0	0	0	.99	41.1
GLASS PREP	5	600	4.0	1	2	588	3	.98	83.0
ARRAY ASSY/TEST	1	60	.0	11	16	640	0	.97	95.3
LAMINATION	6	80	.0	22	74	1671	0	.95	96.5
MODULE TRIM	3	0	.0	2	0	0	0	.99	64.4
MODULE TEST	3	0	.0	1	1	0	0	.95	89.1
TOTAL					3010	24876	34		
COLUMN NUMBER:	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)

to be consumed anyway. For example, a diffusion furnace is not turned off when product is not being fabricated.

On the other hand, if it is determined that a piece of equipment requires electrical power only when product is demanded, then the values calculated above are further multiplied by the equipment utilization factor (column 28) and the factor 0.616. This value, 0.616, is the ratio of assumed annual work hours (5400) divided by the annual calendar hours (8766). Subsequent calculations will utilize these figures in column 24 to determine the cost of electrical power. Some additional factors have been applied for multiple track or multiple tube pieces of equipment in order to exclude power consumption for the unused portions of that particular piece of equipment.

Similar calculations are used to arrive at the requirements for ventilation and deionized water which are contained in columns 25 and 26. Ventilation calculations assume that fume exhaust will be required to operate at all times that the equipment is operational. Thus, exhaust figures are the product of ventilation requirements per machine (column 21), the number of machines per process step (column 23), and the machine efficiency (column 27). Deionized water consumption is usually assumed to be on a demand basis so the figures contained in column 26 represent the product of the deionized water consumption for each machine (column 22), the number of machines utilizing deionized water (column 23), the machine efficiency (column 27), and the machine utilization factor (column 28). If, however, it is determined that deionized water must be consumed at all times that the equipment is operational, the machine utilization factor (column 28) will be excluded from the calculation. The mechanism for this determination, as has been discussed in the previous section, is contained in column fourteen of Table 4.2.

The next report, Table 4.15, presents a summary of direct expense and material items required by each of the process steps and for the process sequence. Included with the standard heading that has appeared at the top of each preceding table is the cost of silicon in dollars per kilogram, and the electrical power rate, both of which are input at the terminal at the beginning of the simulation. These variables have been entered on this table as they are germane to the calculations used to obtain some of the figures presented.

Column 29, Process Expenses, is arrived at in the following way. Expense items are defined as those commodities required to produce the product that do not appear in the final product. Columns 10, 11, and 12 of Table 4.2 contain these expense items in the form of expense dollars per thousand substrates, constant expense dollars per machine, and variable expense dollars per machine respectively. The values contained in column 29 are the sum of these figures. For example, the first step of this process sequence is SICL4 POLY. From Table 4.2 column ten it has been assumed that expenses of $27 per thousand substrates are consumed. From Table 4.11, it has been determined that, in order to produce in one year enough solar cells to generate 50 MW, 3617 substrate equivalents must be produced each hour at this first process step. Since it has been assumed that there are 5400 work hours in a work year then process expenses will be:

$$\frac{\$27}{\text{Thousand Substrates}} \times \frac{8.617\ \text{(Thousand Substrates)}}{\text{Hour}} \times \frac{5400\ \text{Hours}}{\text{Year}} = \$1256.4\text{K}$$

Returning to Table 4.2, it is seen that columns 11 and 12 contain zeros, indicating that no equipment related direct expenses have been identified. Had entries been contained in these columns, they would have resulted in additional process expenses which would be added to the substrate related expenses already calculated. For entries contained in column 11, Table 4.2 the value is simply multiplied times

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TABLE 4.15

MEPSDU PROCESS 10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION 14.00 % CELL EFFICIENCY
SOLAR CONCENTRATION = 1 SOLAR CONSTANTS
SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
DIRECT LABOR RATE = $ 5.00/HOUR
SILICON = $ .40/KILOGRAM POWER RATE = 4.0 CENTS/KWH

EXPENSE & MATERIAL ITEMS

PROCESS STEP	PROCESS EXP(K$)	ELECT EXP(K$)	WATER EXP(K$)	TOTAL EXP(K$)	MATL (K$)
SICL4 POLY	3117.7	473.5	.0	3591.2	275.9
RIBBON ETCH	98.7	22.5	.0	121.1	.0
E-BEAM RTR	13.1	47.4	.0	60.5	.0
TEXTURE ETCH	1088.9	7.9	16.8	1113.7	.0
HI I IMPLANT NRP	3.8	9.5	.0	13.3	.0
IMPLANT ANNEAL	22.8	6.0	.0	28.8	.0
SILICON NITRIDE	136.2	120.0	.0	256.2	.0
PLASMA PATTERN	42.6	7.9	.0	50.5	.0
ELECTROLESS NI	.7	9.1	7.2	17.0	17.6
SINTER	.0	12.4	.0	12.4	.0
ELECTROLESS CU	44.0	9.0	7.2	60.2	380.4
CELL TEST	.0	1.1	.0	1.1	.0
STRING ASSY/TEST	.0	3.1	.0	3.1	87.1
EVA PREP	.0	.1	.0	.1	.0
TEDLAR PREP	.0	.0	.0	.0	.0
GLASS PREP	.0	1.8	3.3	5.1	.0
ARRAY ASSY/TEST	.0	4.5	.0	4.5	5987.5
LAMINATION	9.2	18.2	.0	27.4	.0
MODULE TRIM	54.4	.1	.0	54.5	.0
MODULE TEST	32.6	.3	.0	32.9	.0
TOTAL	4666.5	754.3	34.5	5455.4	6748.6
COLUMN NUMBER:	(29)	(30)	(31)	(32)	(33)

the number of machines required for the process step, column eight, Table 4.12. For entries contained in column 12, Table 4.2, the calculation is the product of that number, the number of machines for each process step (column eight, Table 4.12), the equipment utilization factor (column 15, Table 4.13), and the machine efficiency factor (column four, Table 4.11).

The cost of electrical power directly related to the manufacturing of product is contained in column 30 of Table 4.15. The values contained here include the power necessary to operate each piece of manufacturing equipment, the power required to operate the exhaust ventilation equipment, and the power required to air condition the heat load produced by each piece of equipment plus the make-up air requirement due to ventilation. The assumptions used in this calculation are as follows. The actual equipment operating electrical power is assumed to be 50% of the "nameplate" figures listed in column 24, Table 4.14. The electrical power required to operate the exhaust ventilation system is assumed to be 0.46KW per 1000 CFM of exhaust as defined in column 25, Table 4.14. Air conditioning requirements are assumed to be 40%of the sum of equipment power (column 24) divided by eight, and 15 KW per 1000 CFM of exhaust from column 25. These three values are totalled, multiplied by the electrical power rate (in cents per kilowatt hour) as input at the terminal at the beginning of the simulation, and by 8766 hours to determine the annual cost, in thousands of dollars, of direct electrical power.

Column 31 reflects the annual cost of deionized water. The calculation which determines the cost of this commodity assumes that the quantity of deionized water used (column 26) is used for 324,000 minutes (5400 hours) per year and costs 0.31 cents per gallon. Column 32 is simply the sum of columns 29, 30, and 31 and reflects the total cost of all direct expenses.

The final column of this report, column 33, displays the cost of each of the direct materials used to fabricate solar cells and modules. Contained in this column are the costs of such items as silicon, nickel, copper, interconnects, and module hardware. The cost of each of these items is identified at the first process step in which they are encountered. It should be noted here that the values representing materials costs are entered as though the process sequence yield from that step forward is 100%. Because the actual yield will be less than 100%, some of the direct materials used in a given step will be expended in later steps and not actually appear in the final product. Nevertheless, it is desirable to account for such lost materials as a material cost rather than an expense because this emphasizes the yielded material requirements of the important primary commodities which appear in the finished product.

In general, the calculation used to determine the figure entered in column 33 is simply the product of the number of substrates required per hour for the particular process step in question (column 3, Table 4.11), the cost per thousand substrates processed (column 13, Table 4.2), and the number of working hours in a year (5400). In the special case of silicon substrates, however, a different approach is used.

The calculation that occurs for silicon sheet processes is the product of the number of substrate equivalents required per hour (column 3, Table 4.11), the number of working hours in a year (5400), the area of a single substrate (as read from a file), the thickness of a single substrate (as read from the terminal at the beginning of the simulation), the cost of the silicon bearing chemical (also read from the terminal at the beginning of a simulation), and a value which reflects the efficiency by which silicon sheets are formed from the silicon bearing chemical. This value is the estimated mass of silicon bearing chemical (in kilograms) required to produce 1000 cm^3 of silicon sheet.

The values contained in the program to account for the efficiencies of forming silicon sheets from silicon bearing chemicals are based on the following assumptions. For $SiHCl_3$, it is assumed that a conversion efficiency of 35% will be achieved in the reaction that produces silicon from this chemical. Of the remaining amount of chemical, 58.5% of the original quantity will be converted to $SiCl_4$ and be reclaimable at $0.40 per kilogram. The remaining 6.5% is lost as waste. This waste is treated as an expense category debit and the reclaimable portion is treated as a credit to the expense category. In the case of $SiCl_4$, a conversion efficiency of 65% is assumed. It is further assumed that the value of that which is reclaimed is equal to the cost to reclaim it, thus resulting in a net zero cost. For SiH_4, it is assumed that 100% of the chemical can be converted to silicon. Therefore, the mass of silicon bearing chemicals (in kilograms) required to produce 100 cm^3 of silicon sheet from $SiHCl_3$, $SiCl_4$, or SiH_4 is 11.2562 Kg, 14.1198 Kg, and 2.663 Kg respectively.

For a silicon ingot technology, the value in column 33 is the product of the substrate area, the substrate thickness, the cost of polycrystalline silicon, the density of silicon (2.33 Kg/1000 cm^3), the number of substrates required per hour, and the number of work hours per year. It is assumed that silicon substrates produced from an ingot are first identified as a material at the crystal sawing step.

These first 33 columns of the costing analysis output represent each of the direct requirements of the manufacturing process. The information contained in these tables as well as some additional information, which will be described, is utilized to create subsequent tables containing indirect manufacturing requirements and to create an overall summary of the simulation.

Tables 4.16a through 4.16d illustrate the cost of overhead by category for each of the four phases of the factory life. In addition to the standard heading, each table displays the number of direct labor employees and the number of months within the particular phase. These tables contain eight columns of information which reflect the labor, aggregate payroll, fringe benefits, expenses, depreciation, materials, commissions, and totals for each overhead cateogry. At the bottom of each of these tables is a total for each of the columns. The dollar figures (expressed in thousands of dollars) represent the actual expenses incurred for the duration of the phase. If an entry is $100K for a 12 month phase, with all other things being equal, the value would be $50K for a six month phase. The census figures, however, remain constant with changes in the phase duration since they represent the number of people employed within each functional category. Only integer numbers of employees are considered in this program. For the purpose of including these overhead costs in total costs, fractional years within a phase or multiple years within a phase are annualized in order to perform further costing calculations.

The final reports contained in the simulation are illustrated in Tables 4.17a and 4.17b. Each of these tables serves to summarize the overall costs of manufacturing solar cells and modules. Summarized in each of these tables are all of the inputs such as process name, cell dimension, annual power generating capacity of cells produced, cell efficiency, solar concentration, substrate thickness, direct labor rate, cost of silicon, electrical power rate, and interest rate. The number of months in each phase is contained in the left hand column of Table 4.17a and a listing of process steps is contained in the left hand column of Table 4.17b. Each table also contains the calculated figure for

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TABLE 4.16a

```
MEPSDU PROCESS                                10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION             14.00 % CELL EFFICIENCY
              SOLAR CONCENTRATION =        1 SOLAR CONSTANTS
              SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                  DIRECT LABOR RATE = $ 6.00/HOUR
DIRECT LABOR CENSUS =  306           POWER RATE =  4.0 CENTS/KWH

               OVERHEAD (K$)      PHASE 1 = 12 MONTHS

               CENSUS  PAYROLL  FRINGE    EXP     DEP     MAT    COM      TOTAL

DIRECT FACTORY     0       .0       .0      .0      .0      .0     .0        .0
ENGINEERING       11    344.3     34.1   114.8      .0      .0     .0     493.2
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     52.0      3.1    10.4      .0      .0     .0      65.5
MARKETING/SALES    0       .0       .0      .0      .0      .0     .0        .0
PURCHASING         1     28.0      3.1     5.6      .0      .0     .0      36.7
FINANCE            2     21.8      6.2     4.4      .0      .0     .0      32.4
SECRETARY POOL     1     13.0      3.1      .0      .0      .0     .0      16.1
DATA PROCESSING    0       .0       .0      .0      .0      .0     .0        .0
TRAINING           0       .0       .0      .0      .0      .0     .0        .0
PERSONNEL          1     28.0      3.1     2.8      .0      .0     .0      33.9
CAFETERIA          0       .0       .0      .0      .0      .0     .0        .0
LEGAL              0       .0       .0    30.0      .0      .0     .0      30.0
SECURITY           0       .0       .0      .0      .0      .0     .0        .0
HEALTH             0       .0       .0      .0      .0      .0     .0        .0
G.A.               0       .0       .0      .0      .0      .0     .0        .0

     TOTAL        17    487.1     52.7   168.0      .0      .0     .0     707.8
```

TABLE 4.16b

```
MEPSDU PROCESS                                10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION             14.00 % CELL EFFICIENCY
              SOLAR CONCENTRATION =        1 SOLAR CONSTANTS
              SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                  DIRECT LABOR RATE = $ 6.00/HOUR
DIRECT LABOR CENSUS =  306           POWER RATE =  4.0 CENTS/KWH

               OVERHEAD (K$)      PHASE 2 = 12 MONTHS

               CENSUS  PAYROLL  FRINGE    EXP     DEP     MAT    COM      TOTAL

DIRECT FACTORY     3     84.9      9.3      .0      .0      .0     .0      94.2
ENGINEERING       23    548.3     71.3   206.5      .0      .0     .0     826.1
PRODUCTION CONT    0       .0       .0      .0      .0      .0     .0        .0
BLDG SERVICES      1     10.4      3.1   443.1      .0      .0     .0     456.6
MAINTENANCE       23    424.0     71.3   484.5      .0   326.6     .0    1306.4
MANAGEMENT         2     95.3      6.2    19.1      .0      .0     .0     120.6
MARKETING/SALES    2     60.0      6.2    30.0      .0      .0     .0      96.2
PURCHASING         1     28.0      3.1     5.6      .0      .0     .0      36.7
FINANCE            2     21.8      6.2     4.4      .0      .0     .0      32.4
SECRETARY POOL     1     13.0      3.1      .0      .0      .0     .0      16.1
DATA PROCESSING    0       .0       .0      .0      .0      .0     .0        .0
TRAINING          13    215.2     40.3    21.5      .0      .0     .0     277.0
PERSONNEL          2     38.9      6.2     4.0      .0      .0     .0      49.1
CAFETERIA          0       .0       .0      .0      .0      .0     .0        .0
LEGAL              0       .0       .0    30.0      .0      .0     .0      30.0
SECURITY           0       .0       .0      .0      .0      .0     .0        .0
HEALTH             0       .0       .0      .0      .0      .0     .0        .0
G.A.               0       .0       .0      .0      .0      .0     .0        .0

     TOTAL        73   1539.8    226.3  1248.7      .0   326.6     .0    3341.4
```

TABLE 4.16c

```
                                                10CM CELL CONFIGURATION
   MEPSDU PROCESS                                14.00 % CELL EFFICIENCY
   50.0 MEGA WATT ANNUAL PRODUCTION                 
              SOLAR CONCENTRATION =       1 SOLAR CONSTANTS
              SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                   DIRECT LABOR RATE = $ 6.00/HOUR
   DIRECT LABOR CENSUS =  306           POWER RATE =   4.0 CENTS/KWH

              OVERHEAD (K$)        PHASE 3 = 12 MONTHS

              CENSUS   PAYROLL   FRINGE    EXP      DEP     MAT    COM      TOTAL

DIRECT FACTORY     18     428.4     55.8       .0       .0      .0      .0    484.2
ENGINEERING        23     548.3     71.3    206.5     62.5      .0      .0    888.6
PRODUCTION CONT    20     291.7     62.0     14.6     12.5      .0      .0    380.8
BLDG SERVICES       6      62.4     18.6    443.1       .0      .0      .0    524.1
MAINTENANCE        23     424.0     71.3    484.5       .0   326.6      .0   1306.4
MANAGEMENT          5     225.2     15.5     45.0       .0      .0      .0    285.7
MARKETING/SALES     8     144.5     24.8     72.3       .0      .0   144.0    385.6
PURCHASING          1      28.0      3.1      5.6       .0      .0      .0     36.7
FINANCE             3      32.7      9.3      6.5       .0      .0      .0     48.5
SECRETARY POOL      5      58.7     15.5       .0       .0      .0      .0     74.2
DATA PROCESSING     1      28.0      3.1     52.0       .0      .0      .0     83.1
TRAINING           13     215.2     40.3     21.5       .0      .0      .0    277.0
PERSONNEL           6     150.9     18.6     15.1       .0      .0      .0    184.6
CAFETERIA           0        .0       .0      7.5       .0      .0      .0      7.5
LEGAL               0        .0       .0     30.0       .0      .0      .0     30.0
SECURITY            6      96.0     18.6       .0       .0      .0      .0    114.6
HEALTH              3      54.0      9.3      5.4       .0      .0      .0     68.7
G.A.               10     120.0     31.0     12.0      2.0      .0      .0    165.0

    TOTAL         151    2908.0    468.1   1421.5     77.0   326.6   144.0   5345.2
```

TABLE 4.16d

```
                                                10CM CELL CONFIGURATION
   MEPSDU PROCESS                                14.00 % CELL EFFICIENCY
   50.0 MEGA WATT ANNUAL PRODUCTION                 
              SOLAR CONCENTRATION =       1 SOLAR CONSTANTS
              SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                   DIRECT LABOR RATE = $ 6.00/HOUR
   DIRECT LABOR CENSUS =  306           POWER RATE =   4.0 CENTS/KWH

              OVERHEAD (K$)        PHASE 4 = 96 MONTHS

              CENSUS   PAYROLL   FRINGE    EXP      DEP     MAT     COM       TOTAL

DIRECT FACTORY     27    5076.0    669.6       .0       .0       .0      .0    5745.6
ENGINEERING        23    4386.4    570.4   1652.0    500.0       .0      .0    7108.8
PRODUCTION CONT    20    2333.6    496.0    116.7    100.0       .0      .0    3046.3
BLDG SERVICES       6     499.2    148.8   3544.5       .0       .0      .0    4192.5
MAINTENANCE        23    3392.0    570.4   3876.0       .0   2612.8      .0   10451.2
MANAGEMENT          5    1801.6    124.0    360.0       .0       .0      .0    2285.6
MARKETING/SALES     8    1156.0    198.4    578.4       .0       .0  1152.0    3084.8
PURCHASING          1     224.0     24.8     44.8       .0       .0      .0     293.6
FINANCE             3     261.6     74.4     52.0       .0       .0      .0     388.0
SECRETARY POOL      5     469.6    124.0       .0       .0       .0      .0     593.6
DATA PROCESSING     1     224.0     24.8    416.0       .0       .0      .0     664.8
TRAINING            7     972.8    173.6     97.6       .0       .0      .0    1244.0
PERSONNEL           6    1207.2    148.8    120.7       .0       .0      .0    1476.7
CAFETERIA           0        .0       .0     60.0       .0       .0      .0      60.0
LEGAL               0        .0       .0    240.0       .0       .0      .0     240.0
SECURITY            6     768.0    148.8       .0       .0       .0      .0     916.8
HEALTH              3     432.0     74.4     43.2       .0       .0      .0     549.6
G.A.               10     960.0    248.0    768.0     16.0       .0      .0    1992.0

    TOTAL         154   24164.0   3819.2  11969.9    616.0   2612.81152.0   44333.0
```

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TABLE 4.17a

OVERALL PROCESS SUMMARY

```
MEPSDU PROCESS                                10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION              14.00 % CELL EFFICIENCY
           SOLAR CONCENTRATION =    1 SOLAR CONSTANTS
           SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                 DIRECT LABOR RATE = $ 6.00/HOUR
SILICON = $   40/KILOGRAM              POWER RATE =   4.0 CENTS/KWH
DIRECT LABOR CENSUS =  306             INTEREST RATE =   9.25 %
```

SUMMARY (K$)

FACTORY LIFE		MAT	EXP	LAB	OVR	INT	DEP	TOTAL
PHASE 1	12 MO	0	0	0	708	243	0	951
PHASE 2	12 MO	0	75	0	3341	1336	109	4862
PHASE 3	12 MO	3374	2728	2002	5345	2909	1812	18170
PHASE 4	96 MO	53989	43643	27232	44334	18849	14498	202543
TOTAL COST		57363	46446	29234	53728	23336	16419	226526
TOTAL	$/WATT	.1391	.1126	.0709	.1303	.0566	.0398	.5492
%		25.3	20.5	12.9	23.7	10.3	7.2	100.0

TABLE 4.17b

PROCESS STEP SUMMARY

```
MEPSDU PROCESS                                10CM CELL CONFIGURATION
50.0 MEGA WATT ANNUAL PRODUCTION              14.00 % CELL EFFICIENCY
           SOLAR CONCENTRATION =    1 SOLAR CONSTANTS
           SUBSTRATE(PRE-ETCH)THICKNESS = 105 MICRONS
                 DIRECT LABOR RATE = $ 6.00/HOUR
SILICON = $   40/KILOGRAM              POWER RATE =   4.0 CENTS/KWH
DIRECT LABOR CENSUS =  306             INTEREST RATE =   9.25 %
```

PROCESS STEP SUMMARY ($/WATT)

PROCESS STEP	MAT	EXP	LAB	OVR	INT	DEP	TOTAL
SICL4 POLY	.0057	.0741▲	.0079	.0108▲	.0105▲	.0077▲	.1168
RIBBON ETCH	.0000	.0025	.0070	.0083	.0037	.0023	.0239
E-BEAM RTR	.0000	.0013	.0185▲	.0224▲	.0095	.0087▲	.0604
TEXTURE ETCH	.0000	.0229▲	.0009	.0037	.0018	.0008	.0302
HI I IMPLANT N&P	.0000	.0003	.0030	.0058	.0021	.0020	.0132
IMPLANT ANNEAL	.0000	.0006	.0005	.0036	.0008	.0005	.0060
SILICON NITRIDE	.0000	.0054	.0026	.0061	.0049	.0033	.0223
PLASMA PATTERN	.0000	.0010	.0048	.0127▲	.0054	.0055	.0294
ELECTROLESS NI	.0004	.0004	.0019	.0040	.0011	.0007	.0084
SINTER	.0000	.0003	.0019	.0051	.0019	.0016	.0109
ELECTROLESS CU	.0078	.0012	.0010	.0040	.0012	.0005	.0157
CELL TEST	.0000	.0000	.0047	.0061	.0015	.0009	.0132
STRING ASSY/TEST	.0018	.0001	.0021	.0048	.0016	.0012	.0116
PVB PREP	.0000	.0000	.0005	.0033	.0005	.0001	.0044
TEDLAR PREP	.0000	.0000	.0003	.0031	.0004	.0001	.0039
GLASS PREP	.0000	.0001	.0006	.0032	.0005	.0000	.0044
ARRAY ASSY/TEST	.1234▲	.0001	.0078	.0087	.0059	.0007	.1466
LAMINATION	.0000	.0006	.0032	.0075	.0029	.0017	.0158
MODULE TRIM	.0000	.0011	.0010	.0033	.0005	.0000	.0059
MODULE TEST	.0000	.0007	.0007	.0034	.0008	.0005	.0059
TOTAL	.1391	.1126	.0709	.1299	.0565	.0398	.5487

total direct labor requirements for all three shifts. The summary of costs are contained in columns which assign the costs to materials, expenses, labor, overhead, interest, depreciation, and total. In Table 4.17a these are displayed in terms of the actual cost incurred during each of the four phases, the total cost which represents the sum of these four phases, the cost in dollars per watt and the percentage of total cost assigned to each cost account category. Table 4.17b further summarizes these costs by determining the cost in dollars per watt for each cost account category for each process step.

These last two tables are most helpful when determining cost drivers within a particular process sequence. An evaluation of Table 4.17b clearly shows that the cost of module parts, i.e. glass and frames for example, represent the greatest contribution to the materials costs. Expenses or waste, however, are most significant in the $SiCl_4$ poly silicon and texture etching process steps while labor is most intensive in the E-Beam RTR process step. Overhead cost drivers occur in the $SiCl_4$ Poly, E-Beam RTR, and Plasma Patterning process steps, perhaps suggesting a high maintenance or high labor condition. Interest and depreciation, which are most significant in the $SiCl_4$ Poly and E-Beam RTR process steps, indicate that much higher capital equipment costs or floor space requirements are associated with these process steps than with the other steps in the process sequence. Each of these observations of cost drivers in the different cost account categories, in conjunction with the supporting data from previous tables, are invaluable to pinpointing the areas where cost reduction efforts must be first applied. Significantly high cost drivers in this table may lead to modification of the assumptions that contribute to that cost.

This section has attempted to display each of the costs attendant to manufacturing solar cells and solar modules. The accuracy of the calculations is directly related to the validity of each of the various inputs and should be treated as such. Of more importance than absolute accuracy, this program serves to identify the relative costs of a wide variety of cost components and to compare them, one to another. This comparison process, as has been shown, accurately identifies those areas in a manufacturing process that require the greatest attention in order to achieve the lowest manufacturing cost.

3.4.4 DESCRIPTION OF MOTOROLA PROGRAM SOFTWARE

The Motorola solar costing program has been written in the Xerox Sigma 5-9 Extended FORTRAN IV language. Xerox Sigma 5-9 Extended FORTRAN IV is basically compatible with other FORTRAN systems. It essentially conatins (as subsets) most other FORTRAN languages, including the following:

ANSI (American National Standards Institute) XE.4 Standard FORTRAN
ISO (International Organization for Standardization) TC07/SC5 FORTRAN.
Xerox 9300 FORTRAN IV.
Xerox 900 Series FORTRAN II.
IBM System 360 FORTRAN IV.
IBM 7090/7094 FORTRAN II and IV.

In the Motorola costing program, which is named SOLCOST, calculations occur in the order that was presented in Section 3.4.3, tables 4.11 - 4.17. These calculations occur in the same manner for both a single simulation and for a sensitivity analysis; only the printing format is changed. Each term used in this program is described in commentary (lines 4-127) at the beginning of the FORTRAN program listing. Figure 4.1 shows a block diagram of each of the required inputs for operation of the program. Each of these inputs has been described fully in the preceeding sections. Figure 4.2 shows a simplified block diagram of the computer program's operation. Additional detail regarding the

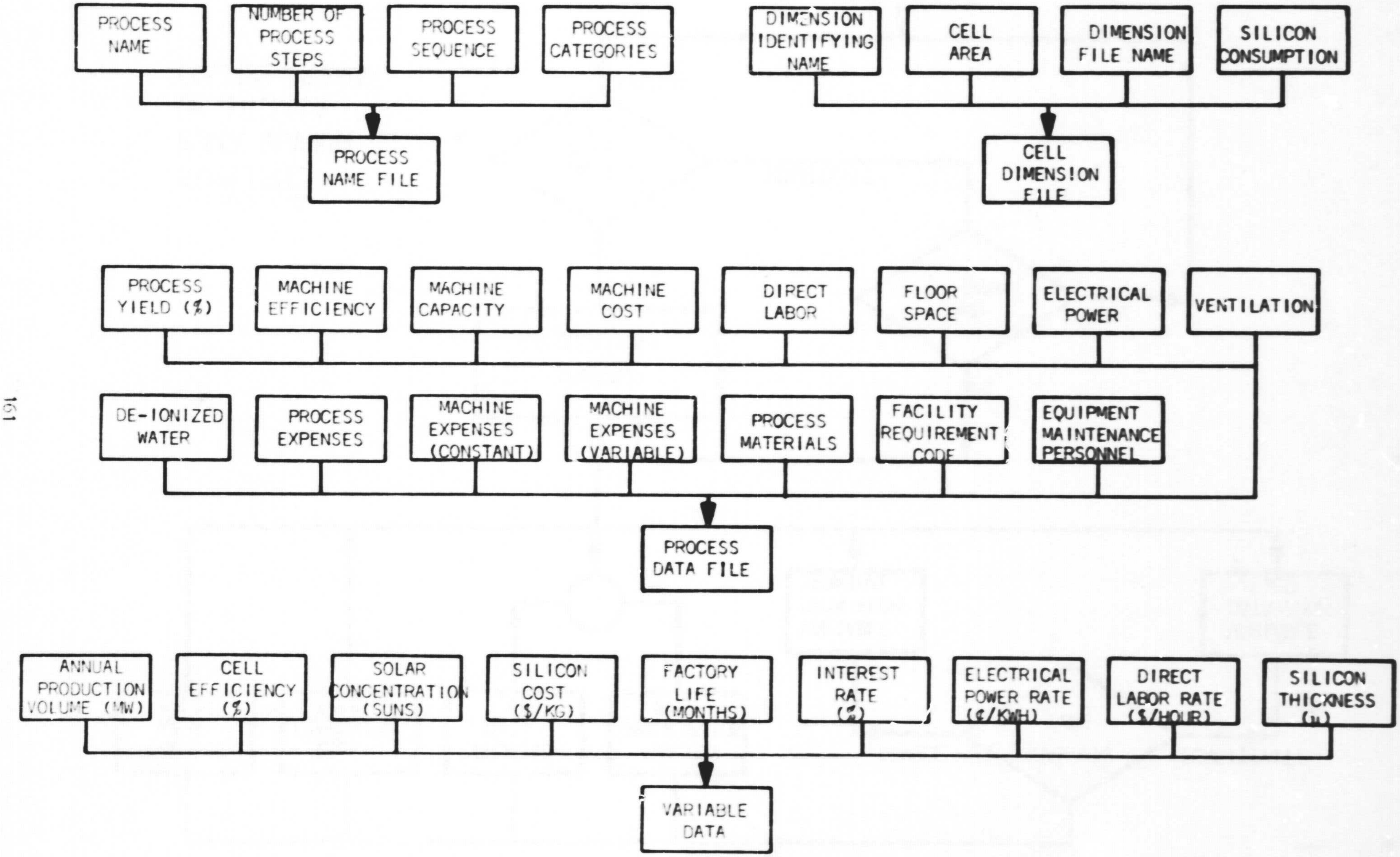

FIGURE 4.1: BLOCK DIAGRAMS OF INPUT DATA.

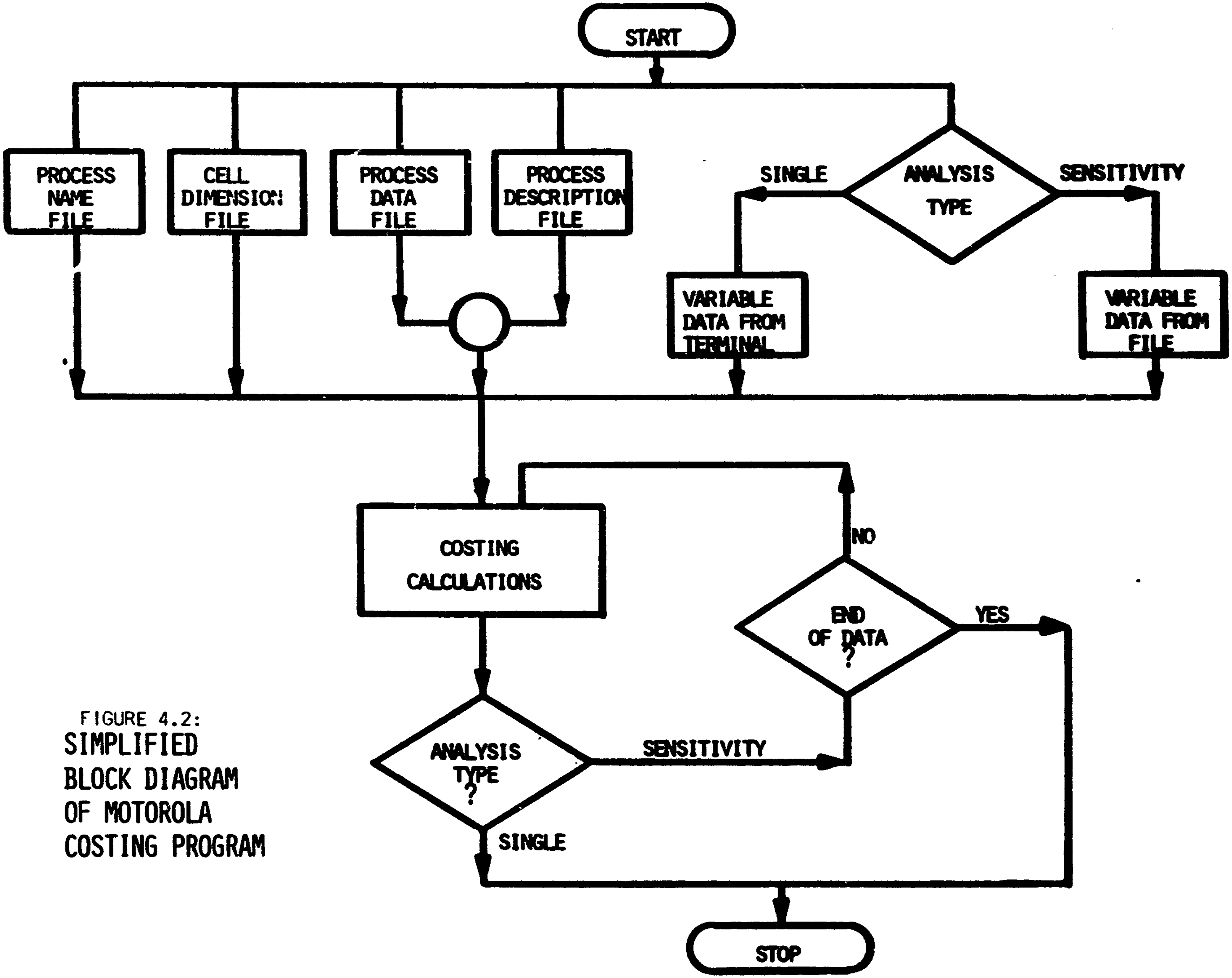

FIGURE 4.2:
SIMPLIFIED
BLOCK DIAGRAM
OF MOTOROLA
COSTING PROGRAM

costing calculations as well as the overall program operation is contained in the listing of the program in the next section.

3.4.5 LISTING OF FORTRAN PROGRAM

This section simply lists the actual FORTRAN program, SOLCOST, as written to run on the Xerox Sigma 9 computer system. As noted in Section 3.4.4, numerous comments which describe program terminology precede the main body of the program. The total listing includes 1106 statement lines and is given on the following 14 pages.

3.4.6 EVALUATION OF SAMIS METHODOLOGY

As part of the Low-Cost Solar Array Project, Jet Propulsion Laboratories, in conjunction with the National Aeronautics and Space Administration, and the U.S. Department of Energy, has created a computer program for the purpose of estimating the manufacturing costs of a photovoltaic industry. This program, entitled the Standard Assembly-Line Manufacturing Simulation (SAMIS), was designed to model a hypothetical U.S. industry which manufactures silicon solar modules. It use has been primarily limited to existing contractors to the several agencies administering photovoltaic contracts, applications for new contracts, and agencies such as JPL, SERI, and Sandia Laboratories. The purpose of SAMIS is to provide a common approach whereby each of the several photovoltaic manufacturing processes can be compared. This section will serve to evaluate the SAMIS methodology in terms of reasonability and accuracy, and to compare it to an independent costing approach developed by Motorola.

3.4.6.1 SAMIS EXECUTION AND COST

Utilization of SAMIS requires the use of a computing system capable of operating in the computing language SIMSCRIPT, as described in Digital Computer User's Handbook, p. 1-264,

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```
C *** MOTOROLA SOLAR COSTING PROGRAM ********************************
C     INCLUDES TABLES 1 THRU 8, AND FILE READ
C
C *** VARIABLE NAMES *********************
C
C     AINT=ANNUAL INTEREST RATE (%)
C     AMT(N)=AMOUNT OF DEBT ACCUMULATED IN PHASE(N)
C     ANALYSIS1=SUBROUTINE FOR SENSITIVITY ANALYSIS DATA
C     AREA=CELL ACTIVE AREA
C     A(K,J2)=PROCESS STEP INPUT ARRAY
C
C     B(J1,J2)=SIMULATION OUTPUT ARRAY
C     BAYPD=PROCESS DESCRIPTON FILE
C
C     C(NPH,J1,J2)=OVERHEAD INPUT ARRAY
C     C1=COST OF FOUR TRACK ENCLOSURE
C     C2=COST OF TRACK APPARATUS
C     C(NPH,J1,J2)=OVERHEAD ARRAY
C     CCM=COST OF COMPLETE MACHINES
C     CEFF=CELL EFFICIENCY(%)
C     CFM=COST OF FRACTIONAL MACHINE
C     CT(NPH,J2)=COLUMN TOTAL(OVERHEAD TABLES)
C     CY=CUMULATIVE YIELD
C
C     DA=DIFFUSION FURNACE AREA(SQ.FT.)
C     DATA=IDENTIFIER FOR 'DIM' FILE TO BE CALLED
C     DEBT(N)=AMOUNT OF DEBT AT END OF PHASE(N)
C     DIM=CELL DIMENSION(FILE NAME)
C     DIM1=CELL DIMENSION(PRINTED STATEMENT)
C     DLD=DIRECT LABOR (DECIMAL)
C     DLR=DIRECT LABOR RATE($/HOUR)
C     D(NPH,J2)=OUTPUT ARRAY OF TABLES 7 AND 8
C     DPS(N)=DEBT PER STEP AT END OF PHASE(N)
C
C     FILE=NAME OF FILE FOR SENSITIVITY ANALYSIS
C     FILES=NAME OF LIST OF CURRENT FILES
C     FM=FRACTIONAL MACHINE
C     FPW=FINISHED PRODUCT WAFERS
C
C     IAN=INTEGER IDENTIFYING ANALYSIS TO BE RUN
C     IDLA=INTEGERIZED DIRECT LABOR
C     IDLAI=TOTAL LABOR FOR PROCESS CATEGORY
C     IDLAII=TOTAL DIRECT LABOR FOR PROCESS SEQUENCE
C     IF=DETERMINES IF FILES SHOULD BE PRINTED
C     IFILE=INTEGER IDENTIFYING FILE TO BE READ
C     INPUT1=SUBROUTINE FOR SENSITIVITY  ANALYSIS HEADINGS
C     IPP=TABLE PRINT COMMAND
C     IPTR=PRINTER SELECTION COMMAND
C     IT=TEMPORARY INTEGERIZER
C     IT1=NUMBER OF SUPERVISORS(MATERIALS & WAFER PROCESSING)
C     IT2=NUMBER OF SUPERVISORS(ASSEMBLY)
C
C     LOOP=0 FOR SINGLE ANALYSIS, 1 FOR SENSITIVITY ANALYSIS
C     LPST=LABOR PER STEP TOTAL
C     LT=DETERMINES IF LABOR TOTAL SHOULD BE PRINTED
C
C
C     N1=FIRST TERM IN SERIES OF PROCESS STEPS
C     N2=SECOND TERM IN SERIES OF PROCESS STEPS
C     N8P=NUMBER OF 8-PACK DIFFUSION FURNACES
C     NAME=PROCESS SEQUENCE IDENTIFIER(FILE NAME)
C     NAME1=PROCESS NAME(PRINTED STATEMENT)
C     NC=PROCESS CATEGORY IDENTIFIER
C     NCM=NUMBER OF COMPLETE MACHINES
C     NMM=NUMBER OF MAINTENANCE MEN
C     NMPH(NPH)=NUMBER OF MONTHS IN PHASE NUMBER(NPH)
C     NMS=NUMBER OF MAINTENANCE SUPERVISORS
C     NPH=NUMBER OF PHASE(1 THRU 4)
C     NPS=NUMBER OF PROCESS STEPS
C     NTM=NUMB TOT MACH(INCL FRACTIONAL) INTEGERIZED UP
C     NTN=NUMBER OF TUBES NEEDED
C     NTPS=NUMBER OF TUBES PER STEP
C     NTU=NUMBER OF TUBES USED FOR ALL DIFF STEPS
C
C     OC=OVERHEAD CATEGORY (NAME FILE)
C     OCT(J1)=OVERHEAD CATEGORY TOTAL(18 CATEGORIES)
C     OD1=OVERHEAD INPUT DATA(PHASE 1)
C     OD2=OVERHEAD INPUT DATA(PHASE 2)
```

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```
C       OD3=OVERHEAD INPUT DATA(PHASE 3)
C       OD4=OVERHEAD INPUT DATA(PHASE 4)
C
C       PD(K)=PROCESS DESCRIPTION OF PROCESS NUMBER K
C       PMT=ANNUAL LOAN PAYMENT IN PHASE FOUR
C       PN(J)=PROCESS NUMBER OF J TH PROCESS STEP
C       PPS=ANNUAL LOAN PAYMENT PER STEP
C       PSC=POLY SILICON COST($/KILOGRAM)
C       PSMM=PROCESS STEP MAINTENANCE MAN
C       PST=POLY SILICON THICKNESS(IN MICRONS)
C       PWRR=ELECTRICAL POWER RATE(CENTS/KWH)
C
C       REPORT=NAME OF OFFLINE PRINT OUTPUT FILE
C
C       SIKG=MASS(KG) OF USABLE INGOT BEFORE SAWING
C       SIL=MASS OF EXPENSE SILICON
C       SKERF=KERF LOSS/SUBSTRATE DUE TO SAWING INGOT (IN CM)
C       SUNS=SOLAR CONCENTRATION
C
C       T1=SUM OF PHASE1 OVR & SQ.FT. DEBT PER PROCESS STEP
C       T2=SUM OF PHASE2 EXP,OVR, & CAPITAL DOLLARS DEBT/PROCESS STEP
C       T3=SUM OF PHASE3 MAT,EXP,LAB, & OVR DEBT/PROCESS STEP
C        T4=PHASE1 INTEREST
C       T5=PHASE2 INTEREST
C       T6=PHASE3 INTEREST
C       T7=PHASE4 INTEREST
C       T(J2)=TOTAL OF COULMNS TABLE 8
C       TABLE=IDENTIFIER FOR TABLE TO BE PRINTED
C       TCFM=TOTAL EXHAUST(CFM)
C       TDEX=TOTAL DIFFUSION EXHAUST(CFM)
C       TDL=TOTAL DIRECT LABOR (BEFORE CATEGORY GROUPING)
C       TDLD=TOTAL DIRECT LABOR(DECIMAL)
C       TDP=TOTAL DIFFUSION POWER(KW)
C       TEL=TOTAL ELECTRICAL(SUM 9(J1,30))
C       TEXP=TOTAL EXPENSE(SUM B(J1,32))
C       TGPM=TOTAL DI WATER(GPM)
C       TKD=TOTAL KILO DOLLARS($K)
C       TKW=TOTAL ELECTRICITY REQUIRED(KW)
C       TMTL=TOTAL MATERIAL(SUM B(J1,33))
C       TNMM=TOTAL NUMBER OF MAINTENANCE MEN
C       TPR=TOTAL PROCESS EXPENSES
C       TSQFT=TOTAL SQ.FT.(MANUFACTURING AREA)
C       TTKD=TOTAL OF TOTAL KILO DOLLARS
C       TW=TOTAL OF DI WATER USED
C
C       VOLUME=SUM OF PHASES 3 & 4 MANUFACTURING VOLUME
C
C       WPC=WATTS PER CELL
C       WPY=WATTS PER YEAR
C
C ***************************************
C
C       THIS PROGRAM CALCULATES THE SEVERAL COSTS ASSOCIATED WITH
C       A SOLAR CELL/MODULE MANUFACTURING FACILITY. ONE OR ALL OF
C       8 TABLES CAN BE SELECTED TO ILLUSTRATE THE NEEDS AND COSTS
C       OF THE SOLAR FACTORY. THESE TABLES HAVE THE FOLLOWING
C       INFORMATION.
C
C          TABLE 1  CUM YIELD, WAFERS REQUIRED, MACHINE CAPACITIES
C          TABLE 2  # OF MACHINES, CAPITAL $, TOTAL SQ.FT.
C          TABLE 3  LABOR BY PROCESS CATEGORY
C          TABLE 4  PROCESS FACILITY REQUIREMENTS
C          TABLE 5  EXPENSE AND MATERIAL ITEMS
C          TABLE 6  FOUR PHASES OF OVERHEAD COST
C          TABLE 7  SUMMARY OF PROCESS SEQUENCE
C          TABLE 8  SUMMARY OF PROCESS STEPS
C
C       IN ORDER TO IMPLEMENT THE PROGRAM, SEVERAL DATA FILES MUST
C       BE CREATED. THESE FILES MUST CONTAIN THE FOLLOWING INFORMATION
C       IN THE EXACT ORDER SHOWN BELOW.
C
C          PROCESS.NAME(UP TO 16 CHARACTERS)
C             1.  PROCESS NAME AS IT IS TO BE PRINTED
C             2.  NUMBER OF PROCESS STEPS
C             3.  ORDER OF PROCESS STEPS
C             4.  NC N1 N2 LT
C                      *
C             N.  NC N1 N2 LT
C
C          CELL DIMENSION(UP TO 8 CHARACTERS)
```

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```
C             1.  CELL DIMINSION AS IT IS TO BE PRINTED
C             2.  AREA OF CELL(SQ.CM/1000)
C             3.  NAME OF DATA FILE TO BE READ(E.G.,10CM OR 12CM)
C             4.  SHEET (0 FOR SHEETS)
C             5.  STKS (0 FOR SHEETS)
C             6.  MASS OF SILICON/1000 WAFERS(1ST INGOT USE)
C             N.  MASS OF SILICON/1000 WAFERS(NTH INGOT USE)
C          OR 6.  AREA OF CELL IN SQ. CM (SHEET)
C
C         IN ADDITION, A DATA FILE FOR A PARTICULAR CELL DIMENSION
C         MUST BE AVAILABLE WITH EACH PROCESS STEP AND CONTAIN 15
C         DATA POINTS. THE ORDER IN WHICH THIS DATA MUST BE
C         PRESENTED FOR EACH PROCESS STEP IS AS FOLLOWS:
C
C          1. PROCESS STEP YIELD(%)
C          2. MACHINE EFFICIENCY
C          3. MACHINE CAPACITY
C          4. COST OF EACH MACHINE(K$)
C          5. LABOR PER MACHINE
C          6. SQ.FT. PER MACHINE
C          7. ELECTRICAL POWER REQUIREMENT PER MACHINE(KW)
C          8. EXHAUST REQUIREMENT PER MACHINE(CFM)
C          9. DI WATER REQUIREMENT PER MACHINE(GPM)
C         10. PROCESS EXPENSE PER 1000 WAFERS
C         11. CONSTANT MACHINE EXPENSES
C         12. VARIABLF MACHINE EXPFNSES(BASED ON MACHINE USAGE)
C         13. MATERIAL COST PER 1000 WAFERS
C         14. FACILITY REQUIREMENT(1=DEMAND,2=CONSTANT)
C         15. MAINTENANCE MEN PER MACHINE
C
C         THE ANSWERS TO THE FOLLOWING QUESTIONS REPRESENT THE
C         VARIABLE INPUTS REQUIRED TO IMPLEMENT THE PROGRAM. SIMPLY
C         FNTER THE TFRM REQUESTED AND PRESS THE CARRIAGE RETURN.
C   ***************************************
C
          INTEGER TABLE,FPN
          INTEGER NAME1(16),DIM1(8)
          INTEGER FILE(3),NMPR(4),NAME(4),DIM(2),DATA(3)
          INTEGER PN(50),PD(60,4),OC(18,4)
          REAL A(60,15),B(50,48),C(4,18,8),CT(4,8),D(5,7)
          REAL PSMM(50),OCT(18),T(40)
C
          LOOP=0
C
          OUTPUT'TERMINAL(=0),FILE(=1) =1'
          READ400,IFILE
C
          OUTPUT'PRINTER=LOCAL(0),OFFLINE(1) =1'
          READ400,IPTR
C
          IF(IFILE.EQ.0)GOTO120
C
          OUTPUT'FILENAME =1'
          READ16,FILE
          CALL OPENF(3,FILE,2)
          TABLE=0
C
          OUTPUT'PROCFSS NAME =1'
          READ16,NAME
          CALL OPENF(4,NAME,2)
          READ(4,8)NAME1
C
          OUTPUT'CELL DIMENSION =1'
          READ16,DIM
          CALL OPENF(2,DIM,2)
          READ(2,8)DIM1
C
          DO1J=16,1,-1
          IF(NAME1(J).NE.1H )GOTO2
    1     CONTINUE
C
    2     CONTINUE
C
          DO3K=8,1,-1
          IF(DIM1(K).NF.1H )GOTO4
    3     CONTINUE
C
    4     CONTINUE
C
          J=J+10
```

```
      K=51-K
C
      OUTPUT'WHICH ANALYSIS =1'
      READ400,IAN
C
      IF(IPTR.EQ.1)CALL CLOSEF(108,1)
      IF(IPTR.EQ.1)CALL OPENF(108,'REPORT ',4)
C
      PRINT20
      PRINT6,NAME1,J,K,DIM1
6     FORMAT(9X,16A1,TN,' PROCESS',TN,8A1,T51,' CELL CONFIGURATION')
C
      REWIND(2)
      REWIND(4)
C
      READ(3,400)WPY,CEFF,SUNS,PSC,NMPH,AINT,PWRR,DLR,PST
      REWIND(3)
C
      CALL INPUT1(NAME1,DIM1,IAN,WPY,CEFF,SUNS,PSC,NMPH,
     &AINT,PWRR,DLR,PST,J,K)
C
120   CONTINUE
C
      IF(IFILE.EQ.0)OUTPUT'PROCESS NAME =1'
      IF(IFILE.EQ.0)READ16,NAME
      IF(IFILE.EQ.0)OUTPUT'CELL DIMENSION =1'
      IF(IFILE.EQ.0)READ16,DIM
C
122   CONTINUE
C
      IF(IFILE.EQ.0)CALL OPENF(4,NAME,2)
      READ(4,8)NAME1
      IF(IFILE.EQ.0)CALL OPENF(2,DIM,2)
      READ(2,8)DIM1
      IF(IFILE.NE.0)LOOP=1
C
8     FORMAT(80A1)
16    FORMAT(20A4)
400   FORMAT(50G)
C
      DO124NPH=1,5
C
      DO125J2=1,7
      D(NPH,J2)=0
125   CONTINUE
C
124   CONTINUE
C
      IF(IFILE.NE.0)GOTO131
C
      OUTPUT'ANNUAL MEGA-WATTS =1'
      READ400,WPY
      OUTPUT'CELL EFFICIENCY(%)=1'
      READ400,CEFF
      OUTPUT'SOLAR CONSTANTS(SUNS) =1'
      READ400,SUNS
      OUTPUT'POLY SILICON COST($/KILO) =1'
      READ400,PSC
      OUTPUT'NUMBER OF MONTHS IN EACH PHASE(4 INPUTS) =1'
      READ400,NMPH
      OUTPUT'ANNUAL INTEREST RATE(%)=1'
      READ400,AINT
      OUTPUT'POWER RATE(CENTS/KWH) =1'
      READ400,PWRR
      OUTPUT'DIRECT LABOR RATE($/HOUR)=1'
      READ400,DLR
      OUTPUT'POLY SILICON THICKNESS(PRE-ETCH MICRONS)=1'
      READ400,PST
C
131   CONTINUE
C
      IF(IFILE.NE.0)READ(3,400,END=121)WPY,CEFF,SUNS,PSC,
     &NMPH,AINT,PWRR,DLR,PST
      IF(WPY.LE.0)GOTO121
C
      PST=PST*1E-4
      WPY=WPY*1000000
C
      READ(4,400)NPS
      READ(4,400)(PN(I1),I1=1,NPS)
```

```
      READ(2,400)WPC
      WPC=WPC*SUNR*CEFF
      FPW=WPY/WPC
      READ(2,16)DATA
C
      CALL OPENF(1,DATA,2)
C
      DO12K=1,68
      READ(1,400)(A(K,J1),J1=1,15)
12    CONTINUE
C
      CALL CLOSEF(1,2)
C
C *** READS PROCESS DESCRIPTION FROM 849PD **************************
C
      CALL OPENF(1,'849PD',2)
      K=1
C
17    CONTINUE
      READ(1,16,END=19)(PD(K,J),J=1,4)
      K=K+1
      GOTO17
C
19    CONTINUE
C
      CALL CLOSEF(1,2)
C
C
C *** CORRECTS COSTS FOR YIELDS(WORKING BACKWARD) *      ************
C
      CY=1
      NTU=0
      TNMM=0
C
      DO9J1=NPS,1,-1
      K=PN(J1)
      CY=CY*A(K,1)/100
      B(J1,1)=A(K,1)
      B(J1,2)=CY*100
      IT=FPW/CY/5400+.5
      B(J1,3)=IT
      B(J1,4)=A(K,2)
      IF(A(K,13).EQ.-1)A(K,3)=A(K,3)/(100*PST)
      B(J1,5)=A(K,3)
      IT=B(J1,4)*B(J1,5)+.5
      B(J1,6)=IT
      B(J1,7)=B(J1,3)/B(J1,6)
      IT=B(J1,7)+.9999
      B(J1,8)=IT
      IF(A(K,4).EQ.-4)NTU=NTU+B(J1,8)
      IF(A(K,4).GE.0)PSMM(J1)=B(J1,8)*A(K,15)
      IF(A(K,4).GE.0)TNMM=TNMM+PSMM(J1)
      B(J1,9)=A(K,4)
      B(J1,10)=B(J1,8)*B(J1,9)
      B(J1,11)=A(K,5)
      IT=B(J1,8)*B(J1,11)+.9999
      B(J1,12)=IT
      B(J1,13)=A(K,6)
      B(J1,14)=B(J1,8)*B(J1,13)
9     CONTINUE
C
      N8P=NTU/8+.9999
      NTN=N8P*8
      DDL=N8P
      DA=N8P*275
      TDP=N8P*140
      TDEX=N8P*125
C
      TTKD=0
      TDL=0
      TSQFT=0
C
      DO26J1=1,NPS
C
      K=PN(J1)
      I4=A(K,4)
      IF(I4.EQ.-4)PSMM(J1)=B(J1,8)/8*A(K,15)
      IF(I4.EQ.-4)TNMM=TNMM+PSMM(J1)
C
      IF(I4.GE.0)GOTO27
```

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```
C
      NCM=B(J1,8)/4
      FM=B(J1,8)/4-NCM
      IF(I4.NE.-4)PSMM(J1)=(NCM+FM)*A(K,15)
      IF(I4.NE.-4)TNMM=TNMM+PSMM(J1)
      NTM=B(J1,8)/4+.9999
      C1=5.5
      C2=13.4
      IF(I4.EQ.-2)C2=13.1
      IF(I4.EQ.-3)C1=4.8
      IF(I4.EQ.-3)C2=12.9
      B(J1,9)=C1+4*C2
      IF(I4.EQ.-4)B(J1,9)=90
      IF(K.EQ.17)B(J1,9)=320
      B(J1,10)=NCM*B(J1,9)
      IF(FM.GT.0)B(J1,10)=B(J1,10)+4*FM*C2+C1
      B(J1,11)=.125
      IF(I4.EQ.-3)B(J1,11)=.25
      IT=B(J1,8)*B(J1,11)+.9999
      B(J1,12)=IT
      B(J1,13)=80
      IF(I4.EQ.-3)B(J1,13)=45
      IF(I4.EQ.-4)B(J1,13)=275
      B(J1,14)=NTM*80
      IF(I4.EQ.-3)B(J1,14)=NTM*45
C
      IF(I4.NE.-4)GOTO38
      IT=B(J1,8)/NTU*NBP*B(J1,9)+.9999
      B(J1,10)=IT
      IT=B(J1,8)/NTU*DDL+.9999
      B(J1,12)=IT
      IT=B(J1,8)/NTU*DA+.9999
      B(J1,14)=IT
   38 CONTINUE
C
C
   27 CONTINUE
C
      TTKD=TTKD+B(J1,10)
      TDL=TDL+B(J1,12)
      TSOFT=TSOFT+B(J1,14)
C
   26 CONTINUE
C
      NMM=TNMM+.9999
      IT=NMM/10/3+.9999
      NMS=3*IT
C
C
C *** PRINTS OUT HEADING ************************************************
C
      IF(IFILE.EQ.0)OUTPUT'WHICH TABLE(1 TO 8, 9 FOR ALL) =1'
      IF(IFILE.EQ.0)READ400,TABLE
C
      IF((IPTR.EQ.1).AND.(IFILE.EQ.0))CALL CLOSEF(108,1)
      IF((IPTR.EQ.1).AND.(IFILE.EQ.0))CALL OPENF(108,'REPORT ',4)
C
C *** TABLE 1 **********************************************
C ******************************************
C
      IF((TABLE.NE.1).AND.(TABLE.NE.9))GOTO25
C
      IF(IPTR.EQ.1)PRINT5
    5 FORMAT(1H1)
C
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      PRINT22
   22 FORMAT(/,26X,'STEP',5X,'CUM',5X,'WAFERS',
     $3X,'MACH',3X,'MACH',3X,'YIELD')
      PRINT23
   23 FORMAT(6X,'PROCESS STEP',7X,'YLD(%)',3X,'YLD(%)',
     $3X,'PER HR',3X,'EFF',4X,'CAP',4X,'CAP',/)
C
      DO10J1=1,NPS
      K=PN(J1)
      PRINT24,(PL(K,J2),J2=1,4),
     $(B(J1,J2),J2=1,6)
   24 FORMAT(6X,4A4,F8.1,F9.1,I9,F8.2,I7,I8)
   10 CONTINUE
```

```
C
      PRINT15,FPW/5400
15    FORMAT(6X,'FINISHED PRODUCT     100.0      100.0',I9,/)
C
25    CONTINUE
C
C *** TABLE 2 *************************************************
C ***********************************************
C
      IF((TABLE.NE.2).AND.(TABLE.NE.9))GOTO37
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      PRINT28
28    FORMAT(/,24X,'#MACH  #MACH    KS    TOTAL',
     &'  LABOR   TOTAL   SOFT   TOTAL')
      PRINT29
29    FORMAT(6X,'PROCESS STEP',6X,'(DEC)   (ACT)',
     & '  MACH    KS',5X,'MACH    DL    MACH    SOFT',/)
C
      DO34J1=1,NPS
      K=PN(J1)
      PRINT35,(PD(K,J2),J2=1,4),(B(J1,J2),J2=7,14)
35    FORMAT(6X,4A4,F7.2,I5,F8.1,I7,F7.2,I5,I8,I7)
34    CONTINUE
C
      PRINT36,TIKD,IDL,TSOFT
36    FORMAT(9X,'TOTAL',25X,I10,I12,I15)
C
37    CONTINUE
C
C *** TABLE 3 *************************************************
C ***********************************************
C
      IPR=0
      IF((TABLE.EQ.3).OR.(TABLE.EQ.9))IPR=1
C
      IF(IPR.NE.1)GOTO39
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      IF(IPR.EQ.1)PRINT40
40    FORMAT(/,32X,'PROCESS GROUPING',/)
      IF(IPR.EQ.1)PRINT41
41    FORMAT(27X,'EQPT        LABOR      LABOR      LABOR      LABOR')
      IF(IPR.EQ.1)PRINT42
42    FORMAT(6X,'PROCESS STEP',8X,'UTL(%)    UTL(%)',
     &4X,'/STEP     (DEC)       (ACT)',/)
C
39    CONTINUE
C
C ***********************************************
C
      TDLD=0
      IDL[illegible]0
132   CONTINUE
C
      READ(4,400,END=141)NC,N1,N2,LT
      IF(NC.EQ.0)GOTO142
C
      IF(IPR.EQ.0)GOTO61
C
      IF(NC.EQ.1)PRINT43
43    FORMAT(5X,'CRYSTAL GROWTH')
      IF(NC.EQ.2)PRINT46
46    FORMAT(5X,'WAFER PREP')
      IF(NC.EQ.3)PRINT47
47    FORMAT(5X,'PHOTOLITHOGRAPHY')
      IF(NC.EQ.4)PRINT143
143   FORMAT(5X,'SURFACE PREPARATION')
      IF(NC.EQ.5)PRINT48
48    FORMAT(5X,'CT/DIELECT FORM')
      IF(NC.EQ.6)PRINT49
49    FORMAT(5X,'METALLIZATION')
      IF(NC.EQ.7)PRINT50
50    FORMAT(5X,'ASSEMBLY')
C
61    CONTINUE
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      C
              LPST=0
              DLD=0
      C
      142     CONTINUE
      C
              DO52J1=N1,N2
              K=PN(J1)
              B(J1,15)=B(J1,7)/B(J1,8)
              IF(A(K,4).EQ.-4)IT=(B(J1,8)/8+.9999)
              IF(A(K,4).EQ.-4)B(J1,15)=B(J1,7)/(IT*8)
              B(J1,16)=B(J1,8)*B(J1,11)/B(J1,12)*B(J1,15)
              B(J1,17)=B(J1,12)
              LPST=LPST+B(J1,17)
              B(J1,18)=B(J1,16)*B(J1,17)
              DLD=DLD+B(J1,18)
              TDLD=TDLD+B(J1,18)
              IF(IPR.EQ.1)PRI[illegible]44,(PD(K,J2),J2=1,4)
             &,(100*B(J1,12)[illegible]J1,16),B(J1,17),B(J1,18)
      44      FORMAT(6X,4A4,F9.1,F16.1,I8,F11.1)
      52      CONTINUE
      C
              IF(LT.NE.1)GOTO148
      C
              IDLA=DLD*1.05+.9999
              IF(IPR.EQ.1)PRINT45,LPST,DLD,IDLA
      45      FORMAT(10X,'TOTAL',26X,I8,F11.1,I7)
              IDLAT=IDLAT+IDLA
      C
      148     CONTINUE
      C
              GOTO132
      C
      141     CONTINUE
      C
              IDLATT=IDLAT
              IF(IPR.EQ.1)PRINT51,IDLATT
      51      FORMAT(/6X,'PROCESS TOTAL',41X,I7,/)
      C
              IF(LOOP.EQ.0)CALL CLOSEF(4)
              IF(LOOP.EQ.1)REWIND(4)
      C
              IPR=0
      C
      C  *** TABLE 4 ***********************************************
      C  *****************************************
      C
              IF((TABLE.EQ.4).OR.(TABLE.EQ.9))IPR=1
      C
              IF(IPR.NE.1)GOTO77
      C
              IF(IPTR.EQ.1)PRINT5
              CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLP)
      C
              IF(IPR.EQ.1)PRINT78
      78      FORMAT(/,27X,'IND EQPT',14X,'PROCESS STEP')
              IF(IPR.EQ.1)PRINT79
      79      FORMAT(25X,'FACILITY REQ',12X,'FACILITY REQ')
              IF(IPR.EQ.1)PRINT80
      80      FORMAT(/,24X,'PWR  VENT  WTR    #',
             &'    PWR   VENT   WTR  MACH  EQPT')
              IF(IPR.EQ.1)PRINT81
      81      FORMAT(6X,'PROCESS STEP',6X,'KW    CFM    GPM    MACH',
             &'  KW     CFM      GPM   EFF    UTLZ',/)
      C
      77      CONTINUE
      C
              TKW=0
              TCFM=0
              TGPM=0
      C
              DO82J1=1,NPS
      C
              K=PN(J1)
              I4=A(K,4)
      C
              B(J1,15)=B(J1,7)/B(J1,8)
              B(J1,20)=A(K,7)
              B(J1,21)=A(K,8)
              B(J1,22)=A(K,9)
```

```
      B(J1,23)=B(J1,8)
      B(J1,24)=B(J1,8)*A(K,7)*A(K,2)
      IF(A(K,14).EQ.1)B(J1,24)=B(J1,24)*B(J1,15)*.616
      B(J1,25)=B(J1,8)*A(K,8)*A(K,2)
      B(J1,26)=B(J1,8)*A(K,9)*A(K,2)
      IF(A(K,14).EQ.1)B(J1,26)=B(J1,26)*B(J1,15)
      B(J1,27)=A(K,2)
      B(J1,28)=B(J1,15)
C
      IF(I4.GE.0)GOTO83
C
      NCM=B(J1,8)/4
      FM=B(J1,8)/4-NCM
      NTM=B(J1,8)/4+.9999
      C1=1.1
      C2=.5
      IF(I4.EQ.-3)C2=.25
      B(J1,20)=C1+4*C2
      IF(I4.EQ.-4)B(J1,20)=140
      B(J1,24)=NCM*B(J1,20)
      IF(FM.GT.0)B(J1,24)=B(J1,24)+4*FM*C2+C1
      B(J1,21)=480
      IF(I4.EQ.-3)B(J1,21)=320
      IF(I4.EQ.-3)B(J1,22)=3.2
      B(J1,25)=B(J1,8)*120*A(K,2)
      IF(I4.EQ.-3)B(J1,25)=B(J1,8)*80*A(K,2)
      IF(I4.EQ.-3)B(J1,26)=.8*B(J1,8)
C
      IF(I4.NE.-4)GOTO84
      B(J1,21)=125
      B(J1,24)=B(J1,8)/NTU*TDP*A(K,2)
      B(J1,25)=B(J1,8)/NTU*TDEX*A(K,2)
84    CONTINUE
C
C
83    CONTINUE
C
      TKW=TKW+B(J1,24)
      TCFM=TCFM+B(J1,25)
      TGPM=TGPM+B(J1,26)
C
82    CONTINUE
C
      DO85J1=1,NPS
      K=PN(J1)
      IF(IPR.EQ.1)PRINT86,(PD(K,J2),J2=1,4),(B(J1,J2),J2=20,27)
     &,100*B(J1,28)
86    FORMAT(6X,4A4,I5,I6,F6.1,I5,I7,I7,I4,F6.2,F7.1)
85    CONTINUE
C
      IF(IPR.EQ.1)PRINT87,TKW,TCFM,TGPM
87    FORMAT(10X,'TOTAL',30X,I6,I7,I4)
C
      IPP=0
C
C *** TABLE 5 ***************************************************
C **************************************************
C
      IF((TABLE.EQ.5).OR.(TABLE.EQ.9))IPR=1
C
      IF(IPR.NE.1)GOTO88
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      PRINT137,PSC,PWRR
137   FORMAT(9X,'SILICON = $',F5.2,'/KILOGRAM',
     &8X,'POWER RATE =',F5.1,' CENTS/KWH')
      PRINT138
138   FORMAT(/,27X,'EXPENSE & MATERIAL ITEMS',/)
      PRINT90
90    FORMAT(25X,'PROCESS    ELECT      WATER',
     &5X,'TOTAL        MATL')
      PRINT91
91    FORMAT(6X,'PROCESS STEP',7X,'EXP(K$)    EXP(K$)',
     &3X,'EXP(K$)    EXP(K$)    (K$)',/)
C
88    CONTINUE
C
      IRR=0
```

```
      TEL=0
      TWA=0
      TEXP=0
      TMTL=0
C
      AREA=WPC/(SUNS*CEFF)*1000
      READ(2,400)SKERF
      READ(2,400)SIKG
      WPX=SIKG*1000/(AREA*(SKERF+PST)*2.33)
C
      DO92J1=1,NPS
C
      K=PN(J1)
      I4=A(K,4)
C
      SIL=0
      IF(A(K,13).LT.0)READ(2,400)SIL
C
      B(J1,29)=B(J1,3)*A(K,10)*5400/1000+
     *B(J1,8)*A(K,11)+B(J1,8)*A(K,12)*B(J1,15)*B(J1,4)
      IF(K.LT.4)B(J1,29)=B(J1,3)*A(K,10)*5400/WPX+
     &B(J1,8)*A(K,11)+B(J1,8)*A(K,12)*B(J1,15)*B(J1,4)
      B(J1,29)=B(J1,29)/1000
      IF(K.LT.4)B(J1,29)=B(J1,29)+SIL/WPX*PSC*B(J1,3)*5400/1000
      IF(K.EQ.4)B(J1,29)=B(J1,29)+AREA*SKERF*2.33*PSC/1000*
     &B(J1,3)*5400/1000
      IF(K.EQ.59)B(J1,29)=B(J1,29)+B(J1,3)*5400/1000*SIL*PST*
     *PSC*15.351/1000
      B(J1,30)=B(J1,24)/8+B(J1,25)*15/1000
      B(J1,30)=B(J1,30)*.4+B(J1,25)*.46/1000+B(J1,24)*.5
      B(J1,30)=B(J1,30)*PWRR/100*8766/1000
      B(J1,31)=B(J1,26)*60*5400*.0031/1000
      B(J1,32)=B(J1,29)+B(J1,30)+B(J1,31)
      IF(A(K,13).GE.0)B(J1,33)=B(J1,3)*A(K,13)/1000*5400/1000
      IF(K.EQ.4)B(J1,33)=AREA*PST*2.33*PSC*B(J1,3)*5400/1E6
      IF(K.EQ.59)B(J1,33)=B(J1,3)*5400/1000*SIL*PST*PSC*11.2562/1000
      IF(K.EQ.60)B(J1,33)=B(J1,3)*5400/1000*SIL*PST*PSC*14.1198/1000
      IF(K.EQ.61)B(J1,33)=B(J1,3)*5400/1000*SIL*PST*PSC*7.003/1000
C
      TPR=TPR+B(J1,29)
      TEL=TEL+B(J1,30)
      TWA=TWA+B(J1,31)
      TEXP=TEXP+B(J1,32)
      TMTL=TMTL+B(J1,33)
C
92    CONTINUE
      IF(LOOP.EQ.0)CALL CLOSEF(2)
      IF(LOOP.EQ.1)REWIND(2)
C
      DO93J1=1,NPS
      K=PN(J1)
      IF(IPR.EQ.1)PRINT94,(PD(K,J2),J2=1,4),(B(J1,J2),J2=29,33)
94    FORMAT(6X,4A4,F8.1,F9.1,F10.1,F12.1,F9.1)
93    CONTINUE
C
      IF(IPR.EQ.1)PRINT95,TPR,TEL,TWA,TEXP,TMTL
95    FORMAT(/,10X,'TOTAL',F15.1,F9.1,F10.1,F12.1,F9.1)
C
      TPF=0
C
C *** TABLE 6 ******************************************
C *******************************************
C
      IF((TABLE.EQ.6).OR.(TABLE.EQ.9))IPR=1
C
      CALL OPENF(1,'CC',2)
C
      DO107J1=1,18
      READ(1,16)(OC(J1,J2),J2=1,4)
      OCT(J1)=0
107   CONTINUE
      CALL CLOSEF(1)
C
      DO100NPH=1,4
C
      IF(NPH.EQ.1)CALL OPENF(1,'OD1',2)
      IF(NPH.EQ.2)CALL OPENF(1,'OD2',2)
      IF(NPH.EQ.3)CALL OPENF(1,'OD3',2)
      IF(NPH.EQ.4)CALL OPENF(1,'OD4',2)
C
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      IF(IPR.NE.1)GOTO96
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      PRINT139,IDLATT,PWRR
139   FORMAT(9X,'DIRECT LABOR CENSUS =',I5,7X,
     &'POWER RATE =',F5.1,' CENTS/KWH')
      PRINT97,NPH,NMPH(NPH)
97    FORMAT(/,20X,'OVERHEAD (K$)',5X,'PHASE ',I1,' = ',I2,' MONTHS')
      PRINT98
98    FORMAT(/,20X,'CENSUS  PAYROLL  FRINGE   EXP',
     &4X,'DEP',4X,'MAT   COM',5X,'TOTAL',/)
C
96    CONTINUE
C
      DO99J2=1,8
      CT(NPH,J2)=0
99    CONTINUE
C
      DO101J1=1,18
C
      READ(1,400)(C(NPH,J1,J2),J2=1,8)
C
      DO102J2=1,7
C
      IF(C(NPH,J1,J2).EQ.-1)C(NPH,J1,J2)=8.796*TSQFT/.49/1000
      IF(C(NPH,J1,J2).EQ.-2)IT1=(IDLAT/2+IDLAT/NMPH(3))/15+.9999
      IF(C(NPH,J1,J2).EQ.-2)IT2=(IDLA/2+IDLA/NMPH(3))/25+.9999
      IF(C(NPH,J1,J2).EQ.-2)C(NPH,J1,J2)=3*IT1+3*IT2+3
      IF(C(NPH,J1,J2).EQ.-3)C(NPH,J1,J2)=(C(NPH,J1,1)-3)*14.5+3*18.5
      IF(C(NPH,J1,J2).EQ.-4)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-5)IT1=WPY/5E6+.9999
      IF(C(NPH,J1,J2).EQ.-5)C(NPH,J1,J2)=IT1+10
      IF(C(NPH,J1,J2).EQ.-6)C(NPH,J1,J2)=158.4+11.2*(IT1-1)
      IF(C(NPH,J1,J2).EQ.-7)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-8)C(NPH,J1,J2)=C(NPH,J1,2)*.1*12/NMPH(NPH)
      IF(C(NPH,J1,J2).EQ.-9)IT1=TSQFT/.49/1000*.118+.9999
      IF(C(NPH,J1,J2).EQ.-9)C(NPH,J1,J2)=IT1
      IF(C(NPH,J1,J2).EQ.-10)C(NPH,J1,J2)=C(NPH,J1,1)*11.2
      IF(C(NPH,J1,J2).EQ.-11)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-12)C(NPH,J1,J2)=8.796*TSQFT/.49/1000
      IF(C(NPH,J1,J2).EQ.-13)C(NPH,J1,J2)=NMM+NMS+1
      IF(C(NPH,J1,J2).EQ.-14)C(NPH,J1,J2)=NMM*17+NMS*23+30
      IF(C(NPH,J1,J2).EQ.-15)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-16)C(NPH,J1,J2)=NMM[illegible]5
      IF(C(NPH,J1,J2).EQ.-17)C(NPH,J1,J2)=(C(NPH,J1,2)+
     &C(NPH,J1,3)+C(NPH,J1,4))/3*12/NMPH(NPH)
      IF(C(NPH,J1,J2).EQ.-18)IT1=WPY/1E7+.9999
      IF(C(NPH,J1,J2).EQ.-18)C(NPH,J1,J2)=IT1+1
      IF(C(NPH,J1,J2).EQ.-19)C(NPH,J1,J2)=36.4+26*(IT1-1)
      IF(C(NPH,J1,J2).EQ.-20)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-21)C(NPH,J1,J2)=C(NPH,J1,2)*.1*12/NMPH(NPH)
      IF(C(NPH,J1,J2).EQ.-22)IT1=IDLAT/15+.9999
      IF(C(NPH,J1,J2).EQ.-22)IT2=IDLA/25+.9999
      IF(C(NPH,J1,J2).EQ.-22)C(NPH,J1,J2)=3*IT1+3*IT2+3
      IF(C(NPH,J1,J2).EQ.-23)C(NPH,J1,J2)=(C(NPH,J1,1)-3)*14.5+3*18.5
      IF(C(NPH,J1,J2).EQ.-24)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-25)IT=WPY/5E6+.9999
      IF(C(NPH,J1,J2).EQ.-25)C(NPH,J1,J2)=IT
      IF(C(NPH,J1,J2).EQ.-26)C(NPH,J1,J2)=C(NPH,J1,1)*10.9
      IF(C(NPH,J1,J2).EQ.-27)C(NPH,J1,J2)=C(NPH,J1,1)*3.1
      IF(C(NPH,J1,J2).EQ.-28)C(NPH,J1,J2)=C(NPH,J1,1)*.1
      IF(C(NPH,J1,J2).EQ.-29)C(NPH,J1,J2)=C(NPH,J1,1)*.2
C
      IF(J2.NE.1)C(NPH,J1,J2)=C(NPH,J1,J2)*NMPH(NPH)/12
      IF(J2.NE.1)C(NPH,J1,8)=C(NPH,J1,8)+C(NPH,J1,J2)
C
102   CONTINUE
C
      DO106J2=1,8
      CT(NPH,J2)=CT(NPH,J2)+C(NPH,J1,J2)
106   CONTINUE
C
      IF(IPR.EQ.1)PRINT104,(OC(J1,J2),J2=1,4),(C(NPH,J1,J2),J2=1,8)
104   FORMAT(6X,4A4,I3,F10.1,2F8.1,2F7.1,F6.1,F9.1)
C
      OCT(J1)=OCT(J1)+C(NPH,J1,8)
101   CONTINUE
C
```

```
      CALL CLOSEF(1)
C
      IF(IPR.EQ.1)PRINT105,(CT(NPH,J2),J2=1,8)
  105 FORMAT(/,10X,'TOTAL',I10,F10.1,2F8.1,2F7.1,F6.1,F9.1)
C
      D(NPH,4)=CT(NPH,8)
C
  100 CONTINUE
C
C
      IPR=0
C
C *** TABLE 7 ****************************************************
C *********************************************
C
      IF((TABLE.EQ.7).OR.(TABLE.EQ.9))IPR=1
C
      IF(IPR.NE.1)GOTO108
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLP)
C
      PRINT89,PSC,PWRR
   89 FORMAT(8X,'SILICON = $',F5.2,'/KILOGRAM',
     &8X,'POWER RATE =',F5.1,' CENTS/KWH')
      PRINT109,3*IDLATT,AINT
  109 FORMAT(9X,'DIRECT LABOR CENSUS =',I5,12X,
     &'INTEREST RATE =',F5.1,' %')
      PRINT140
  140 FORMAT(/,33X,'SUMMARY (K$)',/)
      PRINT110
  110 FORMAT(/,6X,'FACTORY LIFE',7X,'MAT',4X,'EXP',4X,'LAB',4X,
     &'OVR',4X,'INT',4X,'DEP',3X,'TOTAL')
C
  108 CONTINUE
C
      D(2,2)=TEL*.1*NMPH(2)/12
      D(2,6)=TSQFT*177.24/1000*NMPH(2)/12/40
      D(3,1)=TMTL/2*NMPH(3)/12
      D(3,2)=TEXP/2*NMPH(3)/12
      IT=IDLATT/2+IDLATT/NMPH(3)+.9999
      D(3,3)=3*IT*1.8*DLR*1.03*NMPH(3)/12
      D(3,6)=TSQFT*177.24/1000*NMPH(3)/12/40
     &+TTKD/(.5*NMPH(3)/12+NMPH(4)/12)*NMPH(3)/12
      D(4,1)=TMTL*NMPH(4)/12
      D(4,2)=TEXP*NMPH(4)/12
      D(4,3)=3*IDLATT*1.8*DLR*1.03*NMPH(4)/12
      AMT1=D(1,4)+TSQFT*184.04/1000
      AMT2=D(2,2)+D(2,4)+TTKD
      AMT3=D(3,1)+D(3,2)+D(3,3)+D(3,4)
      DEBT1=AMT1+AMT1/2*AINT/100*NMPH(1)/12
      DEBT2=DEBT1+AMT2+AINT/100*NMPH(2)/12*(AMT2/2+DEBT1)
      DEBT3=DEBT2+AMT3+AINT/100*NMPH(3)/12*(AMT3/2+DEBT2)
      PMT=DEBT3*(AINT/100/(1-(1/(1+AINT/100))**(NMPH(4)/12)))
      D(1,5)=DEBT1-AMT1
      D(2,5)=DEBT2-(DEBT1+AMT2)
      D(3,5)=DEBT3-(DEBT2+AMT3)
      D(4,5)=PMT*NMPH(4)/12-DEBT3
      D(4,6)=TSQFT*177.24/1000*NMPH(4)/12/40+
     $TTKD/(.5*NMPH(3)/12+NMPH(4)/12)*NMPH(4)/12
C
      DO111NPH=1,4
C
      DO112J2=1,6
C
      D(NPH,7)=D(NPH,7)+D(NPH,J2)
      D(5,J2)=D(5,J2)+D(NPH,J2)
C
  112 CONTINUE
C
      D(5,7)=D(5,7)+D(NPH,7)
C
      IF(IPR.EQ.1)PRINT113,NPH,NMPH(NPH),(D(NPH,J2)+.5,J2=1,7)
  113 FORMAT(/,6X,'PHASE',I2,I4,' MO',I8,5I7,I8)
C
  111 CONTINUE
C
      IF(IPR.EQ.1)PRINT114,(D(5,J2)+.5,J2=1,7)
  114 FORMAT(/,10X,'TOTAL COST',I9,5I7,I8)
C
```

```
      IF(IPR.EQ.1)PRINT115,(D(5,J2)/
     &((NMPH(4)/12+.25*NMPH(3)/12)*WPY)*1000,J2=1,7)
  115 FORMAT(/,8X,'TOTAL   $/WATT',6F7.4,F8.4)
C
      IF(IPR.EQ.1)PRINT116,(D(5,J2)/D(5,7)*100,J2=1,6)
  116 FORMAT(/,12X,'%',11X,F4.1,5F7.1,3X,'100.0')
C
      IPR=0
C
C *** TABLE 8 ***************************************************
C ******************************************
C
      IF((TABLE.EQ.8).OR.(TABLE.EQ.9))IPR=1
C
      IF(IPR.NE.1)GOTO157
C
      IF(IPTR.EQ.1)PRINT5
      CALL HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
C
      PRINT165,PSC,PWRR
  165 FORMAT(9X,'SILICON = $',F6.2,'/KILOGRAM',
     &7X,'POWER RATE =',F5.1,' CENTS/KWH')
      PRINT166,3*TDLATT,AINT
  166 FORMAT(9X,'DIRECT LABOR CENSUS =',I5,12X,
     &'INTEREST RATE =',F5.1,' %')
      PRINT167
  167 FORMAT(/,24X,'PROCESS STEP SUMMARY ($/WATT)',/)
      PRINT158
  158 FORMAT(/,6X,'PROCESS STEP',8X,'MAT',5X,'EXP',5X,'LAB',
     &5X,'OVR',5X,'INT',5X,'DEP',4X,'TOTAL',/)
  157 CONTINUE
C
      DO164J2=34,40
      T(J2)=0
  164 CONTINUE
C
      DO162J1=1,NPS
      B(J1,34)=B(J1,33)*NMPH(4)/12+B(J1,33)/2*NMPH(3)/12
      B(J1,35)=B(J1,32)*NMPH(4)/12+B(J1,32)/2*NMPH(3)/12
      B(J1,35)=B(J1,35)+B(J1,30)*.1*NMPH(2)/12
      B(J1,36)=B(J1,18)/TDLD*(D(3,3)+D(4,3))
      B(J1,37)=(OCT(1)+OCT(6)+OCT(12)+OCT(14)+OCT(17))*B(J1,18)/
     &TDLD+(OCT(2)+OCT(3)+OCT(7)+OCT(8)+OCT(9)+OCT(10)+
     &OCT(11)+OCT(13)+OCT(15)+OCT(16)+OCT(18))/NPS+OCT(4)*B(J1,14)/
     &TSQFT+OCT(5)*PSMM(J1)/NMM
      T1=B(J1,37)*D(1,4)/D(5,4)+B(J1,14)*184.04/1000
      T2=B(J1,35)*D(2,2)/D(5,2)+B(J1,37)*D(2,4)/D(5,4)+B(J1,10)
      T3=B(J1,34)*D(3,1)/D(5,1)+B(J1,35)*D(3,2)/D(5,2)+B(J1,36)*
     &D(3,3)/D(5,3)+B(J1,37)*D(3,4)/D(5,4)
      DPS1=T1+T1/2*AINT/100*NMPH(1)/12
      DPS2=DPS1+T2+AINT/100*NMPH(2)/12*(T2/2+DPS1)
      DPS3=DPS2+T3+AINT/100*NMPH(3)/12*(T3/2+DPS2)
      PPS=DPS3*(AINT/100/(1-(1/(1+AINT/100))**(NMPH(4)/12)))
      T4=DPS1-T1
      T5=DPS2-(DPS1+T2)
      T6=DPS3-(DPS2+T3)
      T7=PPS*NMPH(4)/12-DPS3
      B(J1,38)=T4+T5+T6+T7
      B(J1,39)=B(J1,14)*177.24/1000*NMPH(2)/12/40+B(J1,14)*
     &177.24/1000*NMPH(3)/12/40+B(J1,10)/(.5*NMPH(3)/12+NMPH(4)/
     &12)*NMPH(3)/12+B(J1,14)*177.24/1000*NMPH(4)/12/40+B(J1,10)/
     &(.5*NMPH(3)/12+NMPH(4)/12)*NMPH(4)/12
      B(J1,40)=B(J1,34)+B(J1,35)+B(J1,36)+B(J1,37)+B(J1,38)+B(J1,39)
C
      DO163J2=34,40
      T(J2)=T(J2)+B(J1,J2)
  163 CONTINUE
C
  162 CONTINUE
C
      DO159J1=1,NPS
      K=PN(J1)
      VOLUME=1000/((NMPH(4)/12+.25*NMPH(3)/12)*WPY)
      IF(IPR.EQ.1)PRINT160,(PD(K,J2),J2=1,4),
     &(B(J1,J2)*VOLUME,J2=34,40)
  160 FORMAT(6X,4A4,6F8.4,F9.4)
  159 CONTINUE
C
      IF(IPR.EQ.1)PRINT161,(T(J2)*VOLUME,J2=34,40)
  161 FORMAT(/,14X,'TOTAL',7X,6F8.4,F9.4)
```

```
C
      IF(IFILE.EQ.1)CALL ANALYSIS1(IAN,WPY,CEFF,SUNS,PSC,NMPH,AINT,
     &PWPR,DLR,PST,A,B,C,D)
C
      IPR=0
C
      IF(IFILE.EQ.0)PRINT20
      IF(IFILE.NE.0)GOTO121
C
  121 CONTINUE
C
C ************************************************
C
      PRINT20
   20 FORMAT(7/)
C
C ************************************************************
      CALL CLOSEF(108,2)
      STOP
      END
C
C ************************************************************
C
      SUBROUTINE HEADING(NAME1,DIM1,WPY,CEFF,SUNS,PST,DLR)
      INTEGER NAME1(16),DIM1(8)
C
      PRINT20
   20 FORMAT(7/)
      DO2J=16,1,-1
      IF(NAME1(J).NE.1H )GOTO3
    2 CONTINUE
C
    3 CONTINUE
      DO4K=8,1,-1
      IF(DIM1(K).NE.1H )GOTO5
    4 CONTINUE
C
    5 CONTINUE
      J=J+10
      K=51-K
      PRINT6,NAME1,J,K,DIM1
    6 FORMAT(9X,16A1,TN,' PROCESS',TN,8A1,T51,' CELL CONFIGURATION')
C
      PRINT21,WPY/1000000,CEFF
   21 FORMAT(6X,F7.1,' MEGA WATT ANNUAL PRODUCTION',F10.2,
     &' % CELL EFFICIENCY')
C
      PRINT156,SUNS
  156 FORMAT(14X,'SOLAR CONCENTRATION = ',I4,' SOLAR CONSTANTS')
C
      PRINT189,PST*1E4+.5
  189 FORMAT(12X,'SUBSTRATE(PRE-ETCH)THICKNESS =',I4,' MICRONS')
C
      PRINT193,DLR
  193 FORMAT(23X,'DIRECT LABOR RATE = $',F5.2,'/HOUR')
C
      RETURN
C
C ************************************************************
C ************************************************************
      END
```

**ORIGINAL PAGE IS
OF POOR QUALITY**

> SIMSCRIPT is based upon the notion that the state of a system can bo described as entities (the things or objects of which the system is composed), attributes (properties associated with entities), and sets (groups of entities). The user is asked to specify all entities explicitly with a complete list of their attributes and possible set memberships, as the first step in developing a simulation model.

Most users of SAMIS do not have an in-house SIMSCRIPT computing capability and are thus required to obtain an account with National CSS, Inc., a nation-wide timeshare computer service. The JPL-SAMIS program is contained on this system and can be copied into the user's account. This copying process encompasses a number of files which contain elements of the simulations to be performed as well as routines for scheduling and running the program. Among this list of required files are seven data files. A limited description of each follows.

The largest of the required files is known as the -EXPENSE DATA file. This file contains each of the cost account items used in a simulation. Contained in this -EXPENSE DATA file are a catalog listing of Facilities, Personnel, Utilities, Byproducts, Commodities, and Resources. Information contained in this file for each of the elements (entities) within each of these categories includes a description of the entity, a cost versus quantity table for a given cost year, an inflation rate figure, and a listing of each of the requirements that any particular entity may have. For example, fork lifts require fork lift operators and fuel oil. This file as copied from SAMIS contains in excess of 5000 listings; however, users may find that one or more entity required for their process may not exist in the -EXPENSE DATA file and that additional information must be added to it. SAMIS provides a mechanism to do this; however, when these new entities are added, the entire file must be loaded into core in order to assure that the new entity is unique -- a very costly process. Moreover, each time a simulation is performed, the entire -EXPENSE DATA file must be loaded into core even though most of the commodities are not selected by the program. An example of the cost of loading the -EXPENSE DATA file is illustrated by a session in which JPLSAMIS was attached and ten expense items were created and saved as a group, resulting in a cost of more than $150.

Another large file required by SAMIS is the -PROCESS DATA file. This file contains a description of each of the requirements (attributes) of an individual process step. Any number of process steps may be contained in this file with no fewer than 35 attributes per process step. This file contains the information that is entered on the JPL Format A. The cost of building and saving this information is somewhat less than that for the cost account catalog data. Two examples illustrate this lower cost. In the first example the following steps were performed.

```
     LOGIN
     LINK SUNY
     SET CORE 1280
     ATTACH JPLSAMIS AS X
     CREATE (1) PROCESS
     DISPLAY ALL
     SAVE PROCESS
     STOP
     LOGOUT
```

This procedure resulted in the use of 100 ARU'S (an ARU is a unit of computer resources used during a terminal session) at $0.20 per ARU plus 0.12 connect hours at $15 per connect hour or a total cost of $21.80. The second example is much the same as the first; however, sixteen processes were created and saved as a group resulting in the use of 238.3 ARU'S and 1.77 connect hours or $74.21. This would suggest that much of the cost is associated with attaching JPLSAMIS and that entities should be created duirng a single session and saved as a group rather than individually.

Two additional files which define the nature of a users simulation are called -COMPANY DATA and -INDUSTRY DATA. These files represent the information contained on the JPL Format B and Format C forms respectively. As a part of the -COMPANY DATA file, which contains 48 individual attributes, an ordered listing of the processes used in the process sequence is entered. This list provides a mechanism by which the program can read and place in order the information contained in the -PROCESS DATA file. The -INDUSTRY DATA file, which contains only ten attributes, identifies the product performance and ties together companies within the industry if more than one is used.

The remaining data files are called -RUN DATA, -STANDARD DATA, and -COMMAND DATA. The -RUN DATA file contains 20 attributes which are designed to specify the size of the industry and to determine the reports that a simulation will generate and the mode and format by which they will be printed. The -STANDARD DATA file contains 85 attributes, most of which deal with accounting procedures. In addition, this file contains such information as the manufacturing year, number of shifts, calendar information, and work hour information. The -COMMAND DATA file is a short file which contains the instructions that a user would type in to initialize a simulation in the terminal mode. These instructions are used for an off-line print simulation only, and simply replace those instructions that the user would have typed in had the simulation been of the immediate type.

In addition to the data files that are described above, five executive files must be copied from JPLSAMIS. These files are:

DEMAND EXEC
BATCH EXEC
SCHUDLE EXEC
RUNB EXEC
OFFP EXEC

These files are required to perform simulations, particularily in the offline mode. Some modification is required in order to assure the user that the run is done in the desired mode and that results of the simulation are routed to the user's nearest NCSS printer.

During the process of building these several files, the user will most likely enter some information which is incorrect and will require editing. The editing process represents one of the more difficult and time consuming elements of operating the JPLSAMIS program. First time or infrequent users of JPLSAMIS find that during the process of editing a file, it is not necessarily apparent whether the section to be edited requires a high-level manipulation command or a low-level manipulation command. The syntax is different for each and the user may occasionally find himself in a situation in which the correct entry is not obvious. Continued entry of incorrect commands will result in the disconnecting of JPLSAMIS and the subsequent loss of all information entered (and not previously saved) during the session. When this occurs, JPLSAMIS must be re-connected and all of the information lost must be re-entered. Close examination of the users guide shows that, in some cases, examples of recovery from some types of errors are not listed. Moreover, those examples which are contained in the users guide are spread throughout the text in such a way that they are difficult to locate. It is suggested that the JPLSAMIS users guide contain a centrally located table of appropriate commands in addition to a more complete indexing of their location within the text.

As can be seen from this list of required files, a significant amount of user preparation is required in order to use SAMIS (at a computing cost of several hundreds of dollars for the preparation alone.) Additionally, once these files are established they are usually maintained in the users account for possible future use. Storage costs are in the vicinity of $180 per month.

C-3

A detailed breakdown of the cost of performing a SAMIS simulation are contained in the following two tables. These tables represent a billing from NCSS for a period in which each of the files required for a simulation was prepared and an offline simulation was performed. Table 4.18 shows a breakdown of the connect, core, and ARU charges for each record type used by the computer. Table 4.19 takes this information and rank orders it to highlight the cost drivers. As is readily seen, the ARU charges represent the most significant portion of the total cost, nearly 70%. Approximatley 90% of these ARU charges are directly attributable to use of the SIMSCRIPT language. It should be noted that charges associated with the use of the SIMSCRIPT language contain a surcharge and, in this example, represent a cost to the user of $346.

By comparison with the $2766.22 session charges in Table 4.18, the computing charges assigned to performing a similar simulation on the Motorola costing program are less than $50.

3.4.6.2 COMPARISON OF SAMIS AND SOLCOST TECHNIQUES

In many aspects, SAMIS and the Motorola computer costing methods are similar. For example, both require the creation of files which identify process steps and a process sequence as well as information which allocates indirect costs. The way in which allocation of indirect costs is performed is the area where SAMIS and Motorola differ the most. The primary difference here is that SAMIS approaches direct needs in a classical hierarchial way in which every function is related to every other function through a needs-implication structure. For example, the number of research engineers is based upon the total number of production personnel when in fact the number of production personnel has no direct bearing on the research function, particularily when evaluating a rapidly changing photovoltaic industry. The Motorola approach to indirect needs views

TABLE 4.18: COST BREAKDOWN OF SAMIS SIMULATION

RECORD TYPE	CONNECT			ADD CORE		ARU			OTHER CHARGES	SESSION CHARGES	NUMBER TIMES USED	SESSIO %
	HOURS	CHARGE	%	CHARGE	%	UNITS	CHARGE	%				
SET ACINFO	2.14	36.15	6.9	32.60	10.1	90.000	18.07	0.9	-	86.82	24	3.1
INTERACTIVE	13.93	210.50	40.4	263.84	82.1	796.815	159.89	8.3	-	634.23	20	22.9
SIM25 ACESS	14.54	-	-	-	-	8641.413	1730.02	90.1	-	1730.02	32	62.5
SCRATCH 20	17.02	255.30	49.0	-	-	-	-	-	-	255.30	41	9.2
BATCH 2	-	-	-	-	-	89.068	7.13	0.4	-	7.13	1	0.3
PRINT HNDLN	-	-	-	-	-	-	-	-	3.00	3.00	6	0.1
SET CORE	1.25	18.75	3.7	25.00	7.8	29.827	5.97	0.3	-	49.72	4	1.8
TOTAL		520.70	100.0	321.44	100.0		1921.08	100.0	3.00	2766.22		100.0
% OF TOTAL			18.8		11.6			69.5	0.1			100.0

SET ACINFO = IDENTIFIES EACH SESSION WITH RESPECT TO ANOTHER
INTERACTIVE = USER INTERACTION WITH NCSS OR SAMICS/SAMIS
SIM25 ACCES = ACCESS OF SAMICS PROGRAM
SCRATCH 20 = ATTACHES 20 CYLINDERS OF DISK ! 120K BYTES/CYL. FOR TEMPORARY SPACE
BATCH 2 = PRIORITY 2 (OVER NIGHT) OFFLINE PRINT
PRINT HNDLN = PAPER CHARGES FOR OFFLINE PRINT
SET CORE = SETS REAL MEMORY SPACE FOR USING SAMIS
ARU = APPLICATION RESOURCE UNIT

TABLE 4.19: SAMIS SIMULATION COST DRIVERS

RECORD TYPE	CHARGE	AMOUNT	%	UNITS	COST PER UNIT
SIM 25 ACCES	ARU	$1730.02	62.5	8641.413	@ $0.20/ARU
INTERACTIVE	CORE	263.84	9.5		
SCRATCH 20	CONNECT	255.30	9.2	17.02	@ $ 15/hour
INTERACTIVE	CONNECT	210.50	6.2	13.93	@ $ 15/hour
INTERACTIVE	ARU	159.89	5.8		
SET ACINFO	CONNECT	36.15	1.3		
SET ACINFO	CORE	32.60	1.2		
SET CORE	CORE	25.00	0.9		
SET CORE	CONNECT	18.75	0.7		
SET ACINFO	ARU	18.07	0.7		
BATCH 2	ARU	7.13	0.3		
SET CORE	ARU	5.97	0.2		
PRINT HNDLN	OTHER	3.00	0.1		
TOTAL		$2766.22	100.0		

CHARGE TYPE		
ARU	$1921.08	69.5
CONNECT	520.70	18.8
ADD CORE	321.44	11.6
OTHER	3.00	0.1
TOTAL	$2766.22	100.0

these needs as unique and perhaps unrelated to the manufacturing function. In fact, the Motorola approach uses the same approach that was used to identify direct needs to identify indirect needs. That is, the several functions required to operate a business were identified and some assumptions were made as to the minimum needs of the particular function as well as its relationship to other aspects of the factory. Table 4.20 illustrates the concept of varying different overhead categories in different ways. As can be seen in this table, most of the functions are constant, based on the assumption that both the product and customer bases are small. Those areas that do vary, vary in accordance with the function most nearly related to them.

Illustrations of the SAMIS approach are shown in the next several tables and figures. Table 4.21 shows the job functions that are implied by the number of production personnel. Figures 4.3a through 4.3d show the remaining implications of these indirect job functions as well as the direct personnel reporting structures. In these figures, 80 separate job functions, excluding secretaries, are implied. Figure 4.4 shows the complexity with which 137 separate entities are generated and related when floorspace is required from the Format A during a simulation. Included in this list are 43 facility entities, 74 personnel entities, 13 utility entities, 2 byproducts, 2 commodities, and 3 resources. A similar structure would be genrated when direct labor personnel are required. In addition, close examination of the chart shows that many of the entities imply themselves in an iterative way. Examples of this self implication process are shown in Figure 4.5. The number of interations conducted by the program are limited for this process so that the effect on cost of these iterations remains small.

TABLE 4.20: OVERHEAD CATEGORY DEPENDENCIES

	VARIES AS A FUNCTION OF:				
OVERHEAD	LABOR	FT^2	CONSTANT	VOLUME	EQPT.
DIRECT FACTORY	X				
ENGINEERING			X		
PRODUCTION CONTROL				X	
BUILDING SERVICES		X			
MAINTENANCE					X
MANAGEMENT			X		
MARKETING/SALES			X		
PURCHASING			X		
FINANCE			X		
SECRETARY POOL			X		
DATA PROCESSING			X		
TRAINING			X		
PERSONNEL				X	
CAFETERIA	BREAK-EVEN				
LEGAL			X		
NURSE			X		
Q.A.				X	

TABLE 4.21:

SAMIS RELATIONS OF OVERHEAD PERSONNEL TO PRODUCTION PERSONNEL

# OF B50501 (TOTAL PRODUCTION PERSONNEL		REFERENT	JOB DESCRIPTION
600		B10161	Administrative Assistant
600		B10321	Auditor
100		B.0481	General Clerk
600		B11121	Director Pub. Relations
100		B11281	Employment Interviewer
600		B12081	Lawyer
100		B12401	Mail Clerk
150		B13361	Nurse
50		B13521	Personnel Clerk
200		B14001	Receptionist
100		B14481	Training Supervisor
100		B20081	Accountant
100		B20321	Bookkeeper
300		B20801	Computer Operator
300		B21121	Keypunch Operator
300		B20961	Financial Analyst
100		B21441	Payroll Clerk
100		B21601	Procurement Clerk
500	5	B21761	Programmer
1000	1		
2000	1		
100		B22081	Purchasing Agent
500	.5	B22401	System Analyst
1000	1		
2000	1		
600		B22561	Treasurer
300		B3128B	Chemical Engineer
200		B31921	Mechanical Draftsman
200		B3208B	Electronics Engineer
*200	16.2	B32161	Engineering Aide
200		B3224B	Industrial Engineer
200		B3240B	Mechanical Engineer
200		B3256B	Production Planner
200		B3272B	Q.C. Engineer
100		B32881	Research Engineer
300		B33521	Production Supervisor Assistant

FIGURE 4.3A

SAMIS PERSONNEL CHART
(MANUFACTURING)

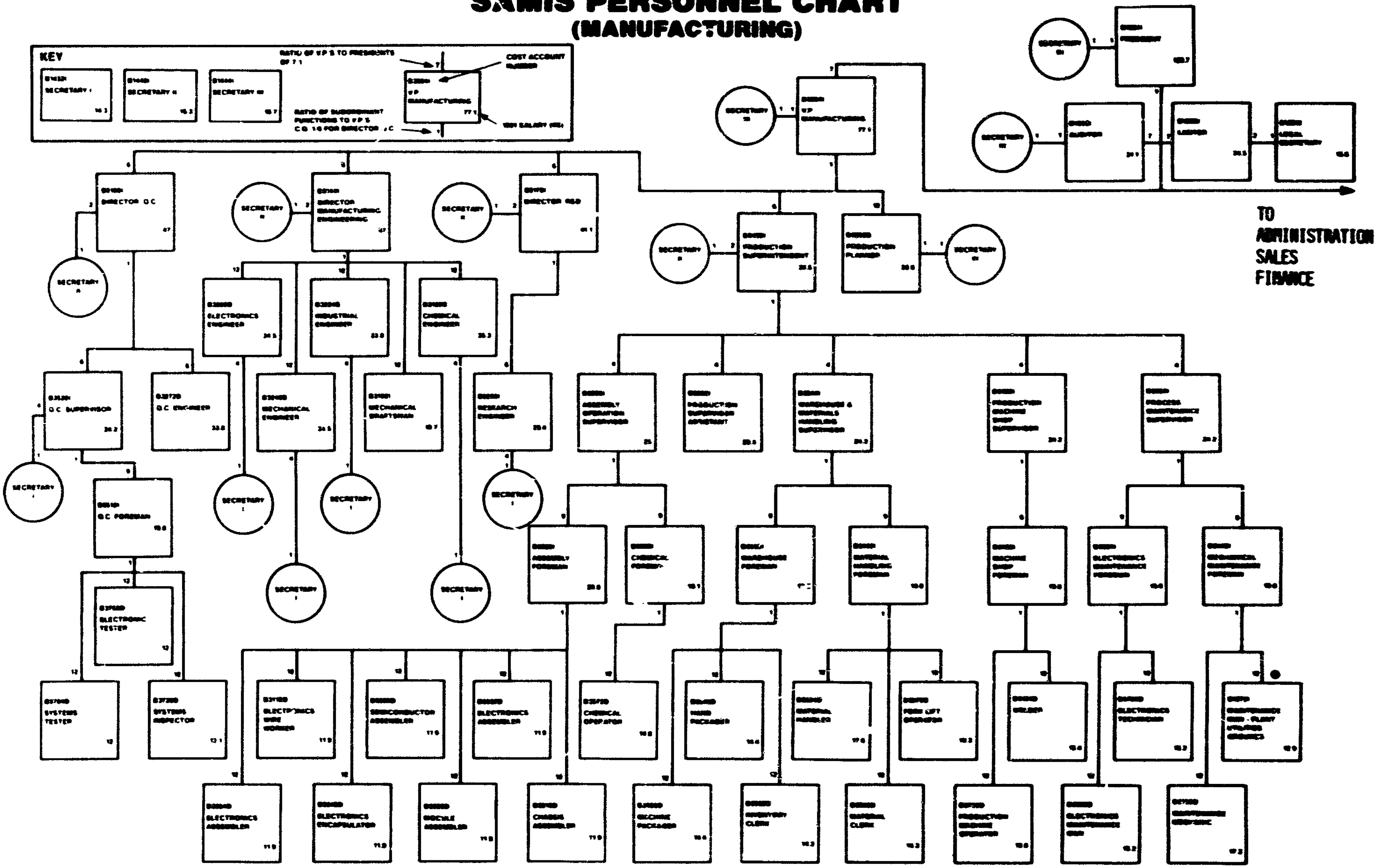


FIGURE 4.3B

SAMIS PERSONNEL CHART
(ADMINISTRATION)

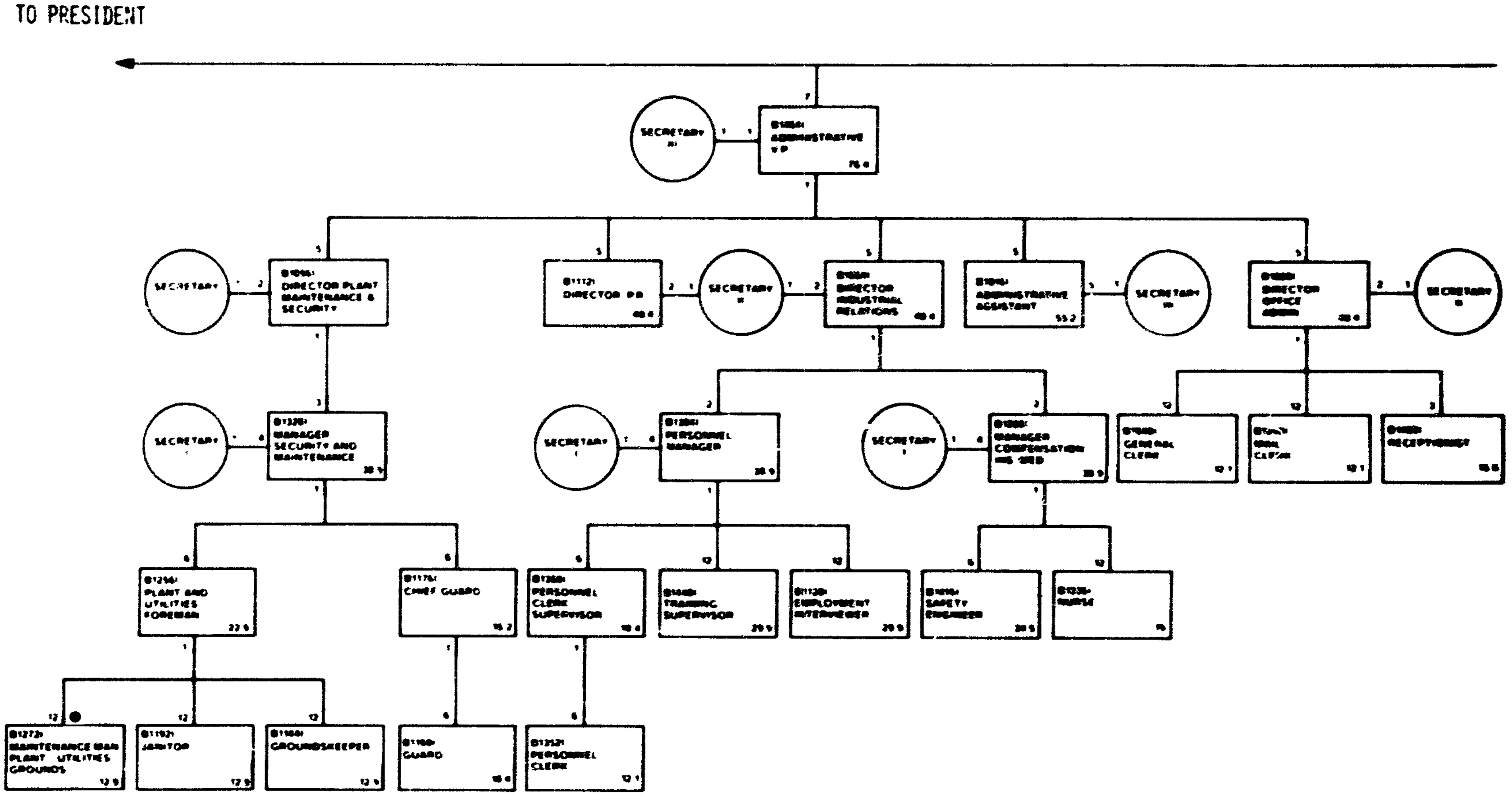


FIGURE 4.3c

SAMIS PERSONNEL CHART
(SALES)

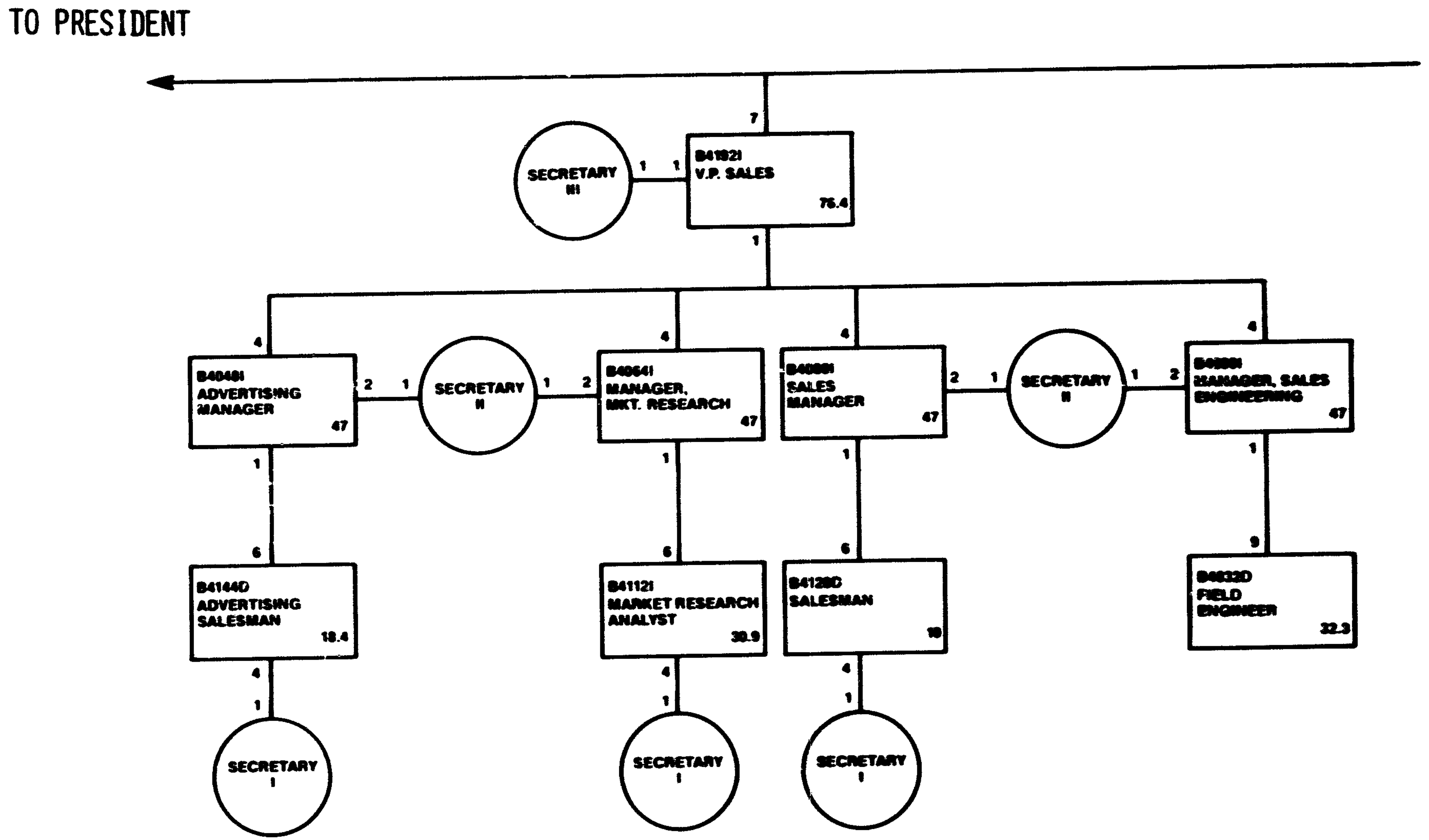


FIGURE 4.3D

SAMIS PERSONNEL CHART
(FINANCE)

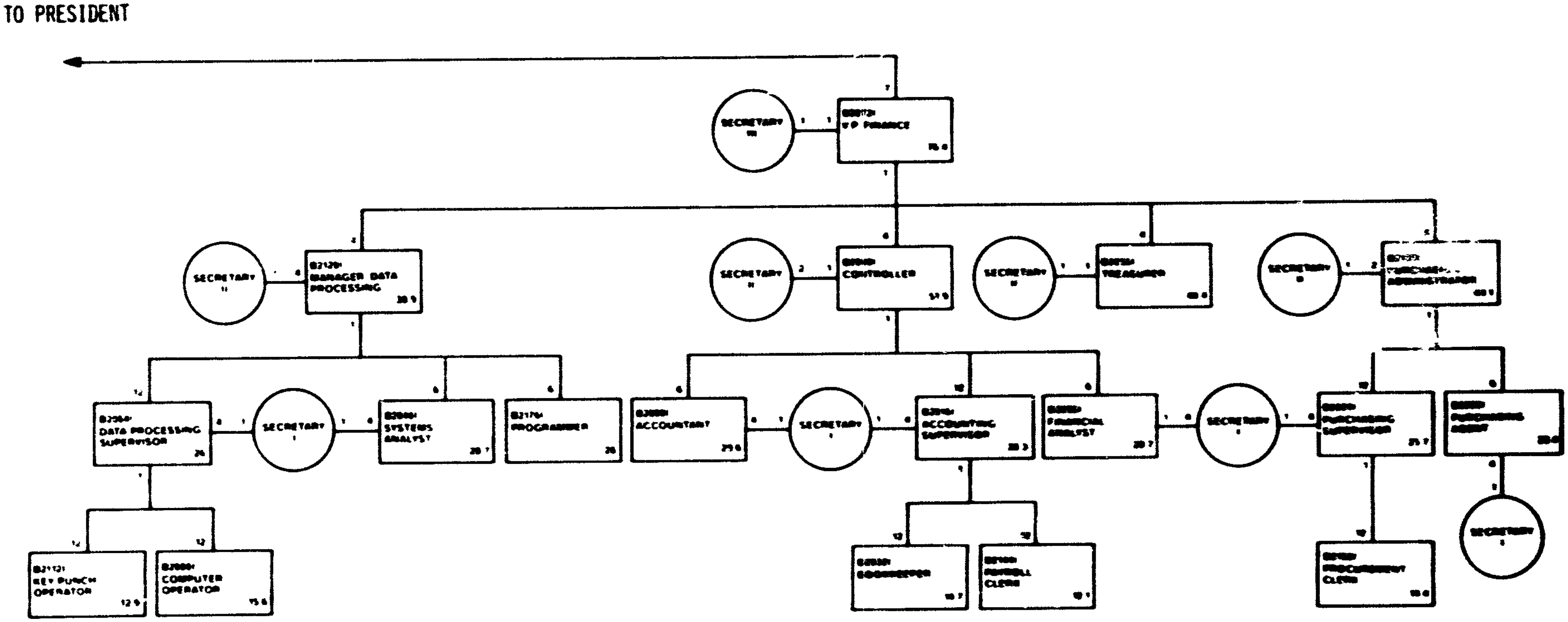


FIGURE 4 4

SAMIS IMPLICATION CHART

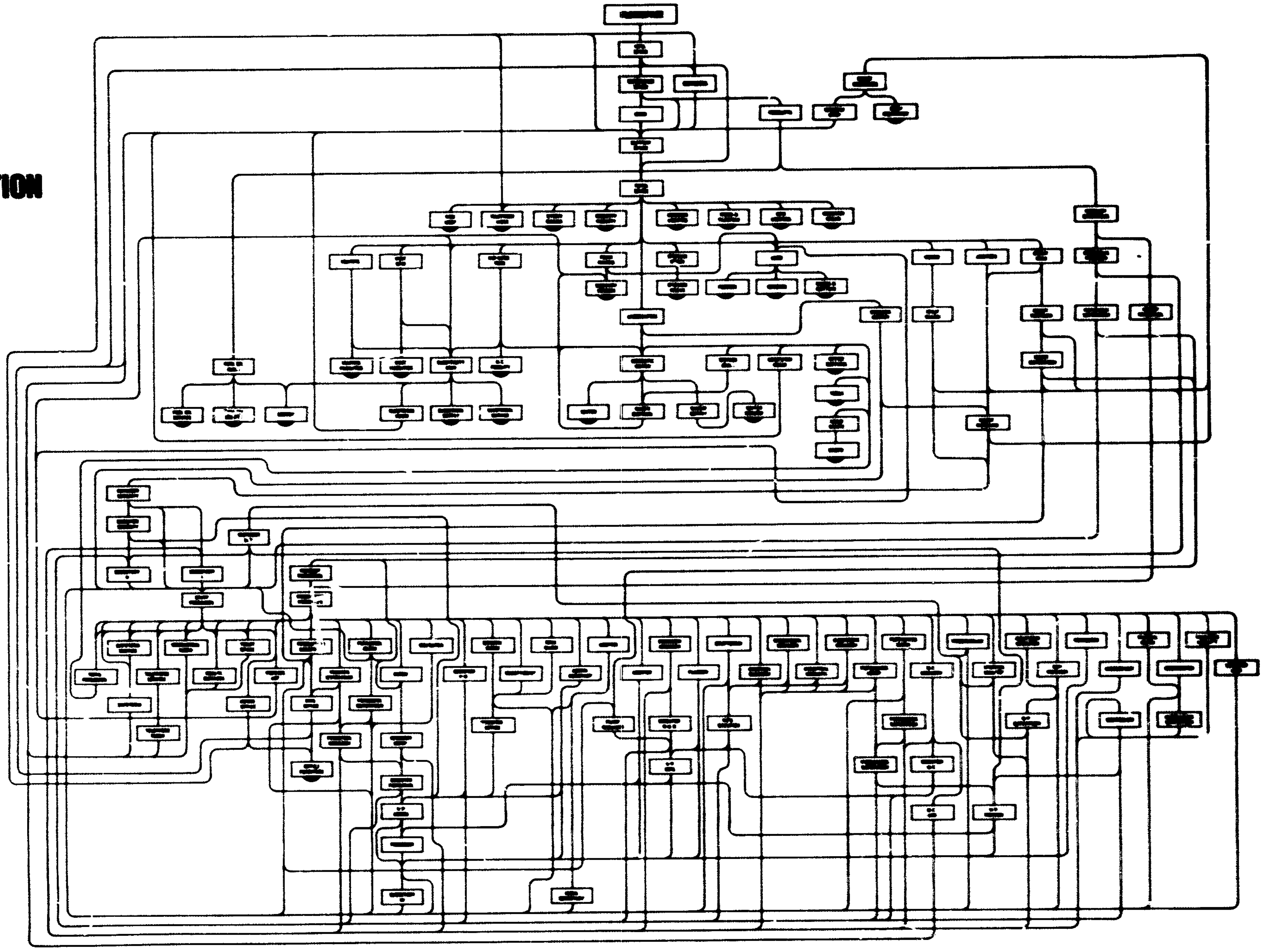
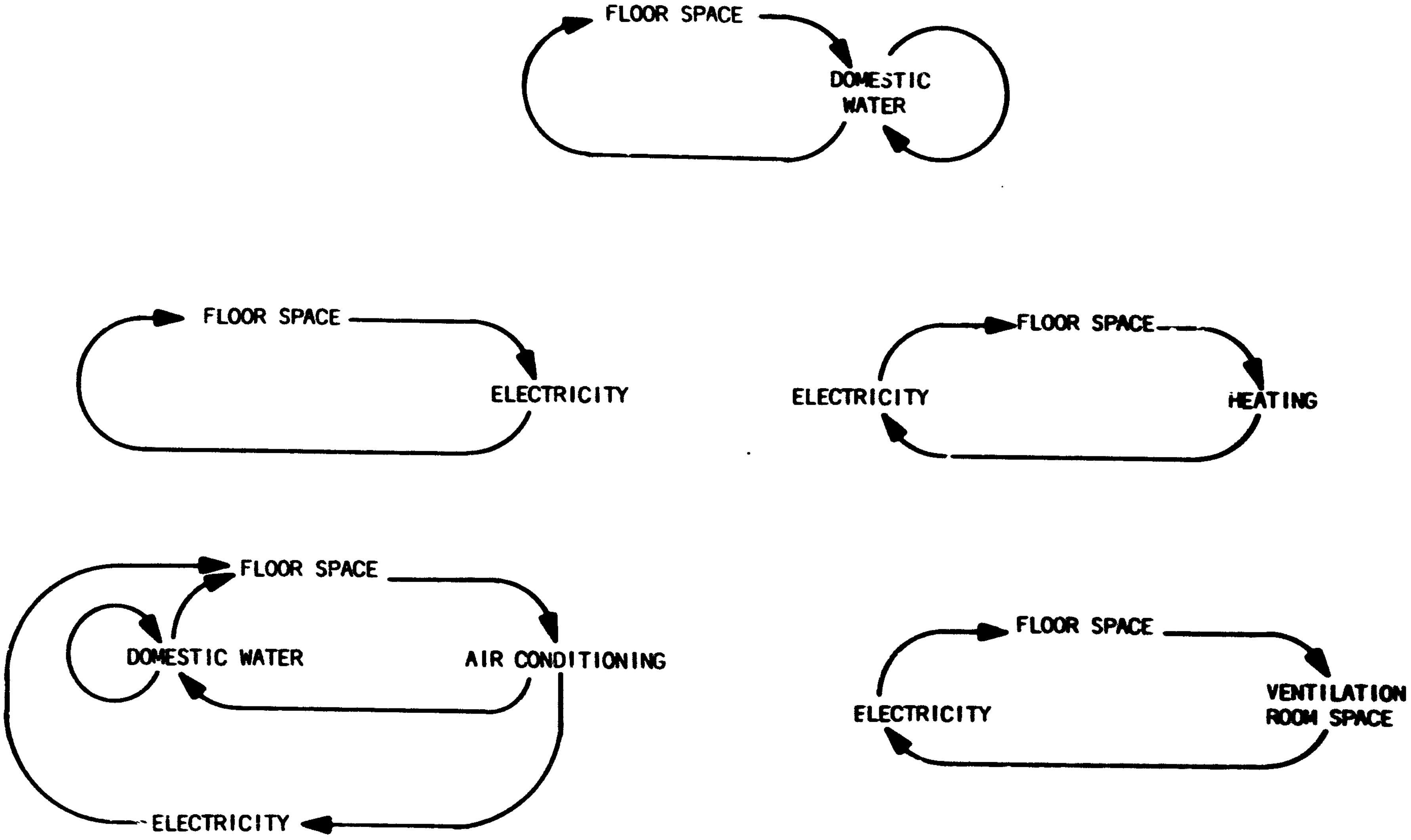


FIGURE 4.5:
DIAGRAM OF ITERATIVE GENERATION EFFECT OF FLOORSPACE UPON FACILATIES



3.4.6.3 SAMIS CRITIQUE

The preceding discussion suggest three problem areas associated with the use of SAMIS. These are cost, complexity, and credibility. The cost of performing a computer simulation for photovoltaic industry costing purposes could be greatly reduced if the code were written in a language more universally accepted. Analysis of the computing costs indicates that the SIMSCRIPT language is much more expensive to operate than Fortran, particularily when considering the 5¢ per ARU surcharge, a 25% increase over the basic rate.

Much of the basic information required by SAMIS would be required by any computerized costing program. However, if the purpose of a computerized costing simulation for the photovoltaic industry is to estimate the manufacturing cost of a particular process and evaluate the sensitivity of this estimated cost to a number of key variables, then SAMIS requires too much information from the user. Perhaps most of the information required by the STANDARD and the COMPANY files should be contained in a separate default file that would only require access if a specific change in one of the inputs was desired. Further simplification should be incorporated into the file building process in terms of writing the users guide in a file-oriented format rather than a command-oriented format. The current approach is very confusing to the inexperienced user who is most likely not familiar with the appropriate commands necessary for the file he is working on.

In terms of credibility, the SAMIS costing model is based upon the notion that the solar photovoltaic industry will be structured in much the same manner as the semiconductor industry. It is believed that, although semiconductor processes are used, the photovoltaic industry, due to stringent cost requirements, will not look like the semiconductor industry, especially in the indirect structure. Further, it is expected that indirect requirements will vary considerably with various processes, both in terms of the kinds of indirect requirements and the amounts of those indirect requirements. Figure 4.4, thus, is probably not valid for many factory scenarios.

Another problem with the use of SAMIS in terms of cost projections is the fact that cost account items are inflated at a rate contained in the cost account catalog for each entity to the year 1986. They are subsequently deflated to a nearer term manufacturing year at a fixed (8%) rate, which is usually significantly lower than the average inflation rate. As a result, the calculated cost of most of the inputs to a manufacturing facility appear higher in manufacturing years prior to 1986 than they would be if they were simply inflated directly to the manufacturing year in the first place.

In review, SAMIS is a computerized costing method which is capable of performing a side-by-side cost comparison of various photovoltaic manufacturing processes. Its value is that it performs this task in a consistent way in an attempt to normalize the assumptions from process to process. Unfortunatley, it cannot (nor can any costing program) evaluate the completeness [illegible] correctness of the input data. Further, it cannot accurately predict the unique indirect requirements of one company compared to another. This report suggests then than SAMIS probably is a valuable tool to JPL to make rough cost comparisons between the several proposed manufacturing processes, but it is probably too costly in both time and money, and too subjective, to be of much use to a photovoltaic manufacturer.

4.0 CONCLUSIONS

Conclusions are organized below according to the four main topics of the technical discussion.

4.1 PROCESS TECHNOLOGY

(1) The use of substrate surface praparation techniques such as texture etching must be evaluated separately for each individual choice of non-Cz substrate material, since different non-Cz materials will react differently in the texturing process. In general, the increase in optical absorption for non-Cz (multicrystalline) material will be less than for optimally oriented single crystal substrates. The effectiveness of texturing becomes an economic trade-off.

(2) The use of caustic etching (sodium hydroxide solution) proved to be a useful technique for isotropically smoothing and preparing various non-Cz surfaces.

(3) With respect to investigations of solar cell substrate drying, tentative conclusions are:

(a) Oven or forced hot air drying may be especailly useful for processed, passivated cells before encapsulation.

(b) Mechanical drying methods such as centrifugation or air blast are capable of producing clean surfaces but are generally too time-consuming and stress-producing to permit use on fragile substrates.

(c) Displacement drying appears to provide the cleanest wafer surfaces, while providing fast and gentle processing.

4.2 CELL DESIGN

Proper metallization pattern design is often neglected but will be extremely important in obtaining maximum performance from low cost, non-Cz substrates. A good design requires a careful tradeoff of cell performance parameters, metallization geometries, and ohmic losses. This is best done by computational procedures which can be exercised to arrive at an optimum design for the specific cell being fabricated.

4.3 METALLIZATION

(1) The plated nickel-copper metallization system is a viable, high performance ohmic contact and conductor system for solar cells fabricated on non-Cz substrates.

(2) Electroless nickel and electroless copper technologies provide feasible means of plating the nickel-copper metallization onto silicon substrates.

(3) Care must be exercised not to exceed certain temperature limits (which are a function of the particular non-Cz substrate material and solar cell design) during solar cell sintering, interconnection, and encapsulation operations if high performance is to be realized and cell I-V characteristic degradation is to be prevented.

4.4 COST ANALYSIS

A costing program which allows inexpensive simulations and sensitivity analyses is extremely valuable for refining cell process sequence choices. The value of costing procedures is not just to establish costs and prices, which are generated, but also to determine specific cost drivers and parameters which influence them.

5.0 RECOMMENDATIONS

(1) Cost-effective and gentle drying techniques suitable for non-Cz solar cell substrates will be required for any process sequence presently envisioned. Accordingly, further development work should be conducted on the promising drying methods identified, with particular emphasis on handling and material transfer considerations.

(2) As part of this contract, a computer program was written in the BASIC language to effect optimum design of front surface metal grid patterns for rectangular non-Cz solar cells. It is recommended that this program, along with empirical data for solar cell and metal conductor performance, be widely applied as a design tool for achieving maximum cell performance.

(3) It is recommended that selectively plated nickel-copper metallization be chosen for cost-effective, terrestrial, non-Cz solar cell fabrication. Both nickel and copper may be applied using electroless plating chemistries.

(4) Feasibility of electroless copper plating for solar cell metallization has been demonstrated. It is recommended that advanced development of electroless copper processing for solar cell applications be carried forward. Specific emphasis should be placed on developing and adapting high volume, high throughput plating equipment suitable for fragile solar cells.

(5) Solar cell manufacturing cost and price estimations are an integral part of developing cost-effective fabrication technologies. Since absolute cost estimates are very difficult to formulate by any method, the cost estimation technique must be capable of making ready cost comparisons and cost sensitivity analyses. It is recommended that a costing methodology (such as the Motorola solar cell/module costing program) which satisfies the requirements above at very low operating expense, be used by the photovoltaic industry.

6.0 NEW TECHNOLOGY

No reportable items of new technoloy were identified.

7.0 APPENDIX A: ZONE ELEMENT CHARACTERISTICS

7.1 SURFACE VOLTAGE DROP AND OHMIC DISSIPATION

Consider the cell surface to be of uniform sheet resistance, R_S, and to carry one-dimensional current and potential distributions, I(x) and v(x), that arise from a net junction current density, J(x), as illustrated in Figure A1. These distributions are governed by

$$dI/dx = \ell J \qquad \text{(A1)}$$

$$dv/dx = -(R_S/\ell)I. \qquad \text{(A2)}$$

Under conditions of uniform photogenerated current density and for $S^2 < (15/2)\,(kT/qR_S J(o))$, it can be shown that J(x) asymptotically approaches a spatially constant value. Consequently, under these conditions the relations above can be satisfied by the distributions

$$I(x) = J \int_0^x \ell(\xi)d\xi \qquad \text{(A3)}$$

$$v(x) = -R_S \int_0^x \frac{I(\xi)}{\ell(\xi)}\,d\xi \qquad \text{(A4)}$$

where J is the net junction current density at the operating point of the substrate and $\ell(\xi)$ is the dimension of the zone normal to the current flow at the general point, ξ, as illustrated in Figure A2. For a pattern boundary such that $\ell(x)$ is of degree less than second, corresponding to present practice, the integrals can be evaluated with sufficient accuracy by means of the trapezoidal and Simpson's rules to yield the first-order approximations.

$$I(x) = (1/2)\,J.\ell(x)\left[\frac{\ell(x) + \ell(o)}{\ell(x)}\right] \qquad \text{(A5)}$$

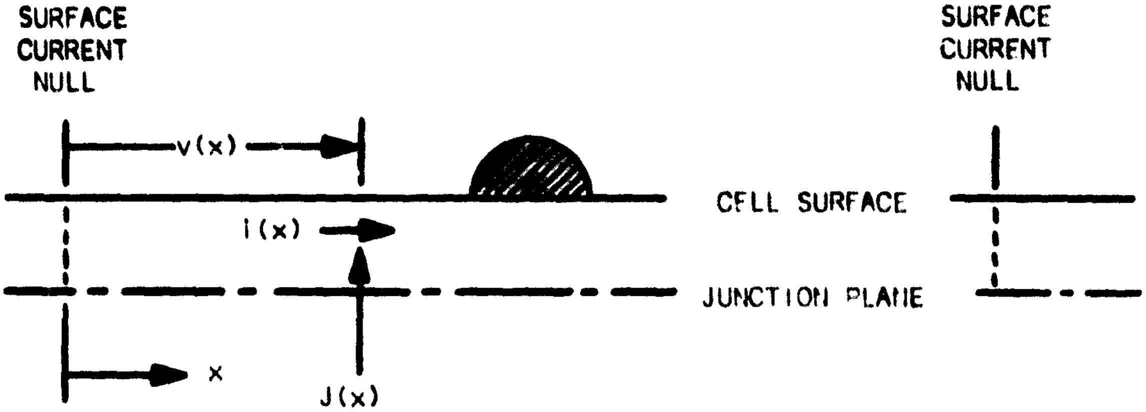


FIGURE A1: SURFACE CURRENT AND POTENTIAL DISTRIBTUIONS AT A ZONE ELEMENT

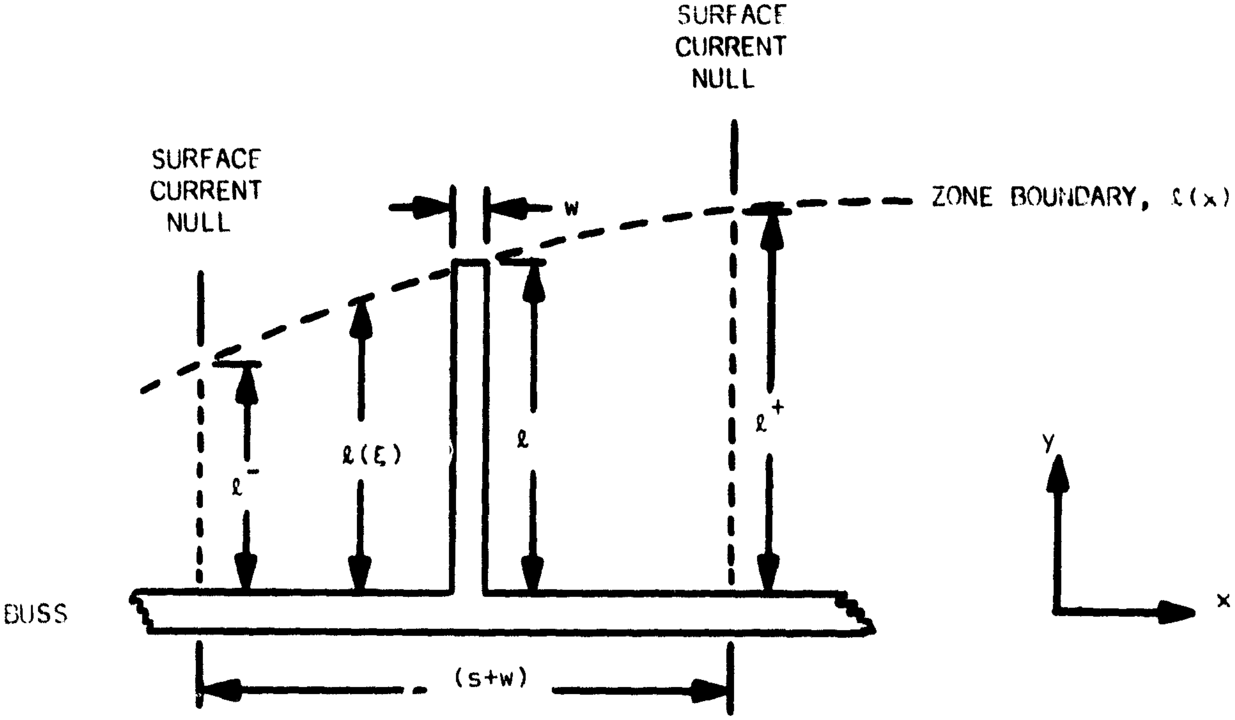


FIGURE A2: CONFIGURATION OF A ZONE ELEMENT.

$$v(x) = -(1/2)\, JR_S x^2 \{1 - (1/3)\left[\frac{\ell(x) - \ell(o)}{\ell(x)}\right]\}. \qquad \text{(A6)}$$

These expressions are exact for linear pattern boundaries and adequate first-order approximations for second degree boundaries as long as the change in length between adjacent collectors is a few percent of their length.

The several restrictions introduced to this point limit the discussion to patterns of relatively close-spaced collectors. It will be seen in what follows, however, that better performance requires such close spacing. In this sense, the discussion is being limited to cases of practical importance.

It follows from (A6) that the maximum voltage drop across the clear surface of the zone element is given by

$$V_{max,s} = (1/8)\, JR_S S^2 \{1 - (1/3)\, [\frac{\ell - \hat{\ell}}{\ell}]\} \qquad \text{(A7)}$$

where $\hat{\ell}$ is the larger of ℓ^+, ℓ^-, as defined in Figure A2, which also defines s.

The ohmic power dissipation over the clear surface of the zone element is of the form

$$P_{\Omega,s} = J^2 R_s \int \frac{i^2(\xi)}{\ell(\xi)}\, d\xi \qquad \text{(A8)}$$

where the integral is over the clear surface of the zone element. Evaluation to first order yields

$$P_{\Omega,s} = (1/12)\, J^2 R_s S^3 \ell \left(\frac{\ell^+ + \ell^-}{2\ell}\right) \qquad \text{(A9)}$$

The area of the zone element,

$$A_o = \int \ell(\xi)d\xi \tag{A11}$$

where the integral is over the entire zone element, becomes, to first order,

$$A_o = (2/3)\ (W\ell/F)\ [1 + (1/2)\ (\frac{\ell^+ + \ell^-}{2\ell})]\quad . \tag{A12}$$

Consequently, under uniform illumination of the zone element with intensity P_I, the fractional ohmic dissipation due to surface currents, to the first order, is given by

$$(P_\Omega/P_I)_s = (1/3)KJR_sW^2\ \frac{(1-F)^3}{F^2}\ [1 + (\frac{\ell^+ + \ell^-}{\ell})] \tag{A13}$$

where $K = (1/12)\ (J/P_I)$.

It is seen that the contribution of the surface currents to the fractional ohmic dissipation of the zone element is independent of the area of the zone element. In the case of a linear zone boundary it is also independent of ℓ. The principal geometric dependence is upon the quantity $W^2\ (1-F)^3/F^2$, indicating an advantage in small linewidths, for the same value of F, i.e., closely-spaced collectors of small linewidth.

7.2 COLLECTOR VOLTAGE DROP AND OHMIC DISSIPATION

The surface current distribution, (A5), leads to the first-order collector current distribution.

$$i(y) = JA_o(1-F)\ (\ell-y)/y \tag{A14}$$

with reference to Figure A2.

Characterizing the collector resistance per unit length as uniform and of the form R_C/W, where R_C is the effective sheet resistance of the collector, leads to a maximum voltage drop across the collector of the form

$$V_{max,c} = \frac{JR_c}{W} \int_0^{\ell} i(y)dy \qquad (A15)$$

which yields, to the first order

$$V_{max,c} = (1/3)\ JR_c\ell^2\ \frac{(1-F)}{F}\ [1 + (1/2)\ (\frac{\ell^+ + \ell^-}{2\ell})] \quad . \qquad (A16)$$

For linear zone boundaries, and for zone boundaries of second degree with sufficiently close-spaced collectors, this becomes

$$V_{max,c} = (1/2)JR_C\ell^2\ (1-F)/F. \qquad (A17)$$

The ohmic dissipation over the collector,

$$P_{\Omega,c} = \frac{J^2R_c}{W} \int_0^{\ell} i^2(y)dy \qquad (A18)$$

is given, to first order, by

$$P_{\Omega,c} = (1/3)\ J^2R_cA_o^2\ (\ell/W)\ (1-F)^2 \qquad (A19)$$

which leads to the collector contribution to the fractional ohmic dissipation of the zone element.

$$(P_\Omega/P_I)_c = 4KJR_cA_o(\ell/W)\,(1-F)^2 \quad . \qquad \text{(A20)}$$

This quantity is seen to be proportional to the zone element area and to the length-to-width ratio of the collector, indicating the desirability of zone element of small dimensions for a given value of F.

7.3 CHARACTERISTICS OF THE ZONE ELEMENT

The fractional power loss due to shadowing by the collector can be written, to the first order, as:

$$(P_{sH}/P_I)_o = \ell w/A_o = (3/2)\ F\ [1 + (1/4)\ (\frac{\ell^+ + \ell^-}{\ell})] \quad . \qquad \text{(A22)}$$

The total fractional ohmic dissipation over the zone element is the sum of (A13) and (A20), which can be written in the form,

$$(P_\Omega/P_I)_o = KJR_S\ \{(1/3)W^2\ (\frac{1-F}{F})\ [1 + (\frac{\ell^+ + \ell^-}{\ell})]$$

$$+ (8/3)\ (R_C/R_S)\ \ell^2\ [1 + (1/4)(\frac{\ell^+ + \ell^-}{\ell})]\}(\frac{1-F}{F})^2 \quad . \qquad \text{(A22)}$$

The maximum voltage drop associated with the zone element is the sum of (A7) and A17);

$$V_{max,o} = (1/8)\ JR_S\ \{W^2(\frac{1-F}{F})\ [1-(1/3)\ (\frac{\ell-\hat{\ell}}{\hat{\ell}})]$$

$$+ (8/3)\ (R_C/R_S)\ell^2\ [1 + (1/4)\ (\frac{\ell^+ + \ell^-}{\ell})]\}\ \frac{(1-F)}{F} \quad . \qquad \text{(A23)}$$