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ANALYSIS AND EVALUATION OF PROCESS AND EQUIPMENT IN TASKS II and IV of the LOW-COST SOLAR ARRAY PROJECT

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Quarterly Report Oct. 1977 to Jan. 1978
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The JPL Low-Cost Silicon 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 arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE.

ABSTRACT

Several experimental and projected Czochralski crystal growing process methods were studied and compared to available operations and cost-data of recent production Cz-pulling, in order to elucidate the role of the dominant cost contributing factors. From this analysis, it becomes apparent that substantial cost reductions can be realized from technical advancements which fall into four categories: an increase in furnace productivity; the reduction of crucible costs through use of the crucible for the equivalent of multiple state-of-the-art crystals; the combined effect of several smaller technical improvements; and a carry-over effect of the expected availability of semiconductor grade polysilicon at greatly reduced prices. Consequently, the specific add-on costs of the Cz-process can be expected to be reduced by about a factor of three by 1982, and about a factor of five by 1986.

A format to guide in the accumulation of the data needed for thorough techno-economic analysis of solar cell production processes has been developed, called the University of Pennsylvania Process Characterization (UPPC) format, and has first been applied, as well as refined, in the Cz crystal pulling analysis. The accumulated Cz process data are presented in this format in the Appendix.

The application of this UPPC format with the SAMICS cost and price determination methodology, at least in its "Interim Price Estimating Guidelines" (IPEG) form, has been established and is detailed in this report.

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1. INTRODUCTION

The manufacturing methods for photovoltaic solar energy utilization systems consist, in complete generality, of a sequence of individual processes. This process sequence has been, for convenience, logically segmented into five major "work areas": Reduction and purification of the semiconductor material, sheet or film generation, device generation, module assembly and encapsulation, and system completion, including installation of the array and the other subsystems. For silicon solar arrays, each work area has been divided into 10 generalized "processes" in which certain required modifications of the work-in-process are performed. In general, more than one method is known by which such modifications can be carried out. The various methods for each individual process are identified as process "options". This system of processes and options forms a two-dimensional array, which is here called the "process matrix".

In the search to achieve improved process sequences for producing silicon solar cell modules, numerous options have been proposed and/or developed, and will still be proposed and developed in the future. It is a near necessity to be able to evaluate such proposals for the technica merits relative to other known approaches, for their economic benefits, and for other techno-economic attributes such as energy consumption, generation and disposal of waste by-products, etc. Such evaluations have to be as objective as possible in light of the available information, or the lack thereof, and have to be periodically updated as development progresses and new information becomes available. Since each individual process option has to fit into a process sequence, technical interfaces between consecutive processes must be compatible. This places emphasis on the specifications for the work-in-process entering into and emanating from a particular process option.

The objective of this project is to accumulate the necessary information as input for such evaluations, to develop appropriate methodologies for the performance of such techno-economic analyses, and to perform such evaluations at various levels. The first application of this developing methodology was made to the Czochralski crystal pulling process.

The Czochralski crystal pulling process is currently, the only practically applied technique for converting high-purity polycrystalline silicon to single crystal, cylindrical ingots for the purpose of producing solar cells. To provide a baseline, this process option was therefore studied in detail, its important parameters were tabulated, and the resulting add-on costs for this pull process were calculated. These data were based either on recent production experience, on experimental runs, or on projections. The detailed production experience data provided by Leybold-Heraeus were found useful in assessing data based on experimental runs or projection relative to those from current commercial experience. These data include crystal geometries, operating parameters, energy, material, labor, equipment and facility requirements, and corresponding add-on costs and prices.

This report was originally planned to be issued as a regular quarterly report, describing the data collection and analysis of the Czochralski crystal pulling process which was predominantly performed during the 4th quarter of last year. However, partially incomplete analyses, significant open questions, the emergence of the SAMICS-IPEG methodology, etc., created the feeling that issuance of the data at that stage might cause more confusion than benefit. The completion of this quarterly report was thus delayed, while the data and their presentation were successively refined, and the price calculations were re-done in the current SAMICS-IPEG methodology. This task has now been completed, and the "quarterly report" is perhaps more in the nature of a "topical report" as a result.

2. Technical Discussion

2.1 ANALYSIS OF THE CZOCHRALSKI CRYSTAL GROWING PROCESS

2.1.1 INTRODUCTION TO THE CZOCHRALSKI STUDIES

We have studied eight processes for growing single, cylindrical silicon crystals using the Czochralski process.

In order to elucidate the economic factors involved in the Czochralski crystal pulling process, available data from four sources were compared. The data used were experience values from Leybold-Heraeus for 7.8 cm diameter ingots (1), with projections made by M. Wolf for 10.2 and 15.2 cm diameter ingots based on this data and on data from IBM (2). Experimental data for a single charge and projected data for multi- and semicontinuous charge techniques contained in Texas Instruments' reports (3) for 12 cm ingots were similarly tabulated, as were sequential and continuous growth projections for 16 cm diameter ingots by Dow Corning (4).

The data were separated into the categories of crystal geometry, operation times including annual output, material requirements including energy consumption, labor needs, and initial capital needs. Costs for all of these items were tabulated, first in their original version of the "per ingot grown" basis, and then normalized to the "per unit mass of useable cylindrical ingot" form for comparison, unit mass being the kg.

It may be noted that so far, only data available from project reports have been collected, without normalizations or independent projections performed. An exception to this rule is the normalization to an 8280 hour work year, the use of SAMICS' energy, labor, indirect cost and return-on-investment rates.

Among the data - the energy consumption, labor, material used, capital costs, and overhead costs were scrutinized. In order to be able to compare the more relevent "specific add-on-costs" for the process rather than the total cost of the work in process resulting from it, the polysilicon costs have been separated out.

Of those processes studied, only data from one (Leybold-Heraeus single charge technique) are based on production experience. Another data set, Texas Instruments' single charge method, is derived from experiments, while the rest are based on projections. Experiments do not involve continuously repeated specialized operations as are required in a production process. Therefore, data based on experimental runs generally can not correctly yield the necessary labor, material and energy requirements.

The available data sets have not been equally detailed or complete. The Leybold-Heraeus data have been the most detailed, and have therefore been taken as the guide in the data presentation and analysis.

In proceeding to the evaluation of processes which are still in the development or even conceptional stages, substantial gaps or uncertainties were found in important information required for both technical and economical evaluations. It was then necessary to fill these gaps with estimates based on extrapolations or analogies. Such estimates always leave some doubt on the accuracy of the evaluations, so that, in the future, "probable error" estimates need to be made to reduce decision mistakes based on yearly evaluations. Nevertheless, collecting this information and carrying out these evaluations at the earliest possible time aids in uncovering the important attributes for which information needs to be obtained at an early stage of the development process.

Additional information on the Leybold-Heraeus process and Wolf's projections are presented in the University of Pennsylvania Process Characterization (UPPC) format, shown in the Appendix.

2.1.2 PROCESS DATA COLLECTION

Tables I to IX summarize most of the data for the Czochralski pulling processes which have been studied in this task. In order to complement these data with the details of the process descriptions which were used in carrying out the analyses, the input-output specifications, material and labor descriptions, material re-cycling, waste treatments, price calculations, etc., University of Pennsylvania characterization (UPPC) formats are included in the appendices for the Leybold-Heraeus, single charge, 7.8 cm diameter ingot method and Wolf's projections for growing 10.2 and 15.2 cm diameter ingots. The prices and costs for Leybold-Heraeus' method was calculated assuming the current silicon price, while the Wolf projections for 10.2 and 15.2 cm diameter ingots were made using the 1982 and 1986 silicon prices, respectively.

The return on equity, which is labeled as "profit plus amortization computation" in the UPPC format has a slightly different format than that listed in Table IX. We have updated the return on equity calculations, after this reporting quarter, in order to conform closer with IPEG. Additional details on the methodology of calculating overhead, handling charges, miscellaneous expenses, capital costs return on equity, etc. is given in Section 2.2.2.

2.1.3 CRYSTAL GEOMETRY

One of the important parameters affecting efficiency and economics of the Czochralski crystal growing process is the geometry of the ingot to be pulled. Therefore, Table I lists the dimensional data of the ingots subjected to analysis by the four groups. Important are the nominal diameter and length of the cylindrical portion of the silicon ingot produced, and the silicon mass not incorporated into the cylindrical ingot. The crystal mass is calculated using the density value of 2.34 g/cm^3 for silicon to relate the ingot dimensions to mass. Defined as the theoretical crystal yield is the mass of the nominal cylindrical portion of the ingot divided by the mass of the silicon furnace charge. A high theoretical yield loses somewhat in relative economic importance as the cost of poly Si decreases from its current high values. All projections included a theoretical crystal yield of 90% or better.

The ingot dimensions, particularly the diameter, could be limited by the requirements of the follow-on processes, particularly the slicing process, rather than the Czochralski pull technique itself. The current workpiece capacity of the Yasunaga multiwire saw, for instance, is 10 cm x 10 cm x 10 cm. However, it should be expected, for the long view, that either more accomodating follow-on processes will be developed, or that workarounds, such as "ingot splitting" (lengthwise sawing), will be employed to take advantage of more economical crystal growing methods. Therefore, the requirements of the follow-on processes are not imposed as limitations on the Czochralski technology.

I. CRYSTAL GEOMETRY

Line Number		Leybold-Heraeus (1) Experience Single Charge	Wolf's projections from (1) Leybold-Heraeus' data Single charge with crucible re-use		Texas Instruments, (2) (April 1977) Experimental Single Charge	Texas Instruments, (2) (April 1977) Projected Multi-charge	Texas Instruments, (2) (April 1977) Projected Semi-continuous	Dow Corning, (3) (July 1977) Projected Sequential Growth	Dow Corning, (3) (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Number of Ingots per Run	1	1	1	1	3	3	10	10
2.	Crystal Diameter (cm)	7.8	10.2	15.2	12	12	12	16	16
3.	Cyl. Crystal Length (cm)	135	140	140	56	56	84	81	81
4.	Cyl. Crystal Mass (kg)	15.1	26.6	60.0	14.8	14.8	22.2	37.8	37.8
5.	Mass of Tapers (kg)	0.7	0.65	2.2	0.7	0.7	0.7	n.a.	n.a.
6.	Mass left in Crucible (kg)	0.4	0.55	0.8	0.8	0.3	0.3	n.a.	n.a.
7.	Total Silicon not used (kg)	1.1	1.2	3.0	1.5	1.0	1.0	4.2	4.2
8.	Silicon Charge per ingot (kg)	16.2	27.8	63	16.3	15.8	23.2	42	42
9.	Theoretical Crystal Yield (%) (I.4÷1.8*100)	93.0	95.7	95.2	90.8	93.8	95.7	90.0	90.0

(1) C.D. Graham, et al., "Research and Development of Low-Cost Processes for Integrated Solar Arrays," University of Pennsylvania, pp. 190-95, ERDA/SE/EC(11-1)-271/FR/76/1 (January 1976).

(2) S.N. Rea and P.S. Gleim, "Large Area Czochralski Silicon," Texas Instruments Incorporated, ERDA/JPL-954477/77/4 (April, 1977).

(3) L.P. Hunt, et al., "Solar Silicon via Improved and Expanded Metallurgical Silicon Technology," Dow Corning, ERDA/JPL-954559-77/2 (July, 1977).

2.1.4 OPERATION TIMES

Operation times are important for calculating labor requirements and depreciation costs. The total cycle time is needed for calculating the total number of crystals grown in a year, and thus relating annual capital costs to the individual ingot pulled. This total cycle time is divided into segments to permit a labor analysis, as various segments show greatly differing labor content. For example, the segment called "loading the poly-Si into the crucible" requires 100% of a laborer's time whereas, during the "pull segment" only occasional monitoring is required so that a laborer can divide his time between several pullers. The length of the pull segment is determined by the crystal size and the mass pull rate, which is defined as the amount of mass of cylindrical silicon crystal pulled per unit time. The mass pull rate is, through the crossectional area and silicon density, related to the "linear pull rate". The latter, however, is limited by thermodynamic effects, leading to the concept of a "limiting pull rate", and to the custom of expressing the actual pull rate as a fraction of the limiting pull rate. From Table II, it is noticeable that actual pull rates between 25 and 62% of the limiting rate are anticipated.

The theoretical limiting pull rate is governed by the silicon solidification rate at the growth (solid-liquid) interface, which, in turn, is directly proportional to the temperature gradient at the growth interface. The temperature gradient is obtained from a non-linear differential equation which is generally solved under various simplifying assumptions or approximations.

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II. OPERATION TIMES

Line Number		Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single charge with crucible re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-Charge	Texas Instruments, (April 1977) Projected Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Ingot Diameter (cm)	7.8	10.2	15.2	12	12	12	16	16
2.	Max pull rate[4] (cm/h)	39.0	34.1	28.0	31.2	31.2	31.2	27.3	27.3
3.	Assumed linear pull rate (cm/h)	9.6	12	17.4	9.0	9.0	10.8	8	8
4.	Pull rate fraction	0.25	0.35	0.62	0.29	0.29	0.35	0.29	0.29
5.	Mass pull rate (kg/h)	1.1	2.3	7.4	2.4	2.4	2.9	3.75	3.75
6.	Load time/ingot (h)	0.2	0.3	0.5	n.a.	n.a.	n.a.	n.a.	n.a.
7.	Melt time/ingot (h)	1.5	1.7	2.0	n.a.	n.a.	n.a.	n.a.	n.a.
8.	Balance temp. time/ingot (h)	0.1	0.1	0.1	n.a.	n.a.	n.a.	n.a.	n.a.
9.	Preparation segment time/ingot (h) (6. + 7. + 8.)	1.8	2.1	2.6	1.8	1.5	0.8	n.a.	n.a.
10.	Seed and Top time/ingot (h)	n.a.	n.a.	n.a.	2.0	2.0	1.3	n.a.	n.a.
11.	Cylindrical crystal pull time/ingot (h)	n.a.	n.a.	n.a.	6.2	6.2	7.8	10.1	10.1
12.	Taper growth time/ingot (h)	n.a.	n.a.	n.a.	1.0	1.0	1.0	n.a.	n.a.
13.	Pull segment time/ingot (h) (10. +11. +12.)	16.2	11.7	8.1	9.2	9.2	10.1	10.1	10.1
14.	Cooling time (h)	2.0	2.5	3.0	1.0	0.3	0.3	n.a.	n.a.
15.	Unload time/ingot (h)	0.2	0.5	0.75	1.0	0.4(e)	0.8	n.a.	n.a.
16.	Clean up time/ingot (h)	0.25	0.33	0.5	0.5	0.2	0.2	n.a.	n.a.
17.	Cool-unload segment time/ingot (h) (14. +15. +16.)	2.45	3.33	4.25	2.5	0.9	1.3	n.a.	n.a.
18.	Total cycle time/ingot (h) (9. + 13. +17.)	20.5	17.1	15.0	13.5	11.6	12.2	14.7	10.7
19.	Downtime (incl. service and repair)/ingot (h)	0.8	0.67	0.67	n.a.	n.a.	n.a.	n.a.	n.a.
20.	Gross cycle time/ingot (18. + 19.) (h)	21.2	17.8	15.6	n.a.	n.a.	n.a.	n.a.	n.a.
21.	Total cycle time per unit mass of cyl. Si (h/kg) (II.18 ÷ I.4)	1.4	0.64	0.25	0.91	0.78	0.55	0.39	0.28

(4) Using Ciszek's formula, $V_{max} = 77.1\ (r)^{-1/2}$ cm/h (see Sec. 3.3)

(e) Estimated

Wilcox et al.[5] obtained an analytical solution to this differential equation by setting to zero the term containing the differential of thermal conductivity with respect to temperature. An improvement of the just mentioned solution is to substitute an inverse temperature dependence of the thermal conductivity in the above mentioned term before any integration operations are performed. This was done by T. F. Ciszek[3] who obtained values which are a factor of $(3/2)^{1/2}$, or 22 percent, larger than those of Wilcox et al. The limiting pull rate as determined by Ciszek is

$$v_{lim} = 77.1/r^{1/2} \text{ cm/h},$$

where r is the cylindrical radius. Another way of solving for the limiting growth velocity was found by J.A. Wohlgemuth, M. Wolf and G.T. Noel which permitted using a more accurate presentation of the silicon thermal conductivity[6]. Their approach permits expansion of the thermal conductivity into a power series in T and fitting the coefficients to the experimental values by the least squares method. The values for v_{lim} thus obtained are 5% lower than those of Ciszek.

The above three theoretical analyses examine an idealized situation of an ingot suspended in an ambient temperature or low temperature environment, with heat flow into the ingot originating only from the molten zone. Thus, these analyses are approaches towards determining a fundamental upper limit for the pull speed. These approaches do not include, design or technology based effects, such as the radiative heat flow from the heating element and the liquid silicon surface to the grown crystal above the liquid-solid-interface. This additional radiative heat flow to the ingot decreases the temperature gradient within the ingot and consequently the actually achievable maximum pull rate. Rea[3] considered this additional heat flow and computed values for v_{max} based on the geometrical conditions obtained by growing a cylindrical ingot from a 12 kg crucible using a Varian Model 2848A furnace. The maximum pull rate obtained by Rea through numerical computations is about 50% of Ciszek's limiting pull rate. Considering Rea's results leads to the conclusion that the assumed linear pull rate shown in column W2, which is over 60% of Wilcox's rate, might be slightly above the currently possible.

Properly designed heat shields should be able to reduce this effect of radiative heat pick-up by the ingot, although probably not entirely eliminate it. An experiment in this direction was carried out at Texas Instruments, but was not successful. Whether, however, the high cooling rate required for such fast growth will be compatible with the attainment of good electrical properties of the grown ingots, is an aspect which will require further investigation.

In Texas Instruments' pull rate experiments[3] with a 12 cm diameter ingot, maximum experimental rates of 12.7 - 15 cm/h, or less than one-half of Ciszek's were obtained. The Texas Instruments workers believe that a practical maximum rate of 12 cm/h can be sustained over long periods. This value is about one-third of the maximum rate listed for the 12 cm diameter ingot in Table II for TI.

In those cases, where the operation times were not adequately broken down into the segments by the data sources, times were, where possible, estimated as indicated by "(e)" or otherwise marked "n.a." (not available). Only the Leybold-Heraeus data and Wolf's projections from the Leybold-Heraeus data contained times for furnace service and repair. How these time requirements were handled by the other two data sources is not clear.

Omitting, the soon to be superceded technology level of the single charge techniques described by Leybold-Heraeus and Texas Instruments, the "unit mass cycle times" (total cycle times divided by the mass of the usable cylindrical portion of the ingot) differ by a factor of about three between the highest (column T12) and the lowest value (column W2). Theoretically, the unit mass cycle time would firstly be expected to depend on the inverse square of the cylindrical radius of the ingot, for constant linear pull rate, as the silicon mass per unit cylindrical ingot length is proportional to r^2. However, since the limiting linear pull rate varies with $r^{-1/2}$, the unit mass cycle time should increase with $r^{1/2}$. The result of these two factors should be a unit mass pull segment time proportional to $r^{-3/2}$.

Additional operating data are listed in Table III. One of these is the relation between the amount of input of high purity grade, polycrystalline silicon and the output of single crystal cylindrical silicon ingots, examined on an annual basis. In addition, this table contains the cooling water and argon consumption for a single charge.

The potential number of pulls per year for each puller was calculated, using the total cycle times (line 18 of Table II), and assuming the puller operates for 8280 hours each year. These operating hours are approximately equivalent to a plant operating continuously during the year except for one one-week plant vacation (including two weekends), two 3-day holidays and one [illegible]-day holiday.

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III. OTHER OPERATING DATA

Line No.		Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single charge with crucible re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, Projected Multi-Charge	Texas Instruments, Projected Semi continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Potential No. of pulls per year[5] (y^{-1}) (8280 h ÷ II.20)	390	465	530	580[(6)]	680[(6)]	645[(6)]	535[(6)]	735[(6)]
2.	Fraction of pulls successful (%)	90	90	90	100	100	100	100	100
3.	No. of successful pulls per year (y^{-1})	350	420	475	580	680	645	535	735
4.	Practical yield of cylindrical crystal (%) (incl. I.9)	80	80	80	90.8	93.8	95.7	90	90
5.	Annual output of good cylindrical Si (kg/y) (III.3*III.4*I.8)	4,540	9,340	23,940	8,585	10,060	14,320	20,225	27,780
6.	Silicon in abandoned pulls (I.8 * (III.1-III.3)) (kg/y)	650	1,250	3,465	0	0	0	0	0
7.	Silicon in tapers and left in crucible (III.3*I.7) (kg/y)	385	505	1,425	870	680	645	2,250	3,090
8.	Silicon in other non-good parts of ingots (III.3*I.8*(1-(III.4)) - III.7) (kg/y)	750	1,830	4,560	0	0	0	0	0
9.	Total non-output silicon (kg/y) (III.6+III.7+III.8)	1,785	3,585	9,450	870	680	645	2,250	3,090
10.	Fraction of non-output Si recyclable (%)	67	67	67	23[(7)]	35[(7)]	35[(7)]	0	0
11.	Non-recyclable silicon (kg/y) III.9(1-(III.10))	595	1,195	3,150	670	440	420	2,250	3,090
12.	Gross silicon input (III.1*I.8) (kg/y)	6,320	12,925	33,390	9,455	10,740	14,965	22,470	30,870
13.	Net virgin silicon input (III.12-III.9+III.11) (kg/y)	5,130	10,535	27,090	9,255	10,500	14,740	22,470	30,870
14.	Mass of silicon lost in process (kg/charge) (11÷1)	1.5	2.6	5.9	1.15[(8)]	0.65[(8)]	0.65[(8)]	4.2[(9)]	4.2[(9)]
15.	Cooling water consumption per charge (m^3)	127	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
16.	Argon consumption per charge (m^3)	6.4	0	0	n.a.	n.a.	n.a.	n.a.	n.a.

(5) Assuming a 8280 h work year
(6) Estimated for 95% availability
(7) Calculated from III.14
(8) I.6 + 0.5*I.5

This basically continuous work schedule was chosen because it minimizes lost pulling time due to interference of the long pull cycles with plant closing times, since puller shutdowns in the middle of a pull cycle are not possible, and unattended pull completion is not within current equipment capabilities. Closing the factory one day a week would result, on average, in the loss of up to one growth cycle per week.

Only in the Leybold-Heraeus data and in Wolf's projections was the experience of unsuccessful pulls and practical yields lower than the theoretical yields acknowledged. It seems optimistic to expect that no pulls would be aborted due to polycrystal formation, crucible breakage, equipment or power failures, etc. The annual output of cylindrical silicon was, in all cases, calculated by multiplying the number of successful pulls by the product of the charge mass and the practical yield, which in most cases was assumed equal to the theoretical yield. For the Leybold-Heraeus data and Wolf's projections, the recyclable silicon was taken as two-thirds of the silicon mass input not incorporated into the output. For Texas Instruments, the recyclable silicon fraction has been taken as equal to one-half of the taper mass, to represent the top taper, divided by the sum of the silicon mass left in the crucible and the total taper mass. In Dow Corning's projections, the "non-cylindrical silicon" mass was given only as the silicon left in the crucible, as there is no recyclable silicon available in this process.

The cooling water consumption was only given for column LH1 while the actual argon consumption was known for columns LH1, W1 and W2. In the latter two processes, pulling is performed under vacuum.

2.1.5 ENERGY REQUIREMENTS

The energy requirements shown in Table IV are of interest by themselves as well as for their cost contribution. In crystal pulling, the direct energy consumption is exclusively electrical energy. The energy costs are computed on the basis of an energy rate of $0.0319/kWh. (SAMICS, (7)).

Where the electrical energy requirements are broken down into the segment consumptions, it can be observed that most of the electrical energy is used (>95%) to compensate for the heat losses during melting the poly-Si chunks and during pulling the cylindrical crystal and the tapers, rather than for performing useful work such as supplying sensible heat or heat of fusion, raising the ingot, activating control functions, etc. The heat losses occur predominantly by radiation from the furnace elements (crucible, heater, etc.) at temperatures above 1400°C to the water-cooled furnace enclosure, despite some interspersed heat shields. Additional active heat loss mechanisms are convection through the helium or argon protective atmosphere in the furnace, and conduction primarily through the heater and crucible supports and the seed-holder.

Since the energy flow rate due to the first two mentioned heat loss mechanisms, radiation and convection, is directly proportional to the surface area of the heated bodies, the energy loss, E, per unit mass of ingot grown will be affected by an increase of the crystal diameter, if this would result in a change of the geometry of the hot zone parts of the furnace. The surface area of the hot zone parts of the furnace which can be taken as of essentially

IV. ENERGY REQUIREMENTS

(Given in kWh/charge except where stated otherwise.)
(Energy costs are obtained at the price of $0.0319/kWh)

Line Number	Energy Requirements Ingot (kWh)	Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single Charge with crucible re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-charge	Texas Instruments, (April 1977) Projected Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Theoretical melt energy per-ingot (kWh)	13	22	50	12	12	18	30	30
2.	Energy loss during meltdown per ingot (kWh)	90	110	200	n.a.	n.a.	n.a.	n.a.	n.a.
3.	Total meltdown energy (1. + 2.)	103	132	250	n.a.	n.a.	n.a.	n.a.	n.a.
4.	Energy loss during pull segment (kWh)	1000	920	1000	n.a.	n.a.	n.a.	n.a.	n.a.
5.	Total energy consumption per charge (3. + 4.) (kWh)	1100	1050	1250	510	520	555	1135	1135
6.	Total energy consumption per unit mass of cylindrical silicon (kWh/kg) ((IV.5*III.1) ÷ III.5)	95	52.5	27.5	34.5	35	25	30	30
7.	Energy cost/per charge ($)	35.10	33.50	40	16.27	16.59	17.70	36.21	36.21
8.	Energy cost per unit mass of cylindrical crystal ($/kg)	3.03	1.67	0.88	1.10	1.12	0.80	0.96	0.96

cylindrical geometry, can be expressed as:

$$A = 2\pi R \cdot L + 2 \cdot \pi R^2$$

$$= 2\pi R \cdot (R + L)$$

If the crystal radius is increased from r_1 to r_2, the radius R of the hot zone parts will need to be increased from R_1 to some value R_2, and possibly the length L of the hot zone parts has to be changed also. The area ratio resulting from a change in hot zone parts radius is:

$$\frac{A_2}{A_1} = \frac{R_2}{R_1} \cdot \frac{R_2 + L_2}{R_1 + L_1}$$

$$= \frac{R_2}{R_1} \left[\frac{\frac{R_2}{R_1} - 1}{\frac{L_1}{R_1} + 1} + \frac{\frac{L_2}{L_1} \cdot \frac{L_1}{R_1} + 1}{\frac{L_1}{R_1} + 1} \right]$$

This ratio thus depends on the three dimensionless quantities $\frac{R_2}{R_1}$, $\frac{L_2}{L_1}$, and $\frac{L_1}{R_1}$. These are to be related to the change in crystal diameter $\frac{r_2}{r_1}$.

Several cases of such relationships can be readily analyzed. Generally, if the length is not changed ($\frac{L_2}{L_1} = 1$), the second term inside the brackets becomes unity. If the ratio $\frac{L_1}{R_1}$ additionally is large, implying that the hot zone parts are of elongated cylindrical geometry (which, however, usually is not the case) then the first term becomes negligible and the area ratio would simply equal the ratio of the hot zone parts radii. If this ratio would be made equal to the ratio of the crystal radii after and before the increase, then:

$$\frac{A_2}{A_1} = \frac{r_2}{r_1} ,$$

and the energy loss rate P would increase by the same ratio. Since the unit mass pull time (UMPT) had been found to be proportional to $\left(\frac{r_2}{r_1}\right)^{-3/2}$ (p. 12), the energy loss per unit crystal mass pulled would, be given by:

$$\frac{E_2}{E_1} = \frac{P_2 \; (UMPT)2}{P_1 \; (UMPT)1} = \frac{r_2}{r_1} \cdot \left(\frac{r_2}{r_1}\right)^{-3/2} = \left(\frac{r_2}{r_1}\right)^{-1/2}$$

For this case, the energy consumption per unit mass pulled would thus decrease proportionally to $\left(\frac{r_2}{r_1}\right)^{-\frac{1}{2}}$. In general, however, this case which neglects the heat transfer from the ends of the cylinder would be considered as somewhat optimistic, since the axial section of the cylinder representing the hot zone parts, approaches in actual cases more the shape of a square, so that $2 < \frac{L_1}{R_1} < 4$ would be more appropriate.

Another single case, although probably beyond the practical worst case, is described by the condition $\frac{R_2}{R_1} = \frac{L_2}{L_1} = \frac{r_2}{r_1}$, where the length of the hot zone posts would also change in the ratio of the crystal diameters. This case is independent of the ratio $\frac{L_1}{R_1}$, and yields:

$$\frac{A_2}{A_1} = \frac{R_2^{\ 2}}{R_1^{\ 2}} = \frac{r_2^{\ 2}}{r_1^{\ 2}} ,$$

Thus, the energy loss per unit mass pulled would increase with $\left(\frac{r_2}{r_1}\right)^{\frac{1}{2}}$.

In reality, the hot zone parts do not have to increase their diameter in the same ratio as the crystal diameter. More appropriate may be a relationship of constant differences Δ, such as caused by the clearance between the crystal and the crucible inside, by the wall thicknesses of the crucible and of the crucible holder, by the clearance between the crucible holder and the heater, etc. This relationship would thus be expressed as:

$$R_1 = r_1 + \Delta$$

$$R_2 = r_2 + \Delta$$

Consequently:

$$\frac{R_2}{R_1} = \frac{r_2 + \Delta}{r_1 + \Delta}$$

$$= 1 + \left(\frac{r_2}{r_1} - 1\right)\left(\frac{1}{1 + \frac{\Delta}{r_1}}\right)$$

This function takes the following values:

$\frac{\Delta}{r_1}$	$\frac{R_2}{R_1}$
0	$\frac{r_2}{r_1}$
$\frac{1}{2}$	$\frac{1}{3} + \frac{2}{3}\left(\frac{r_2}{r_1}\right)$
$\frac{2}{3}$	$0.4 + 0.6\left(\frac{r_2}{r_1}\right)$
1	$\frac{1}{2} + \frac{1}{2}\left(\frac{r_2}{r_1}\right)$
2	$\frac{2}{3} + \frac{1}{3}\left(\frac{r_2}{r_1}\right)$
4	$\frac{4}{5} + \frac{1}{5}\left(\frac{r_2}{r_1}\right)$
∞	1

The area ratio becomes then:

$$\frac{A_2}{A_1} = \left[1 + \left(\frac{r_2}{r_1} - 1\right)\frac{1}{1 + \frac{\Delta}{r_1}}\right]\left[\frac{\left(\frac{r_2}{r_1} - 1\right)\frac{1}{1 + \frac{\Delta}{r_1}}}{\frac{L_1}{R_1} + 1} + \frac{\frac{L_2}{L_1}\,\frac{L_1}{R_1} + 1}{\frac{L_1}{R_1} + 1}\right]$$

or:

$$\frac{A_2}{A_1} = \frac{\left(\frac{r_2}{r_1} + \frac{\Delta}{r_1}\right)\left(\frac{r_2}{r_1} + \frac{\Delta}{r_1} + \frac{L_2}{L_1}\,\frac{L_1}{r_1}\right)}{\left(1 + \frac{\Delta}{r_1}\right)\left(1 + \frac{\Delta}{r_1} + \frac{L_1}{r_1}\right)}$$

This relationship has the form:

$$\frac{P_2}{P_1} = \frac{A_2}{A_1} = C_1\left(\frac{r_2}{r_1}\right)^2 + C_2\left(\frac{r_2}{r_1}\right) + C_3$$

and, consequently, yields the ratio of the energy losses per unit mass pulled:

$$\frac{E_2}{E_1} = \left[C_1\left(\frac{r_2}{r_1}\right)^2 + C_2\left(\frac{r_2}{r_1}\right) + C_3\right]\left(\frac{r_2}{r_1}\right)^{-3/2}$$

$$= C_1\left(\frac{r_2}{r_1}\right)^{\frac{1}{2}} + C_2\left(\frac{r_2}{r_1}\right)^{-\frac{1}{2}} + C_3\left(\frac{r_2}{r_1}\right)^{-3/2}$$

Entering some practical values, such as $\frac{\Delta}{r_1} = 4$ and $\frac{L_1}{r_1} = 15$, and $\frac{L_2}{L_1} = 1$, yields the following values:

$$\frac{A_2}{A_1} = \frac{1}{5\cdot 20}\left\{\left(\frac{r_2}{r_1}\right)^2 + 23\,\frac{r_2}{r_1} + 76\right\}$$

$$= \frac{1}{100}\left(\frac{r_2}{r_1}\right)^2 + \frac{23}{100}\,\frac{r_2}{r_1} + \frac{76}{100}$$

It may be observed, that, at $\frac{r_2}{r_1} = 2$, the magnitude of the linear term of $\frac{r_2}{r_1}$ is only 60% of that of the constant term, but is more than an order of magnitude larger than the quadratic term. The ratio $\frac{A_2}{A_1}$ is only 1.26 in this case, and the energy loss per unit mass pulled would be reduced to less than half the value experienced before the doubling of the crystal radius. Even if the length L_2 of the hot zone parts is increased from L_1 by 20%, the ratio $\frac{A_2}{A_1}$ becomes:

$$\frac{A_2}{A_1} = \frac{1}{100}\left\{\left(\frac{r_2}{r_1}\right)^2 + 26\ \frac{r_2}{r_1} + 88\right\}$$

or, with $\frac{r_2}{r_1} = 2$, $\frac{A_2}{A_1} = 1.44$, which means approximately halving the energy loss per unit mass pulled.

In consequence of the preceding considerations, it seems reasonable to assume that the energy consumption, per unit mass pulled, can be reduced by 25 to 50% in going from the currently prevailing ingot diameter of nominally 3" to one of 6" (i.e. 15 cm). For simplicity, this reduction will be assumed, in the following, to be 33% from its current value. In addition, it has been assumed that the energy losses can be reduced by better furnace design, that means, better heat shielding and insulation of the heater/curcible region. This has been assumed to result in the decrease of the electrical energy requirements by another 17% for a total reduction of 50%.

The energy costs shown in Table IV account only for the process energy consumption, that is, energy input during melting the poly-Si and growing the single crystal ingot. It does not include indirect material and equipment energy content, or the energy consumption for general facility operation. The cost of the electrical energy consumed has been found, however, to be small compared to the total add-on costs in all cases, including the projections to advanced crystal pulling techniques, except for the

Dow Corning projections.

The energy consumption per unit mass of crystal produced (line 6) was calculated by multiplying the energy consumed per charge by the potential number of pulls per year and then dividing by the mass of the annual good cylindrical silicon output.

2.1.6 MATERIAL COSTS

The following materials required for Cz-crystal pulling have been identified: the polycrystal silicon (semiconductor grade or solar grade) and doping charge as direct materials, the seed crystal, argon or helium for protective gas, and the cooling water as indirect materials, and the quartz crucible and furnace replacement parts as expendable tooling.

Wolf's projected data are based on vacuum crystal pulling and therefore do not include argon or helium in the crystal growth process. Vacuum crystal pulling is a method highly recommended by some, but is generally disliked by most practitioners. Consequently, the Texas Instruments group included argon usage at the rate between about 300 and 500 ℓ/kg-Si, and the Dow Corning group of approximately one-tenth of that rate. The cost of argon can be quite significant, given, for instance, as over $30/load in the Texas Instruments data for the single and multi-charge techniques. It has been mentioned, however, that the use of argon can reduce deterioration of furnace elements, preserve the purity of the cylindrical silicon, improve temperature distribution, and extend the lifetime of the quartz crucible.

As previously recognized, with current production techniques, the crucible cost is a determining factor in the add-on costs in growing Czochralski ingots. Crucible costs can be dramatically reduced by "re-utilization". In Wolf's projections from Leybold-Heraeus' data, the crucible is used to grow ten ingots, resulting in a saving of over 50% in indirect material costs. Similarly, in Texas Instruments' multi-charge and semi-continuous growth projections, three ingots are grown before the crucible is replaced. This yields a savings of about one-third of the indirect costs compared to the single use of the crucible. Dow Corning calculated a similar savings by re-using their quartz crucibles to grow ten ingots. This is reflected in the data of Table V, where for the single charge technique, Leybold-Heraeus gives the crucible cost as $225/charge. In contrast, Dow Corning lists a crucible cost of $20/charge by multi-use. The regular ten times re-use of a crucible has yet to be demonstrated, but 4 LSA projects in progress on semi-continuous crystal growth are expected to lead to these data expeditiously. No scientific reasons are known which would prevent multiple crucible use, as long as the crucible is not cooled down significantly, the wall thickness is adequate to survive the slow dissolution by the liquid silicon, deritrification is kept under control, and contamination build-up can be kept under control. If the crucibles, could be used to grow ten ingots, their add-on cost contributions turn out to be, by all projections, still over $0.50/kg-cyl.Si, or at an assumed conversion rate of 1 m^2/kg, more than $0.50 m^{-2}, or approximately 1% of the 1986 goal module cost, rather independently of differences in the remaining attributes of the crystal pulling technology applied.

After reducing crucible costs by multi-use, the next largest material add-on cost item in Leybold-Heraeus' data, Wolf's projections, and Texas Instruments' experimental data is the cost for furnace replacement parts. The Leybold-Heraeus data and Wolf's projections derived from them do not give the number of pulls for which heater elements are used, but the large amount for furnace replacement parts costs apparently represents the practical experience with that particular puller. The magnitude of the replacement parts costs in the

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V. MATERIAL COSTS/CHARGE

Line Number	Material Costs ($/charge)	Leybold-Heraeus Experience Single Charge	Wolf's Projections From Leybold-Heraeus' Data Single Charge with Crucible Re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-charge	Texas Instruments, (April 1977) Projected Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Seed	(10)	(10)	(10)	5	5	5	(10)	(10)
2.	Argon	31.65	0	0	34.50	33	35	(10)	(10)
3.	Crucible	225	20	46.15	125	42	42	20	20
4.	Cooling water	6.23	5.95	7.08	2.89	2.90	3.14	6.42	6.42
5.	Furnace replacement parts	140	93.50	138.50	54	23	23	10	10
6.	Misc. parts and materials	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	17.50	15
7.	Total indirect materials incl. expendable tooling (Sum 1. to 6.)	402.90	119.45	191.73	221.40	105.90	108.15	53.90	51.40
		Polycrystalline Silicon @ $65/kg (present price)							
8.	Silicon lost in process (from III.14)	97.50	169	383.50	74.75	42.25	42.25	273	273
9.	Total add-on materials (7. + 8.)	495	282.50	568	293	145	147	321	418
10.	Poly Si in charge	1053	1807	4095	1060	1027	1508	2730	2730
11.	Total materials (7. + 10.)	1456	1927	4287	1281	1133	1616	2784	2781
12.	Credit from recycled Silicon	195	338	767	22.75	22.75	22.75	0	0
13.	Net total (11. - 12.)	1253	1589	3520	1258	1110	1593	2784	2781
		Polycrystalline silicon @ $40/kg (1982 LSA projection)							
14.	Silicon lost in process	60	104	236	46	26	26	168	168
15.	Total add-on materials (7. + 14.)	457	218	421	265	129	131	216	213
16.	Poly Si in charge	648	1112	2520	652	612	928	1680	1680
17.	Total materials (7. + 16.)	1051	1232	2712	874	718	1033	1734	1731
18.	Credit for recycled silicon	120	218	472	14	14	14	0	0
19.	Net Total (17. - 18.)	931	1014	2240	860	714	1019	1734	1731
		Polycrystalline silicon @ $10/kg (1986 LSA projection)							
20.	Silicon lost in process	15	26	59	11.50	6.50	6.50	42	42
21.	Total add-on materials (7. + 20.)	412	140	244	230	110	112	90	87
22.	Poly Si in charge	162	278	630	163	153	232	420	420
23.	Total materials (7. + 22.)	565	398	822	322	259	338	474	471
24.	Credit for recycled silicon	30	52	108	3.50	3.50	3.50	0	0
25.	Net Total (23. - 24.)	535	346	714	319	255	334	474	471

(10) Included in misc. parts and materials

Leybold-Heraeus and Wolf data is striking and seems much larger than industry experience in general. The latter seems reflected in the Texas Instruments and Dow Corning data. This question of longevity and cost of furnace replacement parts certainly merits further attention. The frequency of replacement of the hot zone parts may possibly be reduced by pulling without intervening cooldowns, which is being instituted with the crucible multi-use. The Texas Instruments projections include use of the heater elements for 25 crystal pulls, while those of Dow Corning assume their use for 100 pulls.

Cooling water costs were determined by using the SAMICS (7) value of $0.566 per 100 kWh of energy dissipated. The actual water quantity required to cool a puller during the growth cycle was not given by three of the four sources. It was assumed by some sources that cooling water costs can be reduced to a small amount by use of a cooling tower (1,4). However, a cooling tower will increase capital and maintenance costs somewhat.

In the available data, only Dow Corning has separated unspecified "miscellaneous costs" from furnace replacements parts. Such "miscellaneous costs" should include the seed crystal, the doping charge, and materials and tools needed for handling the material before and after the pull, etc.

The direct material, that is the polysilicon, costs currently about $65/kg. It comprises the overwhelming part of the total material costs. Since large Si price reductions are expected in the future, a cost comparison will be more meaningful if the poly-Si cost is separated from the other costs. Line 7 of Table V thus shows the add-on material cost per Si charge, excluding the cost of the silicon. The cost of the silicon lost in-process is given separately in Table V for the three different polysilicon process (Lines 8, 14 and 20). The total add-on materials cost is the sum of the indirect materials used and the lost silicon cost. As the price of polycrystalline silicon decreases, the cost contribution of the lost silicon decreases significantly. The Dow Corning projections include the highest fraction of lost silicon. In consequence, they show relatively high total add-on material costs (Table V, lines 9 and 15) for the high silicon prices of $65/kg and $40/kg respectively, but the lowest total add-on material costs of the LSA projected 1986 polysilicon price of $10/kg (Table V, line 21).

Since part of the silicon which does not enter into the cylindrical silicon crystal can be re-used, a credit has been given to the gross add-on materials costs for the re-cycled silicon. This credit is shown in lines 12, 18 and 24 for the three different silicon prices. The net total cost thus includes the credit for recycled silicon. This recycling of silicon not incorporated into the ingot can lead to significant cost reductions. In the Leybold-Heraeus data and in Wolf's projections, only 72% of the gross silicon input is initially incorporated into the ingot. But two-thirds of the non-output silicon is re-processed, which significantly decreases the cost burden, for instance, of the "unsuccessful pulls". The significance of this material recycling is exemplified by a comparison between Wolf's and Dow Corning's projections. The price for a 60 kg ingot, derived from Wolf's projection is about the same as that resulting from the Dow Corning projections, despite the much higher indirect materials cost and the inclusion of "unsuccessful pulls", in Wolf's calculations, whereas Dow Corning did not include recycling. If the silicon recycling assumption would not have been made by Wolf, he would have obtained a significantly higher silicon crystal price than Dow Corning arrived at later. It may be noted that Dow Corning uses in Cz-pulling process for purification, with a significant amount of non-recyclable, impurity-enriched Si resulting as a by-product.

The total material costs for each ingot, which also includes the direct material contained in the good cylindrical silicon (lines 11, 17 and 23), were calculated employing the three different high purity silicon prices: \$65/kg, \$40/kg and \$10/kg. The first number represents the approximate current price for solar grade polycrystalline silicon. The second price is the LSA 1982 assumption, while the last price is the 1986 LSA goal. The higher the silicon price, the more it dominates the total material cost per unit mass. For example, at \$65/kg, the polysilicon cost comprises from 72% (Leybold-Heraeus) to 98% (Dow Corning growth techniques) of the total materials costs. However, comparing the add-on costs of the process is more valid than comparing total costs, since the Czochralski process itself is practically independent of the silicon price, except for the silicon lost in the crystal growing process which seems currently to be about 9% of the input for the Leybold-Heraeus data and the Wolf projections, and between 3 and 10% for the other data.

All costs in Table V are calculated on a "per charge" basis, which means any start to pull a single crystal ingot. Due to unsuccessful pulls and practical yields below the theoretical yields of line 9 in Table I, the "cost per unit mass of good cylindrical silicon" cannot be simply obtained by dividing the cost per charge by the cylindrical silicon mass given in line 4 of Table I. The real cost per unit mass of good cylindrical silicon, rather, has to be calculated by dividing the respective annual cost by the annual production of cylindrical silicon.

2.1.7 LABOR COSTS

To calculate the direct (operator) costs, a labor rate of $6.47/h including fringe benefits was chosen. This value was calculated from the wages paid a machine shop operator II (SAMICS' occupation classification no. 609885) whose yearly wage of $9,400 (7) converts to $4.52/h for a 40 h/week or $6.47/h with fringe benefits and miscellaneous expenses. The fringe benefits were assumed to be 36% of the basic wage (8) and miscellaneous expenses as 5.26% of the total labor costs. The labor hour needs for each ingot grown can be segmented into two areas. One portion consists of the labor monitoring required during the pull cycle, when an operator's time can be divided among several furnaces. There are also fixed operator times for each cycle, taken from the various data sources, during operations such as loading, balancing temperature, and unloading when 100% of a laborer's time is required. In all but one instance, the labor times are approximately one-third of the total cycle time. The exception, Dow Corning's continuous growth process, requires relatively little labor monitoring because of its automatic nature. Servicing labor times were only given for Leybold-Heraeus' single charge technique and Wolf's projections. The servicing labor costs were based on the wages of a maintenance mechanic II (SAMICS No. 638281)(7). The indirect labor costs in Table VI were taken as 25% of the direct labor charges following SAMICS' suggestions (8).

The total labor costs per charge between the three sources differ by a factor of about four; however the low contribution of the labor cost to the total costs makes this difference appear as an insignificant variation in the total add-on costs.

VI. LABOR HOUR REQUIREMENTS AND COSTS (on "Per Charge" basis)

Line Number		Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single Charge with crucible re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-charge	Texas Instruments, (April 1977) Projected Semi continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Fixed operator time (h)	1.5	2.0	2.5	n.a.	n.a.	n.a.	n.a.	n.a.
2.	Machine monitoring time (h)	2.8	2.5	2.7	n.a.	n.a.	n.a.	n.a.	n.a.
3.	Total operator time (h)	4.3	4.5	5.2	4.5	3.9	4.1	6.5	1.6
4.	Operator cost (11) ($)	27.83	29.10	33.65	29.10	25.25	26.55	42.05	10.35
5.	Servicing labor time (h)	0.8	0.67	0.67	n.a.	n.a.	n.a.	n.a.	n.a.
6.	Servicing labor (12) ($)	6.50	5.40	5.40	-	-	-	-	-
7.	Total direct labor cost (4. + 6.) ($)	34.30	34.50	39.05	29.12	25.24	26.53	42.07	10.35
8.	Total indirect labor cost (25% of 7.) ($)	8.58	8.63	9.79	7.28	6.31	6.63	10.52	2.59
9.	Total labor cost (7. + 8.) ($)	42.88	43.13	48.84	36.40	31.55	33.16	52.59	12.94

(11) at $4.52/h + 43.2% loading

(12) at $5.67/h + 43.2% loading

2.1.8 CAPITAL COSTS

The capital costs shown in Table VII have been calculated on an annual basis. Only for Leybold-Heraeus' data and Wolf's projections were installation costs (between 19 and 25% of puller costs) given. For Texas Instruments, the installation cost was assumed to be 25% of the puller cost. Dow Corning gave, in their data, the capital costs without equipment costs as 1.5 times the equipment costs. In Table VII, this value has been divided between installation, misc. equipment and building costs. The other equipment cost (line 3) accounts for items such as resistivity probes, argon regulators, cylindrical silicon handling devices etc., and was taken, in all cases, as 5% of the puller cost.

The total equipment charge rate was calculated from a seven year depreciation, 2% property tax (with equipment assessed at 50% of its cost), 4% insurance premium rate, and a 12% interest on debt on 8.3% of the equipment. To account for miscellaneous expenses the charge rate was divided by 0.95. The above values were suggested by SAMICS (8).

The allocatible building costs were either taken from the data sources, estimated, or marked n.a. (not available). The facilities charge rate was obtained as just described for the equipment charge rate, save a 40 year depreciation was used for the building. A charge for overhead utility use of 31% of the annual capital cost was added to complete the facilities charge given by SAMICS (8). The allocatible building area is equal to area occupied by the equipment plus the space needed for the operator and that needed for servicing access to the equipment. The total building area needed is taken as twice this

VII. CAPITAL COSTS

Line Number		Leybold Heraeus Experience Single Charge	Wolf's Projections from Leybold-Heraeus' Data Single Charge with Crucible Re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-charge	Texas Instruments, (April 1977) Projected Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Puller Cost $	80,000	110,000	185,000	100,000	125,000	200,000	175,000	200,000
2.	Installation Cost $	20,000 (13)	25,000	35,000	25,000 (13)	31,000	50,000 (13)	130,000 (e)	150,000 (e)
3.	Other Equipment Cost $ (5% of 1.)	4,000	5,000	9,000	5,000	6,000	10,000	9,000	10,000
4.	Total Equipment Cost $	104,000	140,000	229,000	130,000	162,000	260,000	314,000	360,000
5.	Depreciable Life y	7	7	7	7	7	7	7	7
6.	Charge Rate y^{-1}	0.214	0.214	0.214	0.214	0.214	0.214	0.214	0.214
7.	Annual Cost $	22,200	29,900	49,000	27,800	34,600	55,500	67,000	83,300
8.	Allocatable Building Area m^2	24	24	40	n.a.	n.a.	n.a.	163	185
9.	Allocatable Building Cost $	18,000	18,000	30,000	n.a.	n.a.	n.a.	123,000	140,000
10.	Depreciable Life y	40	40	40	40	40	40	40	40
11.	Charge Rate y^{-1}	0.117	0.117	0.117	0.117	0.117	0.117	0.117	0.117
12.	Annual Cost $	2,100	2,100	3,510	-	-	-	14,400	16,400
13.	Total Capital Costs (7. + 12.) $	24,300	32,000	52,500	27,800	34,600	55,500	81,400	99,700

(e) Estimated

(13) Estimated as approximately 25% of 1.

equipment area. The additional building area cost, however, is included in the cost multiplier, which is $\$1507/m^2$, for the unit equipment area.

2.1.9 ADD-ON COST SUMMARY

For a comparison of different Cz-pull techniques, it is more important to examine the add-on rather than the total costs, because the high direct material costs of the silicon (the silicon incorporated into good cylindrical crystal) can easily mask otherwise significant cost differences between processes. The add-on costs, though, must include the cost of silicon lost in the process, because the lost direct material forms a valid and significant cost element which is determined by the specific process applied.

The add-on costs listed in Table VIII are given on the "per unit mass of good cylindrical crystal pulled" basis. They were calculated, unless otherwise indicated, by multiplying the item charge cost by the total number of charges per year and dividing this product by the output of good silicon.

The total add-on cost (lines 17, 20 and 23) for the crystal growing process is its total cost, minus the cost of the polycrystalline silicon incorporated into the saleable part of the ingot. It is thus the cost of converting polycrystalline silicon to single crystal cylindrical silicon. As one would expect, the add-on cost exhibits sensitivity to the various crystal growing procedures, while the total cost is more influenced by the poly-silicon cost. The Dow Corning projection for a continuous growth technique gives the lowest total add-on cost ($7.36/kg-Si with silicon at $10/kg) because of their low material and labor numbers. At the other extreme is the single charge state-of-the-art method described by Leybold-Heraeus with its high costs for crucible, replacement parts, argon, and labor. Of these

VIII. ADD-ON COST SUMMARY ($/kg cyl. silicon)

Line Number		Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single Charge with Crucible Re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Texas Instruments, (April 1977) Projected Multi-Charge	Texas Instruments, (April 1977) Projected Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Dow Corning, (July 1977) Projected Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Direct Labor (14)	2.40	1.46	0.74	1.97	1.70	1.19	1.11	0.27
2.	Maintenance Labor (14)	0.56	0.27	0.12	n.a.	n.a.	n.a.	n.a.	n.a.
3.	Other Indirect Labor (14)	0.74	0.43	0.21	0.49	0.43	0.30	0.28	0.07
4.	Total Labor (1. + 2. + 3.)	3.70	2.16	1.07	2.46	2.13	1.49	1.39	0.34
5.	Equipment cost (VII.7 ÷ III.5)	4.89	3.20	2.05	3.24	3.44	3.88	3.31	3.00
6.	Facility cost (VII.12 ÷ III.5)	0.46	0.23	0.14	-	-	-	0.71	0.59
7.	Capital Cost (5. + 6.)	5.35	3.43	2.19	3.24	3.44	3.88	4.02	3.59
8.	Crucible (14)	19.43	1.00	1.02	8.45	2.84	1.89	0.53	0.53
9.	Replacement parts and outside service (14)	12.09	4.68	3.05	3.65	1.55	1.04	0.73	0.66
10.	Seed (14)	n.a.	n.a.	n.a.	0.34	0.34	0.20	n.a.	n.a.
11.	Argon (14)	2.73 (15)	0	0	2.33	2.23	1.58	n.a.	n.a.
12.	Energy	3.03	1.67	0.88	1.10	1.12	0.80	0.96	0.96
13.	Cooling Water (16)	0.54	0.30	0.15	0.20	0.20	0.14	0.17	0.17
14.	Total Indirect Materials	37.82	7.65	5.10	14.75	8.28	5.65	2.39	2.32
15.	Total add-on cost excluding silicon (4.+7.+14.)	46.91	13.25	8.36	21.76	13.85	11.02	7.80	6.25
16.	Lost Si at $65/kg (V.8 ÷ I.4)	8.43	8.43	8.43	5.05	2.85	1.90	7.22	7.22
17.	Total add-on cost (15.+16.)	55.34	21.68	16.79	26.81	16.70	12.92	15.02	13.47
18.	Total Materials (14.+16.+$65)	111.25	81.08	78.53	84.80	76.13	72.55	74.61	74.54
19.	Lost Si at $40/kg (V.14. ÷ I.4)	5.19	5.19	5.19	3.11	1.76	1.17	4.44	4.44
20.	Total add-on cost (15.+19.)	52.10	18.44	13.59	24.87	15.61	12.19	12.24	10.69
21.	Total Materials (14.+19.+$40)	83.01	52.84	50.29	57.86	50.04	46.82	46.83	46.76
22.	Lost Si at $10/kg (V.20 ÷ I.4.)	1.30	1.30	1.30	0.78	0.44	0.29	1.11	1.11
23.	Total add-on cost (15.+22.)	48.21	14.55	9.66	22.54	14.29	11.31	8.91	7.36
24.	Total materials (14. + 22. +$10)	49.12	18.95	16.40	25.53	18.72	15.94	13.50	13.43

(14) Based on cost per charge times III.1 ÷ III.5

(15) Based on $0.14/s. cu. ft. and VI.16.

(16) Based on $0.566 per 100 kWh furnace dissipation.

four, the dominating items are, in the state-of-the-art process, the crucible costs and the furnace replacement parts costs, which are listed in Table V on a per load basis, and in Table VIII related to unit mass of crystal pulled. If both crucibles and furnace parts were replaced five to ten times less frequently, then this cost item would become less significant than the capital costs.

As for any single charge technique of current practice, the total add-on cost (line 15) could be reduced significantly by using the crucible for more than one charge and by eliminating the need for argon (i.e. growing the single crystal under vacuum). However, a key item for reaching the projected low costs, higher mass pull rates are needed. The relatively low productivity of today's pullers has the consequence of high labor, depreciation, and overhead costs per-unit mass of silicon ingot grown.

The multi-charge and semicontinuous techniques, described by TI, offer several advantages over their single charge method. The crucible cost of the single charge method is reduced by 57% and replacement parts cost by more than 50%. The multi-charge indirect materials add-on costs are 44% less than those for the single charge method, while TI's semicontinuous add-on indirect materials cost is more than 62% less.

Dow Corning's total indirect material add-on costs/kg-Si are the lowest listed because of the extremely low labor and materials usage, to which they have been factored. The total material add-on costs ($2.32/kg-Si) for their continuous growth method are given as less than one-half those of the other companies. The D.C. data show very low crucible cost (it is used for ten charges before replacement), and furnace replacement parts costs (the heater elements are re-used 100 times). The low labor costs result, in part, from one operator handling 6 furnaces. The major cost difference between Dow Corning's sequential and continuous growth processes is the labor requirement. The sequential process needs 0.44 operators/puller, resulting in a total labor cost of approximately $1/kg more than for the continuous growth process. The relatively large fraction of non-recylable silicon in the Dow Corning's processes makes their total add-on costs, for the three silicon prices applied, appear more comparable to the process data from the other sources listed than they should otherwise be. The large amount of lost Si is, however, the result of the process applied primarily for purification rather than to crystal growing purposes.

It may be noted that it is recognizable that the cost tabulations based on experimental runs have a tendency to not anticipate all the material, tooling, servicing, and labor requirements experienced in actual production. Consequently, those projections which include seemingly optimistic assumptions should be subjected to some further scrutiny. Similarly, the 100% successful pull rates projected by Texas Instruments and Dow Corning seem optimistic.

There are also indications that the prices from the "commercial experience data" which were used here, are low. One reason for this is that no indirect charges have been applied to the direct material cost. But this alone, apparently, does not bring the costs up to other recently suggested experience values. Further investigations would be needed to clarify this point.

2.1.10 PRICE CALCULATIONS

In order to obtain single crystal ingot prices according to SAMICS' price formula (8), the costs listed in Tables IV to VIII have to be augmented by an "overhead", and "materials' handling charge", and a "return-on-equity".

The correspondence of these items, between our calculations and SAMICS is detailed in the next section.

The overhead listed in Table IX consists of the costs of the working capital, that is the charges of property tax (2%), insurance premiums (4%), and interest on debt (12% on one-sixth the book value). The working capital is assumed to be 15% of the cost of equipment and facility. It should be noted that this overhead is small; however, many of the charges normally assigned to overhead are in this analysis listed in other categories. For instance, the facility charge rate (Table VII) includes the costs of supporting or overhead facilities, such as process support areas, aisles, administrative offices, etc., in addition to the required equipment areas. Also, the "miscellaneous expenses" included by dividing the equipment, facilities, and labor costs by 0.95, would normally be considered to be an overhead expense. The same division by 0.95 applied to the materials costs is here considered a "materials handling charge".

The return on equity, or profit, is calculated by using a 20% rate of return and a financial leverage of 1.20 (the ratio of the total capital to equity capital). The low leverage value has been assumed for SAMICS because the expanding photovoltaic industry will be a high risk venture not able to attract large amounts of debt capital.

IX. OVERHEAD, HANDLING CHARGES, RETURN ON EQUITY AND PRICE ($/kg. cyl. Si)

Line Number		Leybold-Heraeus Experience Single Charge	Wolf's projections from Leybold-Heraeus' data Single charge with crucible re-use		Texas Instruments, (April 1977) Experim'l Single Charge	Projected Multi-charge	Semi-continuous	Dow Corning, (July 1977) Projected Sequential Growth	Continuous Growth
	Designation	LH1	W1	W2	TI1	TI2	TI3	DC1	DC2
1.	Overhead (0.059*VIII.5 + 0.108*VIII.6)	0.34	0.21	0.14	0.19	0.20	0.23	0.27	0.24
2.	Materials handling (5.26% of VIII.14)	1.99	0.40	0.27	0.78	0.44	0.30	0.13	0.12
3.	Return of equity (0.195*(VIII.14 +IX.2)+ 0.19* VIII.4 + 1.24* VIII.5 + 4.255* VIII.6)	16.48	6.93	4.39	7.51	6.37	6.22	7.88	6.77
4.	Add-on price @ $65/kg (VII.17 + IX.1 + IX.2 + IX.3)	74.15	29.22	21.59	35.29	23.71	19.70	23.30	20.50
5.	Price @ $65/kg (IX.4 + $65)	139.15	94.22	86.59	100.29	88.71	84.70	88.30	85.60
6.	Add-on price @ $40/kg (VII.20 + IX.1 + IX.2 + IX.3)	70.91	25.98	18.39	33.35	22.62	18.94	20.52	17.82
7.	Price @ $40/kg (IX.6 + $40)	110.91	65.98	58.39	73.35	62.62	58.94	60.52	57.82
8.	Add-on price @ $10/kg (VII.23 + IX.1 + IX.2 + IX.3)	67.02	22.09	14.46	31.02	21.30	18.06	17.19	14.49
9.	Price @ $10/kg (IX.8 + $10)	77.02	32.09	24.46	41.02	31.30	28.06	27.19	24.49

The "return-on-equity" also contains a return on the start-up capital required in the early years of the plant's life, before profitable production has started. This "one-time amortization cost" actually forms the larger part of the "return-on-equity".

The addition of the above three factors to the add-on cost yields the add-on price. The price is then the sum of the add-on price and the cost of the silicon contained in the cylindrical ingot.

In comparing the cylindrical silicon prices for the different Cz-growing methods, the data for the Leybold-Heraeus and Texas Instruments single charge technique, and Wolf's projections for a 10.16 cm diameter ingot are high compared to the other projections at the polysilicon prices of $65 and $40/kg. The high crucible (as it is used only once), argon, and replacement part costs lead to the high price for Leybold-Heraeus' single charge technique. For Wolf's projection (W1), high replacement part costs along with a high capital cost result in a high cylindrical silicon price per kg. The one-time crucible use for TI's single charge technique is the biggest factor in making this process relatively expensive. At these polysilicon prices, the current and 1982 LSA projected calculated cylindrical ingot prices for the other projections are grouped closely together, there being less than a $5/kg difference between the highest and lowest prices.

The 1986 projected cylindrical crystal ingot prices show greater relative differences than observed for the earlier two years. Wolf's 15.2 diameter ingot projection and Dow Corning's continuous growth technique because of their low crucible, argon and labor costs show the lowest (by about $3/kg) ingot prices listed, while the Texas Instruments semicontinuous and Dow Corning's sequential growth methods form the next lowest group, followed by Wolf's 10.16 cm diameter projections and TI's multicharge approach.

To illustrate the changes in the cost of a Czochralski pulled crystal for the near future, the cost components from Leybold-Heraeus and the Wolf projections from Leybold-Heraeus have been plotted (Figure 1). The 1978 bar is based on Leybold-Heraeus' product or experience and a polysilicon price of $65/kg. The 1982 ingot price is Wolf's 26.6 kg ingot projection, and the 1986 price on Wolf's 60 kg ingot projection.

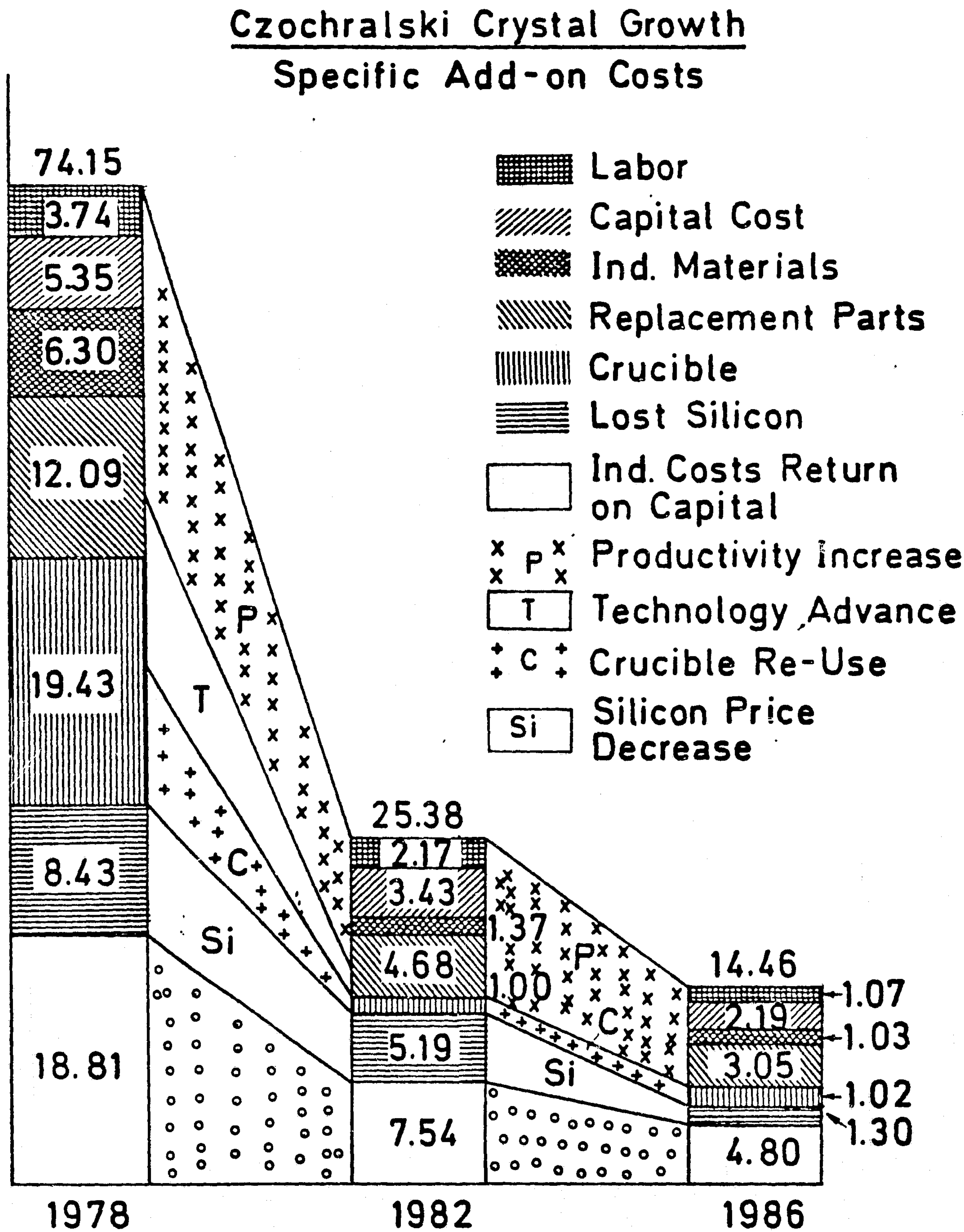
Czochralski Crystal Growth
Specific Add-on Costs
Labor
Capital Cost
Ind. Materials
Replacement Parts
Crucible
Lost Silicon
Ind. Costs Return on Capital
Productivity Increase
Technology Advance
Crucible Re-Use
Silicon Price Decrease
74.15
3.74
5.35
6.30
12.09
19.43
8.43
18.81
25.38
2.17
3.43
1.37
4.68
1.00
5.19
7.54
14.46
1.07
2.19
1.03
3.05
1.02
1.30
4.80
P
T
C
Si
1978
1982
1986

FIGURE 1.

2.2 CORRELATION OF THE "UNIVERSITY OF PENNSYLVANIA PROCESS CHARACTERIZATION (UPPC)" AND THE SAMICS METHODOLOGIES

2.2.1 DISCUSSION OF THE RELATIONSHIP OF SAMICS AND UPPC

With the beginning of this project, the evolution of a standard format and methodology was started which was to guide and ease the tasks of collecting an appropriate and adequate amount of data for process evaluations, and also to provide a format for price calculations. To properly fulfill its task, the format has to be applicable to any of the fabrication process options, which means that it needs to be general and flexible, while it simultaneously has to be adequately detailed. The format should be capable of accomodating industry cost and price computation practices to permit the cross checking of the accumulated data against the costs computed at their source. But then, the costs have to be equally readily computed by the SAMICS methodology to provide a standardized cost picture. Most importantly, however, the method has to provide clear visibility of the key cost drivers of an individual process, as well as of other potential problem attributes. This evolution resulted in the current version of the "University of Pennsylvania Process Characterization (UPPC)" format, in which the process details which were accumulated for the Czochralski crystal pulling process, are presented in the Appendix. The following section details the relationship between the UPPC format and the SAMICS methodology, and derives the various multipliers to be used in applying UPPC in the SAMICS methodology.

2.2.2 CONCEPTUAL AND MATHEMATICAL CORRELATION

In the "Solar Array Manufacturing Industry Costing Standards" (SAMICS) "Interim Price Estimation Guidelines" (IPEG) the "Annual Manufacturing Cost" (including the return on investment) for a solar module or its work-in-process is expressed by the linear relationship (JPL LSA Project document 5101-33, page 2-1):

$$AMC = C_1*EQPT + C_2*SQFT + C_3*DLAB + C_4*MATS + C_5*UTIL. \quad (1)$$

where:

EQPT = original cost of the equipment

SQFT = equipment area in square feet

DLAB = annual direct labor cost

MATS = annual expense for direct materials

UTIL = annual expense for utilities needed directly for the process

According to the equations on page C-1 of JPL document 5101-33, the annual manufacturing cost (unit price times quantity produced annually) is calculated from the following relationship:

$$AMC = PRICE \times QUANTITY$$

$$= \frac{OPR + OTX + INS + INT}{(1-x)} + \frac{RPL - \tau*DEP - ITC + AOC + EQR}{(1-x) * (1-\tau)} - BYP \quad (2)$$

Here, OPR are the annual operating expenses given by:

$$OPR = (1 + FB) * (DLAB + INDLAB) + (MATS + INDMATS) + (UTIL + INDUTIL); \quad (3)$$

The prefix "IND" indicates expenses for the respective indirect cost items, such as "INDMATS" for indirect materials and supplies. Similarly, OTX, INS, and INT are the annual charges on the capital for property taxes, insurance, and interest on debt, respectively, which are related to the costs of the facility (FAC) and of the equipment (EQPT) and to the working capital (WCAP). RPL refers to the annual cost of replacing capital items (equipment and facility), while DEP is the depreciation used for income tax purposes, τ being the income tax rate (50%). ITC is the income tax credit, applicable to new purchases of equipment, EQR is the expected return on investment, and AOC the cost of debt and of the expected return on the equity for the capital required for plant construction and start-up. BYP is the sum of any credits obtained for byproducts sold. IPEG uses the "miscellaneous expense fraction" x, with a value of 0.05, to cover various indirect costs not explicitly accounted for.

For the purposes of accumulating relevant information and analyzing cost contributions of various process options, the "University of Pennsylvania Process Characterization" format (UPPC) has been evolved. Such analyses are more readily performed by use of a relationship whose structure resembles eq (1) rather than eq (2). This type of structure eases the task of identifying the major cost contributors and of approaches towards eliminating or reducing their impact. However, the factors C_1 through C_5 of eq (1) need to be broken into several components according to the origin of the cost contribution, such as operating costs, indirect charges, return on equity, etc. Following the SAMICS system, this can be accomplished by reorganizing eq (2) in a form more similar to eq (1):

$$AMC = \frac{\text{OPR (MATS, INDMATS, UTIL)}}{(1-x)}$$

$$+ \frac{\text{OPR (DLAB, INDLAB)}}{(1-x)}$$

$$+ \frac{OTX\ (EQPT) + INS\ (EQPT) + INT\ (EQPT) + \frac{RPL\ (EQPT) - \tau\ DEP\ (EQPT)}{(1-\tau)}}{(1-x)}$$

$$+ \frac{OTX\ (FAC) + INS\ (FAC) + INT\ (FAC) + \frac{RPL\ (FAC) - \tau DEP\ (FAC)}{(1-\tau)} + OPR\ (INDUTIL)}{(1-x)}$$

$$+ \frac{OTX\ (WCAP) + INS\ (WCAP) + INT\ WCAP)}{(1-x)}$$

$$+ \frac{EQR\ (EQPT,\ FAC,\ WCAP) - ITC\ (EQPT)}{(1-x)\ (1-\tau)}$$

$$+ \frac{AOC\ (MATS,\ INDMATS,\ UTIL,\ DLAB,\ INDLAB,\ EQPT,\ FAC,\ INDUTIL)}{(1-x)\ (1-\tau)} \quad (4)$$

In this form, each term represents a specific cost contribution. The first and second terms express the operating costs based on all materials and supplies usage, and on all labor, respectively, while the third and fourth terms represent the tax, insurance, debt service, and depreciation costs of the equipment and the facility, respectively, and, in the latter case, also the "indirect utility" operating costs for space conditioning and lighting the facility. The fifth term includes the tax, insurance, and debt service costs for the working capital, while the sixth term describes the cost of the expected after-tax return on equity, reduced by the investment tax credit. The seventh term, finally, represents the annual cost of the capital needed for plant construction and start-up, as explained before.

It may be noted that the assignment of the costs of debt service to equipment and facility "costs", and of the expected return on equity to "profit", although common because of existing tax laws, appears somewhat arbitrary in view of the dependence of this division on the leverage exercised by the individual company, and tends to result in variations of the process "costs". It is therefore preferable to include the "profit" in economic comparisons, that is, to make such evaluations on the "price" rather than the "cost" basis. Similarly, the "start-up costs" include filling up the production line with work-in-process, and to build up raw material, supply, and finished goods inventories. Consequently, the real costs of the working capital, as far as they refer to taxes and insurance, may be understated in this treatment. This again emphasizes the benefit of using the price rather than cost for economic evaluations.

In accordance with the organization of cost contributions described by eq (4), the UPPC format provides for tabulation of the materials costs on forms 3 through 5. Form 2 details the input work-in-process, whose input cost (item 1.3) is not loaded with any indirect charges for purposes of calculating the add-on cost or the price of the output work-in-process or finished product. Form 3 allows tabulation of other direct materials (MATS), with their costs summarized in item 2.1, while form 4 similarly summarizes the indirect materials and supplies costs (INDMATS) in item 2.2. Form 5 allows the accumulation of the costs of expendable tooling in item 2.3, and of energy and other utility costs in item 2.4. All material costs are subtotaled in item 2.5. The "miscellaneous cost fraction" x is applied as a factor $(1-x)^{-1}$ to item 2.5, as expressed in the first term of eq (4), and is here called a "materials handling charge", as commonly applied in industry.

In correspondence with eq (3) and (4), the direct labor costs are summarized on form 6 of UPPC in item 3.1, after applying the factor (1 + FB) for fringe benefits which causes a 36% load on the direct labor. Following IPEG, INDLAB is then applied at 0.25 * (1+FB)* DLAB for item 3.2 of the UPPC. The "miscellaneous expense fraction" (x) is applied by multiplying with $(1-x)^{-1}$, or adding an "overhead" charge on labor of 5.26% in item 3.4 of UPPC. As mentioned previously, in the simplified, IPEG type use of the UPPC format, any service labor needed to repair or otherwise maintain the process equipment or to perform any auxiliary functions, is treated as direct labor and included in item 3.1. If single shift, 5 day/week operation is evaluated, the annual labor hours required for one operator at a given process station are multiplied with 1.185, to obtain the total annual labor hours to be expensed in order to assure continuous attention at the work station, even during absenteeism periods. If, however, continuous (7 day per week) 3 shift operation is evaluated, this multiplier becomes 4.7, according to "SAMICS Usage Update Number 1", JPL document 5101-59.

The annual equipment costs are computed according to the third form of eq (4). According to JPL document 5101-33, it is:

$$OTX = \beta * VAL_{tax} \tag{5}$$

$$\begin{aligned} VAL_{tax} &= \tfrac{1}{2} * (FAC + EQPT) + WCAP \\ &= VAL_{book} \end{aligned} \tag{6}$$

where:

$$WCAP = 0.15 * (FAC + EQPT) \tag{7}$$

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$$ACEQT = (\tfrac{1}{2} * \beta + \nu + \tfrac{1}{2} * i * \frac{\lambda - 1}{\lambda} + \frac{1}{7}) * \frac{1}{1-x} * EQPT \qquad (13)$$

$$\underset{OTX}{\uparrow} \quad \underset{INS}{\uparrow} \quad \underset{INT}{\uparrow} \quad \underset{DEP}{\uparrow}$$

$$= 0.2135 * EQPT \quad (\$/y) \qquad (13a)$$

The factor 0.2135 is applied as the annual "charge rate" in item 4.1 of UPPC.

The annual costs ACFAC of the facility are similarly treated, in accordance with the fourth term of eq (4). Excluding the indirect utility costs, the annual facility charges are:

$$ACF = (\tfrac{1}{2}*\beta+\nu+\tfrac{1}{2}*i* \frac{\lambda-1}{\lambda} + \frac{1}{40}) * \frac{1}{1-x} * 1528.5 * AREA \qquad (14)$$

$$= 136.76 * AREA \ (\$/y) \qquad (14a)$$

Equation (14) is the basis of the charge rate of \$136.72/(m^2 y) applied in item 4.2 of UPPC.

The use of indirect energy for lighting and conditioning the facility is, following IPEG, also proportional to the area used:

$$OPR\ (INDUTIL) = 3.74\ (\$/(ft^2\ y))\ *SQFT \qquad (15)$$

$$= 3.74 * 10.764\ (\$/(m^2\ y)) * AREA\ (m^2)$$

$$= 40.26\ (\$/(m^2\ y)) * AREA\ (m^2) \qquad (15a)$$

The sum of eq (14a) and (15a) yields the total annual cost of the facility. Applying the inverse (1-x) factor yields an energy use charge of \$42.38/(m^2 y) for item 4.2 of UPPC. The sum of eq (14a) and the energy use charge then correspond to the fourth term of eq (4), yielding

$$ACFAC = ACF + \frac{INDUTIL}{(1-x)} = 179.14\ (\$/(m^2\ y))\ *\ AREA\ (m^2) \qquad (16)$$

as the subtotal item 4.2 of UPPC for its simplified IPEG application.

From the analytical viewpoint, this simplified breakout is not quite as transparent as desirable, since maintenance costs for both equipment and facility are included in the labor operating costs, while outside repair services and replacement parts are assigned to the materials operating costs. The UPPC format includes provision for full association of all equipment or facility related costs, including maintenance labor and replacement parts and/or outside services. When the format is used in the SAMICS-IPEG mode, this provision is not utilized in the interest of compatibility with the SAMICS methodology.

As previously discussed, the "Other Indirect Costs", shown as item 7.22 of UPPC, are the annual costs of the working capital according to the fifth term of eq (4). According to IPEG, these costs are calculated as

$$ACWC = (\beta + \nu + i*\frac{\lambda-1}{\lambda})\ *\ \frac{1}{1-x}\ *\ 0.15\ *\ (EQPT + FAC)$$

For the equipment, this becomes 0.059 * ACEQT of eq (13) or 0.059 times the amount found on line 4.1 of UPPC. Similarly, the contribution to the annual cost of working capital from the facility, expressed as a factor to the annual facility costs ACFAC of eq (16), shown on line 4.2 of UPPC, becomes:

$$\frac{\beta + \nu + i * \frac{\lambda-1}{\lambda}}{\frac{1}{2}\beta + \nu + \frac{1}{2} i * \frac{\lambda-1}{\lambda} + \frac{1}{40} + \frac{INDUTIL}{FAC}} * 0.15 = 0.108 \tag{18}$$

so that:

$$ACWC = 0.059 * (\text{value line } 4.1) + 0.108 * (\text{value line } 4.2) \tag{19}$$

The costs NREQ of the net expected return on equity are given by the sixth term of eq (4). Following page C-4 of JPL document 5101-33, it is:

$$EQR = r * \frac{1}{\lambda} * VAL_{book} = 0.1667 * (VAL_{book}) \tag{20}$$

with the expected rate r of return on equity being 20%, and:

$$ITC = \alpha * \frac{EQPT}{7} = 0.0143 * EQPT \tag{21}$$

α being 0.1.

Following eq (6) and (7):

$$VAL_{book} = 0.65\ EQPT + 0.65\ FAC \tag{22}$$

so that:

$$NREQ = \frac{EQR - ITC}{(1-x)(1-\tau)}$$

$$= \frac{(0.1667*0.65 - 0.0143) * EQPT + 0.1667 * 0.65 * FAC}{(1-x)\ (1-\tau)}; \tag{23}$$

$$= 0.1980 * EQPT + 0.2281 * FAC \tag{23a}$$

Applying eq's (13a) and (16) together with (11), eq (23a) can readily be expressed in terms of quantities previously obtained in the UPPC format (lines 4.1 and 4.2):

$$NREQ = \frac{0.1980}{0.2135} * ACEQT + \frac{0.2281 * 1528.5}{179.14} * ACFAC$$

$$= 0.9274 * ACEQT + 1.946 * ACFAC \qquad (24)$$

Finally, there is the seventh term of eq (4), the "amortization of start-up costs", AOC, to be dealt with. JPL document 5101-33 gives, on page C-6, AOC as:

$$AOC = 0.030 * EQPT + 21.9 * SQFT + 0.163 * DLAB$$

$$+ 0.096 * MATS + 0.096 * UTIL \qquad (25)$$

The last three terms of eq (25) arise solely from the quantity PVSU on top of page C-6 of JPL document 5101-33, which contains 1.70 * DLAB + MATS + UTIL. The 1.70 factor of DLAB results from the product (1 + FB)*(1+0.25), the latter factor accounting for the indirect labor, so that this 1.70 * DLAB term corresponds to item 3.3 of the UPPC format. Similarly, MATS + UTIL correspond to item 2.5 of the UPPC format. In PVSU, both items are multiplied by 0.096, and for the seventh term of eq (4), they are divided by $(1-x)*(1-\tau)$. Items 2.7 and 3.5 of UPPC contain the division by (1-x) already, so that the corresponding part of the annual cost ACAOC of the amortization of start-up costs (7th term eq (4)) becomes:

ACAOC (MATS, INDMATS, UTIL, DLAB, INDLAB)

$$= \frac{0.096}{(1-\tau)} * \left[(\text{value item 2.7}) + (\text{value item 3.5})\right] \qquad (26)$$

$$= 0.192 * \left[(\text{value item 2.7}) + (\text{value item 3.5})\right] \qquad (26a)$$

The equipment part of ACAOC is obtained as:

$$ACAOC\ (EQPT) = \frac{0.030 * EQPT}{(1-x)\ (1-\tau)} \quad (27)$$

$$= \frac{0.030}{0.95 * 0.5} * \frac{ACEQT}{0.2135}$$

$$= 0.2958 * ACEQT, \quad (27a)$$

making use of eq (13a) and the value obtained in item 4.1 of the UPPC format.

Similarly, the facility part of ACAOC, including the indirect utility costs part of PVSU, becomes:

$$ACAOC\ (FAC) = \frac{21.9 * SQFT}{(1-x)\ (1-\tau)} \quad (28)$$

$$= \frac{21.9}{0.95 * 0.5} * AREA * 10.764$$

With eq (16), this is again relatable to a quantity already obtained in the UPPC format (ACFAC, item 4.2), so that:

$$ACAOC\ (FAC) = \frac{21.9 * 10.764}{0.95 * 0.5} * \frac{ACFAC}{179.14}$$

$$= 2.770 * ACFAC \quad (28a)$$

The sum of all these annual cost terms provides the total annual plant cost, and, after division by the quantity of good output work-in-process or finished product, its price.

3. CONCLUSIONS AND RECOMMENDATIONS

A comparison of the current crystal growing costs with the projected future costs shows that the latter are all based on assumed advancements in technology which have not yet been fully demonstrated. The considerable magnitude of the expected decrease of the add-on costs emphasizes the importance of the realization of the anticipated technology advances. These advances fall into four categories: an increase in furnace productivity, the reduction through multiple use of crucible costs, the combined effect of miscellaneous smaller improvements, and the carry-forward effect of advances in the silicon purification area, which are expected to make polycrystalline silicon available at greatly reduced prices. Approximately half of the projected increase in crystal pulling furnace productivity results from larger diameters than the presently produced crystals have. The diameter is expected to increase from nominally 78mm diameter at present to nominally 102mm by 1982, and to 152mm by 1986. The other half of the productivity increase, however, is expected to come from a higher linear pull rate, which would more closely approximate the thermodynamically computed limit pull rate than current practice does. This prediction of a linear pull rate increase is more risky as two, currently not adequately explored phenomena are involved. The first concerns crystal perfection which may decrease with increasing pulling speed, and may possibly prevent the practical use of the expected pull rates. The second phenomenon is related to the common furnace designs which result in considerable radiative heat transfer from the melt surface and the heater environment to the grown crystal, thus preventing a close approach to the limit growth rates. This spurious radiative heat transfer could, in principle, be reduced by introduction of appropriate heat shields. To what degree this can be achieved in practice, without interfering with other aspects of the crystal growing process, needs to be explored.

The projected crucible cost reductions are also based on two aspects. The primary one is the assumption that crucibles can be used for the equivalent of up to 10 individual crystal pulls, either with re-seeding or with (quasi-) continuous pulling, rather than the currently practiced usage of the crucibles for only one crystal each. The second aspect is related to the finding that crucibles for big charges (over 15 kg) as required for the improvement of furnace productivity, cost considerably more per unit volume than the more commonly used crucible sizes. It has been projected that the fabrication technology for large volume crucibles can be sufficiently improved to bring their co[illegible]r unit volume down to the same value as commonly paid for crucibles in the two to eight kilogram charge range.

Included in the "miscellaneous improvements" is the reduction of the energy consumption per unit mass of crystal pulled, which has been assumed to be reduced to approximately half of the current value. Approximately two-thirds of this reduction result from the assumption that the heat losses per unit mass pulled are directly related to the crystal geometry change, and thus can be reduced by the growing of larger diameter ingots. The other third of the reduction in energy consumption is assumed to be achievable through improvements in furnace design with respect to heat shielding and thermal insulation.

Other technology advances in the area of furnace design have been postulated as achieving considerably reduced annual costs for equipment replacement parts, which become significant after elimination of the now-predominant crucible costs.

The final element in the projected cost reduction is the projected decrease of the polycrystalline silicon price from the current level of $65/kg to $40/kg by 1982, and to $10/kg by 1986. In the analysis of the specific add-on costs, the silicon price enters only through the fraction of the charge which is lost in the process, primarily through the silicon contained in the bottom taper and the small amount remaining in the crucible, both of which are enriched with impurities and therefore not re-usable. As the price of the polycrystine silicon decreases, the cost contribution from this lost silicon will be significantly reduced.

Summarizing, it can be observed that the various recent investigations of the Czochralski crystal growing process came to the same conclusion, with relatively minor variations in detailed approach, that the best approaches to growing cylindrical silicon single crystals at low cost lie in production rate increases through growth of larger diameter ingots, in crucible re-use, and in longer life-time of furnace parts. The four currently active LSA projects in this area are directed at realizing these improvements. Once the results of these efforts are attained, it would be appropriate to re-examine the process attributes and the cost structure of the Czochralski crystal pulling process, and to identify the items to be investigated for the next round of improvements. In this connection, it may be interesting to note that in the multi-charge and semi-continuous pulling techniques (projections by Texas Instruments and Dow Corning), where the crucible costs have been drastically reduced, the capital costs appear as the largest single cost item.

4. NEW TECHNOLOGY

No new technology was developed during this quarter.

5. REFERENCES

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3. Samuel N. Rea and Paul S. Glenn, "Large Area Czochralski Silicon," Texas Instruments, ERDA/JPL-954475-77/4, Final Report (April, 1977).

4. L.P. Hunt, V.D. Dosaj and J.R. McCormick, "Solar Silicon via Improved and Expanded Metallurgical Silicon Technology," Dow Corning, ERDA/JPL-954559-77/2, 4th Quarterly Report (July, 1977).

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7. Theodore Barry and Associates, "SAMICS Support Study, Cost Account Catalog," Jet Propulsion Laboratory, ERDA/JPL-954800-77/2.1, Volume 1, Account C (Sept. 1977).

8. Robert W. Aster and Robert G. Chamberlain, "Interim Price Estimation Guidelines," Jet Propulsion Laboratory, 5101-33 (Sept. 10, 1977).

6. APPENDIX

The University of Pennsylvania Characterization
Formats for Chzochralski Crystal Pulling for 7.8, 10.2 and 15.2 cm
Diameter Cylindrical Silicon Crystal Ingots

Process No. 2 . 1 . 0 1 - 0 1

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Sheet Generation

Subprocess: Ingot Generation

Option: Crystal Pulling (Single Charge)
7.8 cm diameter crystal

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Form 2

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Process No. 2.1.01-01

0.1 Value Added:	$/

Process Description: Single crystal ingot growth by Czochralski pulling, using the Leybold-Heraeus puller type EK2 1600/6000

1. Input Specification:

Name of Item: Polycrystal silicon

Dimensions: Crushed Polyrod or shaped charge

Material: Solar Grade Silicon

Other Specifications: As agreed between individual users and vendors

1.1 Quantity Required: 16.2 kg /charge Unit Cost: 65 $/ kg

1.2 Input Value:	$/
1.3 Input Cost:	1053 $/charge

Note to Item 1.3: Use price, if input produced in own plant

Process No. 2 . 1 . 0 1 - 0 1

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2.1 Direct Materials:

2.11 Type: Doping charge;

Specification: As specified by user;

Quantity Required: ______ __/__; Unit Cost: ______ $/______; Cost: na $/charge

2.1_ Type: ______;

Specification: ______;

Quantity Required: ______ __/__; Unit Cost: ______ $/______; Cost: ______ $/______

2.1_ Type: ______;

Specification: ______;

Quantity Required: ______ __/__; Unit Cost: ______ $/______; Cost: ______ $/______

2.1 Subtotal Direct Materials: 0 $/ charge

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Form 4

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2.2 Indirect Materials (incl. supplies and non-energy utilities):

2.2.1 Type: Cooling Water;

Specification: 127 m^3 of cooling water per charge to dissipate 1100 kWh of heat

cop (SAMICS No. C1128D)

Quantity Required: 1100 kWh/charge Unit Cost: 0.566 \$/100 kWh; Cost: 6.23 \$/charge

2.2.2 Type: Argon, pre-purified

Specification: (SAMICS No. E1112D)

Purity minimum is 99.998%

Quantity Required: 6.4 m^3/charge Unit Cost: 4.945 \$/m^3; Cost: 31.65 \$/charge

2.2_ Type: ____________

Specification: ____________

Quantity Required: ______ ___/___; Unit Cost: ______ \$/______; Cost: ______ \$/______

2.2 Subtotal Indirect Materials:	37.88 \$/charge

Process No. 2 . 1 . 0 1 – 0 1

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2.3 Expendable Tooling:

2.3_ Type: Furnace replacement parts

Quantity Required: ____ ____/____ : Unit Cost: ____ $/____ Cost: 140 $/ charge

2.32 Type: Quartz crucible liner (25 x 25 cm, capacity 30 kg)

Quantity Required: ____ ____/____ : Unit Cost: 225 $/ cruc Cost: 225 $/ charge

2.3_ Type: ____

Quantity Required: ____ ____/____ : Unit Cost: ____ $/____ Cost: ____ $/____

2.3_ Type: ____

Quantity Required: ____ ____/____ : Unit Cost: ____ $/____ Cost: ____ $/____

2.3 Subtotal Expendable Tooling: 365 $/ charge

2.4 Energy

2.4_1 Type: Electricity

Quantity Required: 1100 kWh/charge : Unit Cost: 0.0319 $/ kWh Cost: 35.09 $/ charge

2.4_ Type: ____

Quantity Required: ____ ____ : Unit Cost: ____ $/____ Cost: ____ $/____

2.4 Subtotal Energy Costs:	35.09 $/charge
2.5 Subtotal 2.2 to 2.4:	437.98 $/charge
2.6 Handling Charge: 5.26 % of item 2.5	23.03 $/charge
2.7 Subtotal Materials and Supplies: (2.5 + 2.6)	461.01 $/charge

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3.1 Direct Labor:

3.11 Category: Crystal Puller Operator (SAMICS #609885) Activity: Machine monitoring

Amount Required: 2.8 h/charge ; Rate: $ 4.52 /h; Load 36 %; Cost: 17.21 $/charge

3.12 Category: Crystal puller operator (SAMICS #609885) Activity: Loading, unloading, cleaning, etc.

Amount Required: 1.5 h/ charge ; Rate: $4.52 /h; Load 36 %; Cost: 9.22 $/charge

3.13 Category: Maintenance Mechanic (SAMICS #638281) Activity: Servicing

Amount Required: 0.8 h/ Charge ; Rate: $ 5.67 /h; Load 36 %; Cost: 6.17 $/charge

3.1 Direct Labor Subtotal: 32.60 $/charge

3.2 Indirect Labor: Total taken as 25% of direct

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2_ Category: ______ Activity: ______

Amount Required: ______ h/ ______ ; Rate: $ ______ /h; Load ______ %; Cost: ______ $/ ______

3.2 Indirect Labor Subtotal: 8.15 $/charge

3.3 Subtotal 3.1 and 3.2	40.75	$/charge
3.4 Overhead on Labor: 5.26 %	2.125	$/charge
3.5 Subtotal Labor	42.875	$/charge

Process No. 2 . 4 . 0 1 - 0 1

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4.1 Equipment

4.11 Type: C_z Crystal Puller, Leybold-Heraeus type EK2 1600/6000

Cost: 80,000 $; Installation Cost: 20,000 $; Throughput: 4540 kg /y;

Plant Oper'g Time 8280 h/y; Machine Avail'ty: 95% %; Machine Oper'g Time 7866 h/y

Servicing Costs: Labor see 3.13 h/y at ____ $/h; Parts or Outside Service: see 2.31 $/y

Useful Life: 7 y; Charge Rate: 21.4 % of Cost/y; Capital Cost: 21400 $/y | 54.87 $/charge

4.12 Type: Other equipment (resistivity tester, scale, etc.)

Cost: 4000 $; Installation Cost: ____ $; Throughput: ____ /h;

Plant Oper'g Time ____ h/y; Machine Avail'ty: ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ $/h; Parts or Outside Service: ____ $/y

Useful Life: ____ y; Charge Rate: 21.4 % of Cost/y; Capital Cost: 856 $/y | 2.19 $/charge

4.1_ Type: ____

Cost: ____ $; Installation Cost: ____ $; Throughput: ____ /h;

Plant Oper'g Time ____ h/y; Machine Avail'ty: ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ $/h; Parts or Outside Service: ____ $/y

Useful Life: ____ y; Charge Rate: ____ % of Cost/y; Capital Cost: ____ $/y | ____ $/____

4.1 Subtotal Equipment Cost: 57.06 $/charge

Process No. 2 . 4 . 0 1 – 0 1

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4.2 Facilities:

4.21 Type: Crystal growing area Floor Area: 12 m^2; Throughput: 390 charges /y

Charge Rate: 179.13* $/($m^2$·y):

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____ h/y at ____ $/h

Supplies: ____ $/y

Outside Services: ____ $/y

Total Cost: 2149.56 $/y — 5.51 $/charge

4.2_ Type: ____ Floor Area: ____ m^2; Throughput: ____ ____/y

Charge Rate: ____ $/($m^2$·y):

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____ h/y at ____ $/h

Supplies: ____ $/y

Outside Services: ____ $/y

Total Cost: ____ $/y — ____ $/____

4.2_ Type: ____ Floor Area: ____ m^2; Throughput: ____ ____/y

Charge Rate: ____ $/($m^2$·y):

Energy Use:

Heating ____ ____/y at ____$/____

Air Cond'g ____ ____/y at ____$/____

Lighting ____ ____/y at ____$/____

Maintenance Costs:

Labor: ____ h/y at ____ $/h

Supplies: ____ $/y

Outside Services: ____ $/y

Total Cost: ____ $/y — ____ $/____

4.2 Subtotal Facilities:	5.51 $/ charge
4.3 Equipment and Facilities Subtotal :	62.58 $/ charge

* Includes energy use

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5. Salvaged Material (Work-in-process)

5.1	Quantity of Work-in-Process 1. Contained in Good Output Work-in-Process (per Computation Unit)	4540 kg / y	
5.21	Input Work-in-process 1. Not Contained in Good Output Work-in-Process ("Amount Required" from 1.1 minus 5.1)	1785 kg / y	
5.22	Net Amount of 5.21 which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐	1190 kg / y	
5.23	Credit for 5.22 at the Market Value of 65 $/ kg :	______ $/ ______	
5.24	Cost of Reprocessing Material of 5.22 at the Average Reprocessing Cost of ______ $/ ______ :	______ $/ ______	
5.25	Net Credit for 5.22 (5.23 minus 5.24):		______ $/ ______
5.26	Material of Type 1. Lost in Process (5.21 minus 5.22)	595 kg / y	
5.3	Cost of Work-in-Process Lost (Amount 5.26 Times Unit Cost 1.1)		99.16 $/charge
5.4	Cost of Work-in-Process Contained in Good Output Work-in-Process (Amount 5.2 Times Unit Cost from 1.1)		756.66 $/charge

Salvaged Materials Summary:

5.8	Total Net Credits for All Salvaged Materials (5.25 + 5.67 + 5.76)	______ $/ ______

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Page 1 of 1

Process No. 2 . 1 . 0 1 – 0 1

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6. Byproducts and Wastes

6.1 Solid Byproducts/Wastes

6.11 Type (Composition): Quartz crucible   Quantity Produced: 1 /charge

Physical Shape/Size: 25 x 25 cm   Energy Content: ______ kWh/ ______

Density: 2.63-2.66 g/cm^3; Water Solubility: 0 g/l at - °C: pH: ______

Toxicity: ______ Biodegradable: no   Other Remarks: ______

Type of Disposal: land fill

Input Material for: ______ Cost/(Credit) ______ $/ ______;   Cost: ______ $/ ______

6.2 Liquid Byproducts/Wastes (inorganic):

6.22 Type (Composition): Cooling water   Quantity Produced: 127 m^3/ charge

Density: 1 g/cm^3; Suspended Solids: -   Amount: - mg/l   pH: 7

Toxicity: -   Heavy Metal Content: - mg/l   Other Remarks: ______

Type of Disposal: recycled through cooling tower

Input Material for: ______ Cost/(Credit) ______ $/ ______   Cost: ______ $/ ______

Carry: ______ $/ ______

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6.3 Liquid Byproducts/Wastes (organic)

Carry from Form 10 ______ $/______

6.3_ Type (Composition): ________________ Quantity Produced: _____/_____

Density: ________ g/cm^3; Toxicity: ________ COD: ________ mg/l; BOD: ________ mg/l

Ignition Point: _____ ^oC; Explosive Mixture in Air: ___% to ___%: Other Remarks: ________

____

Type of Disposal: ________________________________

Input Material for: ________________ Cost(Credit) _____$/_____; Cost: ______$/______

6.4 Fumes, Gaseous Byproducts/Wastes

6.4_ Type (Composition): Argon Quantity Produced: 6.4 m^3 / charge

Energy Content (Combustion): 0 kWh/______; Explosive Mixture in Air na % to ___%.

Ignition Point: _____ ^oC; Aerosol ☐ Precipitates in _____ minutes pH ______

Toxicity ____________ Requires Scrubbing ☐ Type of Scrubber: ____________

(enter scrubber under 4.1, 4.2, scrubber effluent under 6.1 to 6.3)

Other remarks: Argon is contaminated with dopant fumes, SiO_x, etc.

____

Type of Disposal: Exhausted into air

Operating Costs: __________$/________; Cost: ______$/______

6. Subtotal: Byproduct/Waste Disposal Cost:

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7. Process Cost Computation

7.11	Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	566.45 $/charge
7.22	Other Indirect Costs: (0.059 *(4.1) + 0.108* (4.2)) % of 7.11	3.96 $/charge
7.21	Total Operating Add-on Costs of Process:	570.41 $/charge
7.22	G & A ______ % of 7.21	$/
7.31	Total Gross Add-On Cost of Process	570.41 $/charge
7.32	Credit for Salvaged Material (5.8)	- $/
7.33	Cost of Work-in-Process Lost (5.3)	99.16 $/charge
7.34	Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	669.57 $/charge
7.35	Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	756.66 $/charge
7.36	Loading on Item 7.35 at Rate ______ %	0 $/ 0
7.37	Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	1426.23 $/charge

7.41	Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	16.2 kg / charge
7.42	Practical Yield	72 %
7.43	Effective Yield (7.41 x 7.42)	11.66 kg / charge
7.44	Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	11.66 kg /charge

7.51	Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	122.31 $/ kg
7.52	Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	57.42 $/ kg

Process No. 2 . 1 . 0 1 - 0 1

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8. Price Computation

8.1 Alternate 1

8.11 Profit at Expected Rate of 20 %: 11.48 $/charge
(Profit before income taxes; applied to 7.52)

8.12 Price of Process (7.52 + 8.11) 68.90 $/kg

8.13 Price of Work-in-Process (7.51 + 8.11) 133.79 $/kg

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8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 57.065 $/ charge from Subtotal 4.1 = 52.92 $/charge

1.946* 5.51 $/ charge from Subtotal 4.2 = 10.72 $/charge

Subtotal = 63.64 $/charge

8.22 Costs of Amortization of the One-Time Cost:

0.192* 461.01 $/ charge from Subtotal 2.7 = 88.51 $/ charge

0.192* 42.875 $/ charge from Subtotal 3.5 = 8.23 $/ charge

0.2958* 57.065 $/ charge from Subtotal 4.1 = 16.88 $/ charge

2.77* 5.51 $/ charge from Subtotal 4.2 = 15.26 $/ charge

Subtotal = 128.88 $/ charge

8.23 Total Net Cost of Equity (8.21 + 8.22): 192.53 $/charge

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 11.66 kg / charge from 7.44)

16.51 $/ kg

8.25 Price of Process (7.52 + 8.24) 73.93 $/ kg

8.26 Price of Work-in-Process (7.51 + 8.24) 138.82 $/ kg

Process No. 2 . 1 . 0 1 - 0 1

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9. Process Economic Evaluation:

9.1	Process Cost Balance (7.52 - 0.1)	______ $/ ______
9.2	Relative Process Performance (9.1 ÷ 0.1)	______
9.3	Output Cost (7.51)	122.31 $/ kg
9.4	Output Value (0.2 + 0.1)	______ $/ ______
9.5	Relative Excess Cost [(9.3 - 9.4) ÷ 9.4]	______

Process No. 2 . 1 . 0 1 - 0 1

Form 15

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0. Output Specification:

Name of item: Cyl-crystal

Dimensions: 7.8 cm dia., 135 cm length

Material: single crystal silicon

Other Specifications: Cyl. crystal mass = 15.1 kg

resistivity is as specified

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Process No. 2.1.01-06

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Sheet Generation

Subprocess: Ingot Generation

Option: Crystal Pulling

Wolf's Projection (1982)

(10.2 cm in diameter)

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15	1 to 1			
16	1 to 0			

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Process No. 2 . 1 . 0 1 - 0 6

0.1 Value Added:	$/

Process Description: Single crystal ingot growth done by Czochralski pulling under vacuum and with melt replenishment. From Wolf's 1982 projection of data obtained for a Leybold-Heraeus Ek2 1600/6000 type puller.

1. Input Specification:

Name of Item: Polycrystalline silicon

Dimensions: Crushed polyrod or shaped charge

Material: Solar grade silicon (SoG)

Other Specifications: As agreed between individual users and vendors

1.1 Quantity Required: 27.8 kg /charge Unit Cost: 40 $/ kg-Si

1.2 Input Value:	$/
1.3 Input Cost:	1112.0 $/ charge

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 2 . 1 . 0 1 - 0 6

Form 3

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2.1 Direct Materials:

2.1 1 Type: Doping charge;

Specification: as specified by user

;

Quantity Required: ______ ___/___; Unit Cost: ______ $/______; Cost: na $/ charge

2.1_ Type: ______;

Specification: ______;

Quantity Required: ______ ___/___; Unit Cost: ______ $/______; Cost: ______ $/______

2.1_ Type: ______;

Specification: ______

;

Quantity Required: ______ ___/___; Unit Cost: ______ $/______; Cost: ______ $/______

2.1 Subtotal Direct Materials:	- $/charge

Process No. 2 . 1 . 01 - 06

Form 4

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2.2 Indirect Materials (incl. supplies and non-energy utilities):

2.2 1 Type: Cooling water;

Specification: 1050 kWh of heat to be dissipated per charge

Actual quantity of water not known

(SAMICS no. C1128D)

Quantity Required: 1050 kWh/charge; Unit Cost: 0.566 $/charge; Cost: 5.95 $/charge

2.2 2 Type: misc. parts and materials

Specification: ______

Quantity Required: ______ /____; Unit Cost: ____ $/____; Cost: ____ $/____

2.2_ Type: ______

Specification: ______

Quantity Required: ______ /____; Unit Cost: ____ $/____; Cost: ____ $/____

2.2 Subtotal Indirect Materials: 5.95 $/charge

Process No. 2 . 1 . 0 1 – 0 6

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2.3 Expendable Tooling:

- 2.3 1 Type: Furnace replacement parts
  - Quantity Required: na ___/___: Unit Cost: na $/___ Cost: 93.5 $/charge
- 2.3 2 Type: quartz crucible
  - Quantity Required: 0.1 crucible/charge Unit Cost: 200 $/crucible Cost: 20 $/charge
- 2.3 _ Type: ______
  - Quantity Required: ___ ___/___: Unit Cost: ___ $/___ Cost: ___ $/___
- 2.3 _ Type: ______
  - Quantity Required: ___ ___/___: Unit Cost: ___ $/___ Cost: ___ $/___

2.3	Subtotal Expendable Tooling:	113.50 $/charge

2.4 Energy

- 2.4 1 Type: Electricity
  - Quantity Required: 1050 kWh /charge: Unit Cost: 0.0319 $/___ Cost: 33.50 $/charge
- 2.4 _ Type: ______
  - Quantity Required: ___ ___: Unit Cost: ___ $/___ Cost: ___ $/___

2.4	Subtotal Energy Costs:	33.50 $/charge
2.5	Subtotal 2.1 to 2.4:	152.59 $/charge
2.6	Handling Charge: 5.26 % of item 2.5	8.025 $/charge
2.7	Subtotal Materials and Supplies: (2.5 + 2.6)	160.6 $/charge

Process No. 2.1.01-06

Form ι

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3.1 Direct Labor:

3.11 Category: Crystal Puller Operator (SAMICS #609885) Activity: Machine monitoring

Amount Required: 2.5 h/charge; Rate: $4.52 /h; Load 36 %; Cost: 15.37 $/charge

3.12 Category: Crystal Puller Operator (SAMICS #609885) Activity: Loading, unloading, cleaning, etc.

Amount Required: 2 h/charge Rate: $4.52 /h; Load 36 %; Cost: 12.29 $/charge

3.13 Category: maintenence mechanics (SAMICS #638281 Activity: Servicing

Amount Required: 0.67 h/charge; Rate: $5.67 /h; Load 36 %; Cost: 5.17 $/charge

3.1 Direct Labor Subtotal: 32.83 $/charge

3.2 Indirect Labor: Total taken as 25% of direct

3.2_ Category: ______ Activity: ______

Amount Required: ____ h/____; Rate: $____ /h; Load ____ %; Cost: ____ $/____

3.2_ Category: ______ Activity: ______

Amount Required: ____ h/____; Rate: $____ /h; Load ____ %; Cost: ____ $/____

3.2_ Category: ______ Activity: ______

Amount Required: ____ h/____; Rate: $____ /h; Load ____ %; Cost: ____ $/____

3.2 Indirect Labor Subtotal: 8.21 $/charge

3.3 Subtotal 3.1 and 3.2	41.04	$/charge
3.4 Overhead on Labor: 5.26 %	2.11	$/charge
3.5 Subtotal Labor	43.15	$/charge

Process No. 2 . 1 . 0 1 - 0 6

Form 7
Page 1 of 1
Revision ___ Date 3/78

4.1 Equipment

4.11 Type: C_z-crystall puller (modified Leybold-Heraeus)

Cost: 110,000 $; Installation Cost: 25,000 $; Throughput: 465 charge /y;

Plant Oper'g Time ___ h/y; Machine Avail'ty: ___ %; Machine Oper'g Time ___ h/y

Servicing Costs: Labor see 3.13 h/y at ___ $/h; Parts or Outside Service: see 2.31 $/y

Useful Life: 7 y; Charge Rate: 21.4 % of Cost/y; Capital Cost: 28890 $/y — 62.12 $/charge

4.12 Type: Other equipment (resistivity tester, scale, etc)

Cost: 5000 $; Installation Cost: ___ $; Throughput: ___ /h;

Plant Oper'g Time ___ h/y; Machine Avail'ty: ___ %; Machine Oper'g Time ___ h/y

Servicing Costs: Labor ___ h/y at ___ $/h; Parts or Outside Service: ___ $/y

Useful Life: ___ y; Charge Rate: 21.4 % of Cost/y; Capital Cost: 1070 $/y — 2.30 $/charge

4.1_ Type: ___

Cost: ___ $; Installation Cost: ___ $; Throughput: ___ /h;

Plant Oper'g Time ___ h/y; Machine Avail'ty: ___ %; Machine Oper'g Time ___ h/y

Servicing Costs: Labor ___ h/y at ___ $/h; Parts or Outside Service: ___ $/y

Useful Life: ___ y; Charge Rate: ___ % of Cost/y; Capital Cost: ___ $/y — ___ $/___

4.1 Subtotal Equipment Cost: 64.42 $/charge

Process No. 2 . 1 . 0 1 - 0 6

4.2 Facilities:

4.21 Type: Crystal growing area Floor Area: 12 m^2; Throughput: 465 charge /y

Charge Rate: 179.13* $/($m^2$·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: 2149.56 $/y — 4.62 $/charge

4.2_ Type: ______ Floor Area: ______ m^2; Throughput: ______ ______/y

Charge Rate: ______ $/($m^2$·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y — ______$/______

4.2_ Type: ______ Floor Area: ______ m^2; Throughput: ______ ______/y

Charge Rate: ______ $/($m^2$·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y — ______$/______

4.2 Subtotal Facilities:	4.62 $/charge
4.3 Equipment and Facilities Subtotal :	69.04 $/charge

* Includes energy use

Process No. 2 . 1 . 0 1 – 0 6

5. Salvaged Material (Work-in-process)

5.1	Quantity of Work-in-Process 1. Contained in Good Output Work-in-Process (per Computation Unit)	9340 kg / y	
5.21	Input Work-in-process 1. Not Contained in Good Output Work-in-Process ("Amount Required" from 1.1 minus 5.1)	3585 kg / y	
5.22	Net Amount of 5.21 which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ – ☐☐	2390 kg / y	
5.23	Credit for 5.22 at the Market Value of - $/ - :	$/	
5.24	Cost of Reprocessing Material of 5.22 at the Average Reprocessing Cost of - $/ - :	$/	
5.25	Net Credit for 5.22 (5.23 minus 5.24):		- $/ -
5.26	Material of Type 1. Lost in Process (5.21 minus 5.22)	1195 kg / y	
5.3	Cost of Work-in-Process Lost (Amount 5.26 Times Unit Cost 1.1)		102.79 $/charg
5.4	Cost of Work-in-Process Contained in Good Output Work-in-Process (Amount 5.2 Times Unit Cost from 1.1)		803.44 $/charg

Salvaged Materials Summary:

5.8	Total Net Credits for All Salvaged Materials (5.25 + 5.67 + 5.76)	$/

Process No. 2 . 1 . 0 1 – 0 6

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Page 1 of 1

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6. Byproducts and Wastes

6.1 Solid Byproducts/Wastes

6.1 1 Type (Composition): Quartz crucible Quantity Produced: ______/______

Physical Shape/Size: Quartz Energy Content: ______ kWh/______

Density: 263-266 g/cm^3; Water Solubility: ______ g/l at ______ °C: pH: ______

Toxicity: none Biodegradable: no Other Remarks: ______

Type of Disposal: Land fill

Input Material for: ______ Cost/(Credit) ______ $/______; Cost: ______ $/______

6.2 Liquid Byproducts/Wastes (inorganic):

6.2 2 Type (Composition): Cooling water Quantity Produced: na /______

Density: ______ g/cm^3; Suspended Solids: ______ Amount: ______ mg/l pH: ______

Toxicity: ______ Heavy Metal Content: ______ mg/l Other Remarks: ______

Type of Disposal: recycled through cooling tower

Input Material for: ______ Cost/(Credit) ______ $/______ Cost: ______ $/______

Carry: ______ $/______

Process No. 2 . 1 . 0 1 – 0 6 Revision ______ Date 3/78

7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	272.79 $/charge
7.22 Other Indirect Costs: (0.059 * (4.1) + 108 * (4.2)) % of 7.11	4.30 $/charge
7.21 Total Operating Add-on Costs of Process:	277.08 $/charge
7.22 G & A ______ % of 7.21	______ $/______
7.31 Total Gross Add-C.. Cost of Process	277.08 $/charge
7.32 Credit for Salvaged Material (5.8)	- $/ -
7.33 Cost of Work-in-Process Lost (5.3)	102.79 $/charge
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	379.87 $/charge
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	803.44 $/ charge
7.36 Lo. .ing on Item 7.35 at Rate ______ %	______ $/______
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	1183.31 $/ charge

7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	27.8 kg / charge
7.42 Practical Yield	72 %
7.43 Effective Yield (7.41 x 7.42)	20.01 kg /charge
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	20.01 kg /charge

7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	59.13 $/ kg
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	18.98 $/ kg

Process No. 2 . 1 . 0 1 - 0 6

Form 13-1
Page 1 of 1
Revision ____ Date 3/78

8. Price Computation

8.1 Alternate 1

8.11 Profit at Expected Rate of 20 %: 3.79 $/ kg
(Profit before income taxes; applied to 7.52)

8.12 Price of Process (7.52 + 8.11) 22.77 $/kg

8.13 Price of Work-in-Process (7.51 + 8.11) 62.92 $/kg

Process No. 2.1.01-06

Form 13-2
Page 1 of 1

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8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274*	64.42	$/ charge	from Subtotal 4.1 =	59.74	$/charge	
1.946*	4.62	$/ charge	from Subtotal 4.2 =	8.99	$/charge	
			Subtotal =	68.46	$/charge	

8.22 Costs of Amortization of the One-Time Cost:

0.192*	160.60	$/ charge	from Subtotal 2.7 =	30.83	$/ charge
0.192*	43.15	$/ charge	from Subtotal 3.5 =	8.28	$/ charge
0.2958*	64.42	$/ charge	from Subtotal 4.1 =	78.59	$/ charge
2.77*	4.62	$/ charge	from Subtotal 4.2 =	21.85	$/ charge
			Subtotal =	139.55	$/ charge

8.23 Total Net Cost of Equity (8.21 + 8.22): 208.01 $/charge

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 20.01 kg /charge from 7.44)

10.395 $/ kg

8.25 Price of Process (7.52 + 8.24) 29.37 $/ kg

8.26 Price of Work-in-Process (7.51 + 8.24) 69.525 $/ kg

Process No. 2.1.01-06

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9. **Process Economic Evaluation:**

9.1	Process Cost Balance (7.52 - 0.1)	\$/
9.2	Relative Process Performance (9.1 ÷ 0.1)	
9.3	Output Cost (7.51)	59.13 \$/ kg
9.4	Output Value (0.2 + 0.1)	\$/
9.5	Relative Excess Cost [(9.3 - 9.4) ÷ 9.4]	

Process No. 2 . 1 . 0 1 - 0 6

Form 15

Revision ______ Date 3/78

0. Output Specification:

Name of item: Cyl. crystal ingot

Dimensions: 10.2 cm in dia., 140 cm length

Material: single crystal silicon

Other Specifications: cyl. crystal mass = 26.6 kg

resistivity is as specified

PRECEDING PAGE BLANK NOT FILMED

Process No. 2.1.01-07

Form 1

University of Pennsylvania

PROCESS CHARACTERIZATION

(UPPC)

Process: Sheet Generation

Subprocess: Ingot Generation

Option: Crystal Pulling (Single Charge)

Wolf's Projection (1986)

(15.2 cm diameter)

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Process No. 2 . 1 . 0 1 - 0 7

0.1 Value Added:	_____ $/ _____

Process Description: Single crystal ingot growth via Czochralski multi-pulling: done under vacuum with melt replenishment from Wolf's 1986 projection of data obtained for a Leybold-Heraeus Ek2 1600/6000 type puller.

1. Input Specification:

Name of Item: Polycrystalline Silicon

Dimensions: Pellets

Material: Solar grade silicon

Other Specifications: As agreed between individual users and vendor

1.1 Quantity Required: 63 kg / charge Unit Cost: 10 $/ kg

1.2 Input Value:	10 $/ kg
1.3 Input Cost:	10 $/ kg

Note to Item 1.3: Use price, if input produced in own plant.

Process No. 2 . 1 . 0 1 - 0 7

Form 3

Revision ______ Date 3/78

2.1 Direct Materials:

2.11 Type: Doping Charge;

Specification: as specified by user

______

______;

Quantity Required: ______ __/__; Unit Cost: ______$/______; Cost: n.a. $/ charge

2.1_ Type: ______;

Specification: ______;

______

______

Quantity Required: ______ __/__; Unit Cost: ______$/______; Cost: ______$/______

2.1_ Type: ______;

Specification: ______

______

______;

Quantity Required: ______ __/__; Unit Cost: ______$/______; Cost: ______$/______

2.1 Subtotal Direct Materials: - $/ charge

Process No. 2 . 1 . 0 1 - 0 7

Form 4

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2.2 Indirect Materials (incl. supplies and non-energy utilities):

2.21 Type: Cooling water;

Specification: 1250 kWh of heat to be dispached/charge;

requiring 127 m^3/charge of water

(SAMIS C1128D)

Quantity Required: 1100 kWh ___/charge Unit Cost: 0.566 $/ 100kWh; Cost: 7.08 $/charge

2.22 Type: Misc. parts and materials

Specification: ______

Quantity Required: ______ ___/___; Unit Cost: ______$/______; Cost: ______$/______

2.2_ Type: ______

Specification: ______

Quantity Required: ______ ___/___; Unit Cost: ______$/______; Cost: ______$/______

2.2 Subtotal Indirect Materials: 7.08 $/charge

Process No. 2.1.01-07

Form 5

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2.3 Expendable Tooling:

2.3 1 Type: Furnace replacement parts

Quantity Required: na ____/____: Unit Cost: na $/____ Cost: 138.50 $/charge

2.3 2 Type: Quartz crucible

Quantity Required: 0.1 crucible /charge Unit Cost: 461.5 $/crucible Cost: 46.15 $/charge

2.3 _ Type: ____

Quantity Required: ____ ____/____: Unit Cost: ____ $/____ Cost: ____ $/____

2.3 _ Type: ____

Quantity Required: ____ ____/____: Unit Cost: ____ $/____ Cost: ____ $/____

2.3 Subtotal Expendable Tooling:	184.65 $/charge

2.4 Energy

2.4 1 Type: Electricity

Quantity Required: 1250 kWh / charge: Unit Cost: 0.0319 $/charge Cost: 39.875 $/charge

2.4 _ Type: ____

Quantity Required: ____ ____: Unit Cost: ____ $/____ Cost: ____ $/____

2.4 Subtotal Energy Costs:	39.875 $/charge
2.5 Subtotal 2.2 to 2.4:	231.60 $/charge
2.6 Handling Charge: 5.26 % of item 2.5	12.182 $/charge
2.7 Subtotal Materials and Supplies: (2.5 + 2.6)	243.78 $/charge

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3.1 Direct Labor:

3.1 1 Category: Crystal Puller Operator (SAMICS #609885) Activity: Machine Monitoring
Amount Required: 2.7 h/charge; Rate: $4.52 /h; Load 36 %; Cost: 16.60 $/charge

3.1 2 Category: Crystal Puller Operator (SAMICS #609885) Activity: Loading, unloading; clearing, etc.
Amount Required: 2.5 h/ charge; Rate: $ 4.52 /h; Load 36 %; Cost: 15.35 $/charge

3.1 3 Category: Maintenance Mechanic (SAMICS #638281) Activity: Servicing
Amount Required: 0.67 h/ charge; Rate: $ 5.67 /h; Load 36 %; Cost: 5.14 $/charge

3.1 Direct Labor Subtotal: 37.09 $/charge

3.2 Indirect Labor: Total taken as 25% of direct

3.2_ Category: ______ Activity: ______
Amount Required: ____ h/ ____; Rate: $ ____ /h; Load ____ %; Cost: ____ $/____

3.2_ Category: ______ Activity: ______
Amount Required: ____ h/ ____; Rate: $ ____ /h; Load ____ %; Cost: ____ $/____

3.2_ Category: ______ Activity: ______
Amount Required: ____ h/ ____; Rate: $ ____ /h; Load ____ %; Cost: ____ $/____

3.2 Indirect Labor Subtotal:	9.27	$/charge
3.3 Subtotal 3.1 and 3.2	46.36	$/charge
3.4 Overhead on Labor: 5.26%	2.46	$/charge
3.5 Subtotal Labor	48.82	$/charge

Process No. 2 . 1 . 01 - 07

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4.1 Equipment

4.1 1 Type: C_z-Crystal Puller, Leyhold-Heraeus Type E

Cost: 185,000 $; Installation Cost: 35,000 $; Throughput: 530 charge /y;

Plant Oper'g Time ____ h/y; Machine Avail'ty: ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor See 3.13 h/y at ____ $/h; Parts or Outside Service: See 2.31 $/y

Useful Life: ____ y; Charge Rate: 21.4 % of Cost/y; Capital Cost: .47080 $/y — 88.83 $/charge

4.1 2 Type: Other equipment cost (resistivity tester, scale, etc.)

Cost: 9,000 $; Installation Cost: ____ $; Throughput: ____ /h;

Plant Oper'g Time ____ h/y; Machine Avail'ty: ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ $/h; Parts or Outside Service: ____ $/y

Useful Life: ____ y; Charge Rate: 21.4 % of Cost/y; Capital Cost: 1926.0 $/y — 3.62 $/charge

4.1_ Type: ____

Cost: ____ $; Installation Cost: ____ $; Throughput: ____ /h;

Plant Oper'g Time ____ h/y; Machine Avail'ty: ____ %; Machine Oper'g Time ____ h/y

Servicing Costs: Labor ____ h/y at ____ $/h; Parts or Outside Service: ____ $/y

Useful Life: ____ y; Charge Rate: ____ % of Cost/y; Capital Cost: ____ $/y — ____ $/____

4.1 Subtotal Equipment Cost:	92.45 $/charge

Process No. 2 . 4 . 0 1 - 0 7

Form 8
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4.2 Facilities:

4.2.1 Type: Crystal growing area Floor Area: 12 m^2; Throughput: 530 ______/y

Charge Rate: 179.13* $/($m^2$·y):

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: 3582.60 $/y | 6.76 $/charge

4.2_ Type: ______ Floor Area: ______m^2; Throughput: ______ ______/y

Charge Rate: ______$/($m^2$·y);

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y | ______$/______

4.2_ Type: ______ Floor Area: ______m^2; Throughput: ______ ______/y

Charge Rate: ______$/($m^2$·y):

Energy Use:

Heating ______ ______/y at ______$/______

Air Cond'g ______ ______/y at ______$/______

Lighting ______ ______/y at ______$/______

Maintenance Costs:

Labor: ______h/y at ______$/h

Supplies: ______$/y

Outside Services: ______$/y

Total Cost: ______$/y | ______$/______

4.2 Subtotal Facilities:	6.76 $/charge
4.3 Equipment and Facilities Subtotal :	99.21 $/charge

* Includes energy use

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Process No. 2 . 1 . 0 1 - 0 7

5. Salvaged Material (Work-in-process)

5.1	Quantity of Work-in-Process 1. Contained in Good Output Work-in-Process (per Computation Unit)	23940 kg / y	
5.21	Input Work-in-process 1. Not Contained in Good Output Work-in-Process ("Amount Required" from 1.1 minus 5.1)	9450 kg / y	
5.22	Net Amount of 5.21 which is sold for Credit As-Is or After Applying Re-Process ☐ . ☐ . ☐☐ - ☐☐	6300 kg / y	
5.23	Credit for 5.22 at the Market Value of ______ $/______ :	______ $/______	
5.24	Cost of Reprocessing Material of 5.22 at the Average Reprocessing Cost of ______ $/______ :	______ $/______	
5.25	Net Credit for 5.22 (5.23 minus 5.24):		______ $/______
5.26	Material of Type 1. Lost in Process (5.21 minus 5.22)	3150 kg / y	
5.3	Cost of Work-in-Process Lost (Amount 5.26 Times Unit Cost 1.1)		59.43 $/charg
5.4	Cost of Work-in-Process Contained in Good Output Work-in-Process (Amount 5.2 Times Unit Cost from 1.1)		451.69 $/charg

Salvaged Materials Summary:

5.8	Total Net Credits for All Salvaged Materials (5.25 + 5.67 + 5.76)	______ $/______

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Process No. 2 . 1 . 01 - 07

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6. Byproducts and Wastes

6.1 Solid Byproducts/Wastes

6.1_ Type (Composition): Quartz crucible Quantity Produced: ______/______

Physical Shape/Size: 25 x 25 cm Energy Content: ______ kWh/______

Density: 2.63-2.66 g/cm^3; Water Solubility: 0 g/l at ______ °C; pH: ______

Toxicity: none Biodegradable: no Other Remarks: ______

Type of Disposal: ______

Input Material for: ______ Cost/(Credit) ______ $/______; Cost: ______ $/______

6.2 Liquid Byproducts/Wastes (inorganic):

6.2_ Type (Composition): cooling water Quantity Produced: na /______

Density: ______ g/cm^3; Suspended Solids: ______ Amount: ______ mg/l pH: ______

Toxicity: ______ Heavy Metal Content: ______ mg/l Other Remarks: costs are included in 2.21

Type of Disposal: recycled through cooling tower

Input Material for: ______ Cost/(Credit) ______ $/______ Cost: ______ $/______

Carry: ______ $/______

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Process No. 2 . 1 . 0 1 – 0 7

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7. Process Cost Computation

7.11 Manufacturing Add-On Costs (sum of 2.7, 3.5, 4.3, 6.)	391.8 $/charge
7.22 Other Indirect Costs: ______ % of 7.11 0.059 *(4.1) + 0.108 * (4.2)	6.182 $/charge
7.21 Total Operating Add-on Costs of Process:	397.98 $/ charge
7.22 G & A ______ % of 7.21	______ $/ ______
7.31 Total Gross Add-On Cost of Process	397.98 $/ charge
7.32 Credit for Salvaged Material (5.8)	- $/ ______
7.33 Cost of Work-in-Process Lost (5.3)	59.43 $/ charge
7.34 Specific Add-On Cost of Process (7.31 + 7.33)-(7.32)	457.41 $/ charge
7.35 Cost of Input Work-in-Process Contained in Good Output Work-in-Process (5.4)	451.69 $/ charge
7.36 Loading on Item 7.35 at Rate ______ % .	______ $/ ______
7.37 Cost of Output Work-in-Process (7.34 + 7.35 + 7.36)	909.1 $/ charge

7.41 Theoretical Yield (or Conversion Rate, if output units of work-in-process do not equal input units)	63 kg / charge
7.42 Practical Yield	72 %
7.43 Effective Yield (7.41 x 7.42)	45.36 kg / charge
7.44 Number of Units of Good Output Work-in-Process per Computation Unit Used up to 7.35	45.36 kg /charge

7.51 Cost of Unit of Good Output Work-in-Process (7.37 ÷ 7.44)	20.04 $/ kg
7.52 Specific Add-On Cost per Unit of Good Output Work-in-Process (7.34 ÷ 7.44)	10.08 $/ kg

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8. Price Computation

8.1 Alternate 1

8.11 Profit at Expected Rate of 20 %: 2.01 $/ kg
(Profit before income taxes; applied to 7.52)

8.12 Price of Process (7.52 + 8.11) 12.09 $/ kg

8.13 Price of Work-in-Process (7.51 + 8.11) 22.05 $/ kg

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8.2 Alternate 2 (SAMICS Methodology):

8.21 Profit Computation:

0.9274* 22.45 $/charge from Subtotal 4.1 = 85.74 $/charge

1.946* 6.76 $/charge from Subtotal 4.2 = 13.15 $/charge

Subtotal = 98.89 $/charge

8.22 Costs of Amortization of the One-Time Cost:

0.192* 243.78 $/charge from Subtotal 2.7 = 46.80 $/ charge

0.192* 48.82 $/charge from Subtotal 3.5 = 9.37 $/ charge

0.2958* 92.45 $/charge from Subtotal 4.1 =112.789 $/ charge

2.77* 6.76 $/charge from Subtotal 4.2 = 31.97 $/ charge

Subtotal =200.93 $/ charge

8.23 Total Net Cost of Equity (8.21 + 8.22): ~~299.82~~ $/ ~~charge~~

8.24 Profit and Amortization of Start-up Costs per Unit of Good Output Work-in-Process:
(Divide Subtotal 8.23 by 45.36 kg / charge from 7.44)

6.6 $/ kg

8.25 Price of Process (7.52 + 8.24) 16.68 $/ kg

8.26 Price of Work-in-Process (7.51 + 8.24) 26.64 $/ kg

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9. Process Economic Evaluation:

9.1 Process Cost Balance (7.52 - 0.1)	\$/
9.2 Relative Process Performance (9.1 ÷ 0.1)	
9.3 Output Cost (7.51)	20.04 \$/ kg
9.4 Output Value (0.2 + 0.1)	\$/
9.5 Relative Excess Cost [(9.3 - 9.4) ÷ 9.4]	

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0. Output Specification:

Name of item: Cyl. Crystal

Dimensions: 15.2 cm in dia., 140 cm in length.

Material: single crystal silicon

Other Specifications: cyl. crystal mass = 60.0 kg

resistivity is as specified