440
3/14/80

DR. 940

DOE/JPL/954654-9

SILICON WEB PROCESS DEVELOPMENT

Quarterly Report, July 1—September 30, 1979

By

C. S. Duncan
R. Seidensticker
R. H. Hopkins
J. P. McHugh

F. E. Hill
M. E. Skutch
J. M. Driggers

MASTER

Work Performed Under Contract No. NAS-7-100-954654

Westinghouse Research and Development Center
Pittsburgh, Pennsylvania

U.S. Department of Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Solar Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been printed directly from copy supplied by the originating organization. Although the copy supplied may not in part or whole meet the standards for acceptable reproducible copy, it has been used for reproduction to expedite distribution and availability of the information being reported.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$8.00
Microfiche \$3.50

LOW COST SOLAR ARRAY PROJECT
Large Area Silicon Sheet Task

SILICON WEB PROCESS DEVELOPMENT

QUARTERLY REPORT

July 1 to September 30 1979

C. S. Duncan, R. Seidensticker, R. H. Hopkins,
J. P. McHugh, F. E. Hill, M. E. Skutch, J. M. Driggers
Westinghouse Research & Development Center
Pittsburgh, Pennsylvania 15235

Contract No. NAS 954654

"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."

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TECHNICAL CONTENT STATEMENT

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability of responsibility for the accuracy, completeness of usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights."

TABLE OF CONTENTS

	Page
1. SUMMARY	1
2. INTRODUCTION	2
3. TECHNICAL PROGRESS	4
3.1 Background.	4
3.2 Output Rate Technology.	4
3.2.1 Evaluation of Lid/Shield Configurations to Increase Web Width	6
3.2.2 Operation of WA Furnace for Growth Speed Improvements	11
3.2.3 Growth System Characterization and Thermal Modeling for Equipment Design.	14
3.2.3.1 System Temperature Measurements	15
3.2.3.2 Velocity-Thickness Measurements	16
3.2.3.3 Modeling the Performance of Lid/Shield Configurations.	18
3.3 Melt Replenishment Development.	25
3.3.1 Silicon Feeding Technology	25
3.3.2 Melt Level Sensing System.	30
3.4 Solar Cell Evaluation	31
4. CONCLUSIONS.	34
5. PLANS FOR FUTURE WORK.	35
6. NEW TECHNOLOGY	36
7. REFERENCES	37
8. ACKNOWLEDGEMENTS	38
9. APPENDICES	39
9.1 Growth Run Summaries.	40
9.2 Averaged Solar Cell Data for Web Crystals	54
9.3 Updated Program Plan.	56
9.3.1 Milestone Chart.	57
9.3.2 Program Labor Summary JPL 954654, Phase III.	58
9.3.3 Program Cost Summary JPL 954654, Phase III	59
9.4 Engineering Drawings for the Melt Level Sensor System	60

LIST OF ILLUSTRATIONS

Figure	Page
1 Combined Silicon Web Polysilicon and Wafer Cost as a Function of Area Output Rate.	5
2 The J-181 Baseline Lid and Top Shield Configuration	7
3 The Thermal Environment Around a Growing Web Crystal. Critical Regions for Stress Generation are Noted.	8
4 The J-181 Lid and a Slitted Top Shield Designed to Reduce Inductive Coupling Effects.	10
5 The WA Growth Facility, New Unit Now Being Operated Primarily to Develop Designs Favorable to Higher Web Growth Rates	13
6 J-181 Thermal Model Configuration	23
7 Components of Web Velocity-Thickness Relationship	24
8 Schematic Illustration of Silicon Web Melt Replenishment Geometry Including Two Chambered Crucible and Feed Hole Through Which Silicon Pellets are Added to Replace the Silicon Crystallized into Web	26
9 Perforated or Solid Shields were Used to Control Temperatures at the Feed End of the Susceptor During Web Growth.	28
10 New Crucible Barrier Design (C) Used to Eliminate Melt Dewetting Observed with Hotter End Shields. Older Designs Previously used, A and B.	29
11 Comparison of Cell Efficiency for 16x40mm and 10x10mm Solar Cells Made on the Same Web Crystals	33

LIST OF TABLES

Table	Page
1 Some Recent Throughput Results	12
2 Lid and Shield Temperatures for J-181 Configurations	17
3 Velocity-Thickness Data for J-181 Configurations	19
4 Coefficients from Melt Partial Velocity Calculations	21
5 Cell Data for 16x40mm and 10x10mm Test Cells Made on the Same Web Crystals.	32

1. SUMMARY

Silicon dendritic web is a ribbon form of single crystal silicon produced from the melt without die shaping, and capable of fabrication into the second quarterly report on Phase III of a DOE/JPL-sponsored effort to develop silicon web process technology for the production of low cost terrestrial solar cells and arrays.

We have recently produced the widest silicon web crystal 47mm, and demonstrated the highest web area output rate to date, $27\text{cm}^2/\text{min}$. The latter result is particularly significant. Web growth at this rate sustained by means of melt replenishment for prolonged periods produces a projected web wafer cost (including polysilicon) about equal to the JPL 1986 sheet cost objective even if \$25/kg silicon is used for feedstock. When \$10/kg silicon becomes available the projected web wafer cost falls significantly below the JPL cost goal.

Melt replenishment technology development is thus a key requirement for the web process. Recently we demonstrated five hours of simultaneous web growth from a melt replenished by silicon pellets injected at a controlled rate. This is more than double the previous best result. A laser melt level sensor required to monitor melt position for closed loop control of the replenishment rate has been designed. The components have been procured, and the sub system is now in final assembly stages.

Direct measurements of web system temperatures coupled with determinations of web growth parameters have been used to verify the computer model developed for the web process. This tool can now be used with some confidence to guide the design of system components to improve web area output rates. We have also verified the correlation between cell performance predicted from 1cm^2 diagnostic solar cells and larger area devices made on web. Cell efficiencies of 12 to 14% are typical even for experimental crystals produced under unoptimized growth conditions

2. INTRODUCTION

Silicon dendritic web is a ribbon form of silicon which grows directly from the melt without dies and can produce solar cells with AM1 conversion efficiency over 15%. The primary objective of this program is to develop the technology to produce silicon web at a cost compatible with the national goal of 50 cents per peak watt (70 cents per watt in 1980\$) of photovoltaic output power. This is the second quarterly report of the Phase III effort under JPL Contract 954654, Silicon Web Process Development, and covers the period July 1, 1979 to September 30, 1979.

Readers are referred to Reference 1 for a detailed description of the major technical results underlying the development of silicon web for low cost solar cells. Briefly, we showed there that most of the technical requirements to meet the 1986 cost goals have now been demonstrated. However, to sustain the necessary area output rates, and to grow web for periods long enough to attain economic viability, the development of an operational melt replenishment system and closed-loop growth system controls were identified as necessary. These two developments thus form major objectives for the Phase III effort.

Besides the development of replenishment and control techniques, the Phase III technical effort also calls for the systematic evaluation of advanced thermal trimming techniques to increase web width and speed still further, for coupling of output rate and replenishment technologies, design of a semi-automated experimental web growth machine, for detailed characterization of web material produced during the experimental program, and for an update of the economic analysis to reflect new technical and cost information generated during the program.

During the period covered by this report the dominant activities have been to improve web width and output rate and to increase the period of simultaneous growth of web crystal with melt replenishment. Significant advances have taken place in both areas, and the highlights of the work are presented in the text. We have also collected and analyzed data to characterize the performance of specific growth geometries, validate computer models of web growth and use this information as a design tool for future advances in web growth hardware. Finally, we have verified that the performance of web solar cells projected from diagnostic test cells is representative of larger area cell efficiency.

3. TECHNICAL PROGRESS

3.1 Background

The experimental philosophy of the web development program has been to conduct parallel efforts to increase web width and growth velocity, combine these elements as advances in each technology are achieved to provide an overall improvement in area output rate. Similarly, melt replenishment technology, a requirement for sustained high output rate growth,¹ is undergoing concurrent development.

During this reporting period the primary emphasis of our activities has been to increase both web output rate and the time period for simultaneous growth with replenishment. Considerable success was achieved in both areas: a new maximum output rate of $27.1 \text{ cm}^2/\text{min}$ was reached, and five hours of growth with replenishment was accomplished. The highlights of this work are presented in the following sections; detailed summaries of all experimental runs are tabulated in the Appendices.

3.2 Output Rate Technology

During the past quarter the J-furnace was dedicated largely to a study of those parameters affecting web width; the new WA furnace was applied to growth velocity experiments. The impact of top shield configuration on stress-induced deformation and general growth behavior was a major topic of the J-furnace experiments. In the course of the work new highs in web width, 47.1mm, and web output rate, $27.1 \text{ cm}^2/\text{min}$ were reached. As Figure 1—a cost analysis based on SAMICS-IPEG methodology¹—emphasizes, even with \$25/kg silicon the projected silicon web wafer cost (including polysilicon) falls below the JPL 1986 goal when the demonstrated $27.1 \text{ cm}^2/\text{min}$ output rate can be sustained by melt replenishment to provide continuous automated growth.

Curve 713010-A

Figure 1 Combined silicon web polysilicon and wafer cost as a function of area output rate.

Beside the output rate studies themselves, effort was made to measure accurately the lid and shield temperatures corresponding to actual growth conditions—important input data to our computer simulations of web growth. Thickness-velocity data, key tools for characterizing the effectiveness of specific growth geometries, were also determined.

3.2.1 Evaluation of Lid/Shield Configurations to Increase Web Width

Our previous experimental results led to the development of the J-181 lid/shield configuration, Figure 2, a geometry which yielded wide crystals and produced relatively stable growth conditions. As part of a series of experiments to characterize this configuration we recently produced the widest web crystal so far grown, 47.1mm. Because of the excellent results obtained this configuration became a baseline for modifications designed to further raise web output rate. These modifications included variations in the number of top shields, shield spacing and shield temperature. These changes serve to adjust the vertical temperature distribution that the web "sees" and thus the temperature profile in the web itself. In this way, the thermally generated elastic stress in the web can be reduced, deformation eliminated and web width increased.¹

The rationale for the approach is suggested schematically in Figure 3 which depicts the thermal environment surrounding a growing web crystal. As the figure illustrates, a critical region is that one to two centimeters above the crystal-liquid interface where manipulation of the thermal profile affects the generation of elastic stress. Previous thermal modeling of web growth¹ indicated that reduction in the temperature of the outermost thermal shield reduces stress and thus should improve web width. Growth speed should also be raised. (This result was borne out initially in developing the J-181 configuration¹).

Figure 2 The J-181 Baseline Lid and Top Shield Configuration

Figure 3 The thermal environment around a growing web crystal. Critical regions for stress generation are noted.

Thus the next step was to add an additional, or fourth, thick (1.5mm) shield to the J181 stack to further reduce top shield temperature. The result was negative; for this configuration seeding and button initiation were difficult, and polycrystalline starts occurred frequently. However, when a thin (0.5mm) shield was placed directly on top of the third shield of the J181 stack (Figure 2), excellent results were achieved. The highest output rate attained to date, $27.1\text{cm}^2/\text{min}$ was achieved with this configuration.

A drawback to the thin shield approach is that the shield can become warped with repeated usage. This diminishes the day to day reproducibility for the configuration and its utility in an engineering sense. Other related configurations, e.g. J187 (see Appendix) exhibited some of the same difficulties, nevertheless the principle of operation for high output rate was demonstrated.

Simply stacking extra shields to reduce top shield temperature is not a completely efficient approach because the shields themselves can couple inductively and thus be heated in the same way that the lid and susceptor heat. This reduces their shielding effectiveness. For this reason modifications were made to the shields themselves to reduce the coupling effect. This was accomplished by slitting the periphery of the shield, see Figure 4. The reduction in coupling to the shields is quite evident visually—they glow much less on heating than comparable unslitted shields—and also from actual measurements of shield temperatures (see section 3.2.3).

Utilizing this concept we have begun a series of experiments in which the position and spacing of the slotted shields are varied systematically with the J181 lid as a basis. So far a major attribute of these "cold" shields is that they provide extremely stable growth conditions. Initiation of growth is easy, and once started, the web crystals propagate with only occasional operator surveillance and parameter adjustment. The next series of experiments will involve reducing the height of the shield stack which model calculations and initial experience suggest should be beneficial for controlling elastic stress and further raising web width.

Figure 4 The J-181 lid and a slitted top shield designed to reduce inductive coupling effects.

In summary, the arrangement and type of top shield provides a sensitive method to shape the temperature distribution in the web which affects web width, speed and output rate. Reducing the upper shield temperature has been very beneficial, as some of the recent J-furnace data compiled in Table 1 suggest. An added impact, improvement of growth stability can also be achieved this way. Beyond this, the trend of the results are in qualitative agreement with predictions from our thermal model of web growth.¹ Thus, as more quantitative results are obtained from the modeling (see section 3.2.3) to guide the design of lid/shield configurations we anticipate still further improvements in output rate.

3.2.2 Operation of WA Furnace for Growth Speed Improvements

During this quarter a new web furnace designated WA was made operational. The new furnace, pictured in Figure 5, has capabilities similar to the J and RE furnaces but is somewhat simplified in design compared to those units². Twenty runs have been completed to date with this equipment (see Appendix for details). The primary objectives of this initial work have been to assure that all furnace systems operated satisfactorily and then to begin studies designed to increase web growth velocity.

In the first series of runs the furnace was checked for leaks, and to assure that the argon gas system and temperature controls functioned properly. A calibration of pull speed and temperature adjustments was also made. Following the initial shakedown activities several runs were made with two standard growth configurations, RE-1 and J-181 for purposes of comparing growth behavior in the WA furnace with that in the J and RE furnaces. The first runs of this kind were hindered by the accumulation of oxide near the edges of the growth slot and on some portions of the shields. This problem (which also developed during early runs on the other equipment) was eliminated by improving preparation of the shield cleaning coupled with minor modifications in the melt down procedure and in the way the heat shields were positioned for growth. A succession of oxide free runs followed in which no aspirators or other gas flow management schemes were required to maintain system cleanliness.

TABLE 1 SOME RECENT THRUPUT RESULTS

<u>Run No.</u>	<u>Throughput cm²/min</u>	<u>Width mm</u>	<u>Growth Velocity cm/min.</u>
J-189	16.6	36.0	4.5
J-192	18.7	36.0	5.2
J-195	21.5	35.8	6.0
J-196	27.1	35.7	7.6
J-200	15.8	47.2	3.3
J-212	16.5	32.9	5.0
J-213	16.6	32.0	5.2

Figure 5 The WA growth facility, new unit now being operated primarily to develop designs favorable to higher web growth rates.

Experiments to test methods for increasing web growth velocity were initiated at this point. Improvements in growth velocity hinge on increasing the transport of the latent heat of fusion out of the growing crystal.¹ As Figure 3 suggests one of the most effective ways to do this is to raise the amount of radiative heat loss from the web. This can be accomplished by reducing the bevel angle on the growth lid so that the radiative view factor is made correspondingly greater. Shields folded over the hot bevel section can also be used to reduce radiative transport to the web. In the first experiments the standard 45° bevel was replaced by a 30° bevel on the growth lid. The modified lid design resulted in about a twenty per cent increase in growth velocity compared to the standard 45° bevel used with the same top shields. Future experiments will test the use of top shields spaced more closely together and folded over the bevel to improve speed.

3.2.3 Growth System Characterization and Thermal Modeling for Equipment Design

An important adjunct to the web growth studies themselves is development of a data base characterizing specific system configurations and analysis techniques to provide design guidance for future improvements. Thus we recently have been evaluating and improving the correlation between observed web growth behavior and the mathematical models which describe the growth process. As noted earlier, qualitative agreement between the computer simulation¹ and measurement has been good but quantitative agreement is hindered because some parameters, such as lid and shield temperatures, used in the model are known only approximately. The purpose of the work described below is to give better insight into the relationship between the imposed growth conditions and the way web actually grows and to identify directions for improved system design.

The first step toward developing system designs with enhanced output rates is to evaluate just how well the model used for design guidance actually describes the performance of a specific growth geometry. To accomplish this actual temperatures at critical regions

had to be measured, and a suitable growth parameter to compare with the model had to be identified.

The most important system parameters seem to be the temperature at the slot in the susceptor lid and the concomitant temperature of the top susceptor shield. The choice of growth parameter is less direct. The most appropriate data would be the temperature distribution along a growing web. However, the task of measuring this profile with the necessary accuracy in both temperature and position is formidable. A relatively simple measurement, that of the ribbon thickness as a function of velocity, provides a great deal of information, especially the initial slope of the temperature distribution. The following subsections describe these measurements as well as the validation of the thermal model.

3.2.3.1 System Temperature Measurements.

To provide data for the thermal modeling and lid design effort, thermocouple measurements were made of the lid and the top shield temperatures of a J181 configuration (see Figure 2) with the melt at the "hold temperature". Small holes were drilled in the lid and shield near one side of the mid position of the slot, such that the thermocouple beads were centered in the thickness dimensions. The lid temperature was measured with a Type B (Pt-30%Rh/Pt-6%Rh) couple with the bead inserted deeply into the material; the long "immersion depth" created by running the leads between the lid and the first top shield would minimize temperature measurement errors. The top shield temperature was measured by a Type K (Chromel-Alumel) couple and in this case, the bead was secured in the hole with an alumina slurry cement to assure thermal contact. The thermocouple outputs were fed into a data logger and monitored until a steady state thermal situation was reached.

Two modifications of the J181 configuration were analyzed. In the first configuration (baseline) the 1.5mm thick top shields were solid and thus coupled to some extent with the induction field. In the second modification, the periphery of the top shields was interrupted with slits 12 mm deep about 1mm wide and spaced every 12mm as in Figure 4.

The intent of this modification was to reduce the inductive coupling to the shields, and this was successful as can be seen from the data, Table 2. The data also show that the lid temperature is relatively insensitive to coil height, while the top shield temperature is more strongly affected. When these data were compared with the temperatures previously used in the thermal modeling, it was found that the measured lid temperature was about 50°K colder than originally assumed,¹ but that the shield temperatures were from 50°K to 150°K hotter than had been assumed on the basis of a radiation equilibrium between the lid and shields. Even in the case where the shields were slit, it appears that the top shield is somewhat hotter than anticipated. This may be due in part to conductive transport of heat through the gas and in part to some residual heating by the induction field. In any case, apparently reliable data is now available for use in future thermal modeling.

3.2.3.2 Velocity-Thickness Measurements

The relation between the thickness of a web crystal and its growth velocity is dependent on the rate at which the latent heat of fusion can be removed from the growth front. As such, both the heat loss to the supercooled liquid and the heat loss through the web itself make a contribution so that the interpretation of measure velocity-thickness (v-t) relation is not completely unambiguous. As will be discussed later, however, the contribution from the supercooled melt can be ascertained with reasonable exactness, so that the web contribution can be extracted from the combined data.

Generation of the experimental v-t data is straightforward; once growth is started, the pull speed on the crystal is varied incrementally to provide segments of different thicknesses. The only major caution is to allow 10 to 15 cm of growth at each speed in order to reach steady state. If the twin planes do not grow out of the ribbon as it thins, then the speed can be set at normal rate and growth continued. There is, in fact, some suggestion that thinning the crystal may improve its quality by eliminating dislocations.

TABLE 2 LID AND SHIELD TEMPERATURES FOR J181 CONFIGURATIONS

<u>Coil Position</u>	<u>Shield Type</u>	<u>Lid Temp., °C</u>	<u>Top Shield Temp., °C</u>
100.0 mm	Solid	1354.7	963.1
102.7	"	1351.3	941.7
105.0	"	1344.6	927.4
101.0	Slitted	(open T.C.)	878.6

Note that in the coil position column, higher numbers mean a lower coil position relative to the susceptor.

The most convenient means of presenting velocity-thickness data is to tabulate the coefficients a and b in the equation

$$v = a + \frac{b}{t} \quad (1)$$

where t is the ribbon thickness. This empirical equation not only proves to be an excellent fit to the experimental data but also, as will be seen, is a very good representation of the modeling results. Some representative data on crystals grown from the J181 type lid configurations are given in Table 3. Several minor modifications of the configuration are included and it is evident that there is very reasonable reproducibility between crystals grown from the same configuration and even among the different modifications. Rather than include the correlation coefficient for the data, the root-mean-square deviation for the velocity, S, is given in the table. In most cases S is about 0.01 to 0.05 cm/min which is of the order of accuracy in determining the pull speed setting, i.e about 1 division on the control dial.

One particular data set is worth notice. Crystals J211-1 and J211-5 were the first and last crystals grown in furnace run J-211. Between the growth of the two crystals, about 45 gm of material had been drawn from the melt causing the melt level to fall about 2mm. This change in melt height is apparently reflected in the "b" coefficient of Eq.1.

3.2.3.3 Modeling the Performance of Lid/Shield Configurations

The approach we adopted for the modeling effort was to establish a baseline calculation for the J181 growth configuration using the measured lid and shield temperatures. The results of the calculations were then compared with experimental data to evaluate the overall validity of the model. As mentioned in the foregoing section, the simplest data which can be used for this comparison is the relationship between the web thickness and the growth velocity. In order to match the empirical data, two models must be evaluated: first, a calculation of the heat loss to the meniscus and supercooled melt, and second, a calculation

TABLE 3 VELOCITY-THICKNESS DATA FOR J181 CONFIGURATIONS

Crystal	Configuration (See Notes)	ΔT °C	a cm/min	b $\mu\text{m-cm/min}$	S cm/min	REMARKS
J197-1	Std.	4.3	1.33	167	.019	Full (185 gm) crucible
J198-2	M1	3.4	1.17	146	.028	8 gm removed by growth
J199-1	M1	5.0	1.17	154	.029	5 gm removed
J211-1	M2	3.6	1.17	150	.006	Full (185 gm) crucible
J211-5	M2	3.7	1.22	107	.02	45 gm removed by growth

Notes: The lid configuration are as follows

Std. - Identical to Figure 2.

M1 - Added thin shield placed directly on top of J181 (std) top shield

M2 - Added heavy shield; top two shields slitted to reduce coupling.

of the heat dissipated from the crystal itself. For all intents, these calculations are independent and the results can be conveniently expressed as partial velocities, v_{melt} and v_{web} , with $v_{\text{total}} = v_m + v_w$.

Meniscus Heat Loss

The thermal model of the heat loss to the meniscus follows the same approach as the model for the heat loss from the web as described in appendix 6.5 of the 1978 annual report of this project.³ For this calculation, the most critical geometrical and thermal parameters are the temperature of the susceptor lid near the growth slot, the effective thickness of the lid itself, the width of the slot, the position of the interface below the lid, and of course the melt undercooling.

Although the geometry of the J181 configuration is well defined, a range of parameters were modeled to evaluate the sensitivity of the melt partial velocity, v_m , to changes in the lid configuration. Although the results must be nonlinear over an extended range of ribbon thickness, the calculations proved to be a very good fit to an equation analogous to equation 1, namely

$$v_m = a_m + \frac{b_m}{t}, \quad (2)$$

where the subscript, m, implies the coefficients apply to the melt heat transfer.

The results of the current modeling, Table 4, are given in terms of the coefficients a_m and b_m in Eq. 2. The most striking feature of these numbers is that they are relatively independent of the lid geometry and are mainly dependent on the melt undercooling. Furthermore, comparison with some earlier data showed that the coefficients were nearly the same even though the geometrical factors were different. Thus, an almost "universal" set of parameters a_m and b_m can be used to represent the partial velocity due to the melt for both modeling purposes and for analysis of experimental data.

TABLE 4

COEFFICIENTS FROM MELT PARTIAL VELOCITY CALCULATIONS

ΔT °C	LIN mm	LID mm	SLOT mm	a_m cm/min	b_m μm-cm/min
4	1	6	6	.32	75
4	1	10	6	.31	72
4	2	6	6	.31	74
4	2	10	6	.30	71
2	2	10	6	.19	41
6	2	10	6	.41	99

ΔT = melt undercooling

LIN = interface distance below lid

LID = effective lid thickness

SLOT = slot width

a_m, b_m = coefficients in $v_m = a_m + b_m/t$

Web Heat Loss

The temperature distribution and concomitant heat fluxes were calculated for the J181 lid and shield configuration using the experimental lid and shield temperatures in the model. The basic features of the model are shown in Figure 6 in which the actual J181 configuration is compared with the model parameters. Temperature/heat flux data was calculated for three web thicknesses, 100, 150 and 250 μm in order to derive a velocity-thickness curve. The three temperature curves were very nearly the same except for a few millimeters near the interface. Again it was found that for the range of crystal thicknesses involved the data could be represented well by an equation of the form

$$v_w = a_w + \frac{b_w}{t} \quad (3)$$

where the subscript w implies the coefficients are for the web. A fit to the data with $a_w = 0.88$ and $b_w = 64$ exhibited an rms deviation from linearity of 0.014 cm/min.

Combined Results

Since the form of the velocity-thickness is the same for both the melt and the web partial velocities, the like coefficients can be summed to give the total velocity as illustrated in Figure 7. The result can be expressed explicitly as

$$v_t = (a_m + a_w) + \frac{(b_m + b_w)}{t} \quad (4)$$

For the present modeling results, this gives

$$v_t = 1.19 + \frac{137}{t} \quad (5)$$

where t is in μm and v is in cm/min.

TC	TS	TBEVEL	TAS	TLID	ZD	ZH
1623	1460	.6	1213	1.0	1.35	1.85

Dimensions in CM

Temp. in °K

• Thermocouple Location

Figure 6 J181 Thermal Model Configuration

$$V_{\text{total}} = V_{\text{melt}} + V_{\text{web}}$$

$$V_i = a_i + \frac{b_i}{t} \quad i = \text{total, melt or web}$$

Figure 7 Components of web velocity-thickness relationship

The model results should be compared with the experimental results given in Table 3. Omitting the data for J211-5, which represents a melt lowered by several millimeters from the other cases, the average coefficients are $a_{\text{expt}} = 1.21 \pm .08$ and $b_{\text{expt}} = 154 \pm 9$. These numbers can be compared with the model results of $a_t = 1.19$ and $b_t = 139$. The agreement is quite good, especially considering the fact that the experimental data represents a (small) range of melt heights and super-coolings. The present model is apparently a good tool for predicting the velocity-thickness characteristics of new lid designs and will be applied in the near future to guide the development of designs for improved output rate performance.

3.3 Melt Replenishment Development

3.3.1 Silicon Feeding Technology

As described previously^{1,2} we have shown that melt replenishment is required to sustain high output rate web growth for prolonged periods, and that a feasible method to do this is to feed silicon pellets at a programmed rate as the web is grown. The experimental configuration is depicted in Figure 8. The thrust of the current development effort is to extend the period of growth with replenishment to practical operating periods. Two types of studies have been carried out during the past quarter (1) replenishment with restricted growth slots to control web width and (2) replenishment with wide growth slots like the J181 configuration. Key results of the activity are given here; the details of all runs (conducted in the RE furnace) appear in the Appendix.

The initial runs this quarter were to investigate methods to control web width while feeding. The purpose was to provide an extended growth period by controlling web width below the 47mm size at which stress-induced bending is observed (see section 3.2). Adjustable shields (molybdenum pieces) were placed over the ends to the growth slot to manipulate the melt temperature profile and thus control web width. We observed a decrease in widening rate by this approach and in fact were able to control web width within about 2mm for lengths up

Figure 8 Schematic illustration of silicon web melt replenishment geometry including two-chambered crucible and feed hole through which silicon pellets are added to replace the silicon crystallized into web. (The argon jet helps eliminate oxide collection near feed hole and growth slot 2).

to about a meter. It was difficult to grow for more extended periods due to the accumulation of silicon oxide on the moveable molybdenum shields. Although the principle appears to work, alternative engineering approaches will have to be taken to implement the idea.

The next series of runs employed a J181 lid configuration. Variations in the type and amount of thermal shielding placed on the feed end of the susceptor, Figure 9, were made to evaluate their effect on the rate of pellet melting during replenishment. Two types of end shields, perforated and solid, were tested. The fraction of the shield perforated was used to control the radiative heat loss from the susceptor end and thus adjust the heat balance.

The perforated shields never performed satisfactorily; silicon tended to freeze in the feed and growth chambers when pellets were fed into the liquid. Adjustments to the aspirator argon flow rate and to the work coil position failed to eliminate the problem. We concluded that solid shields would be required to keep the feed chamber sufficiently hot to melt the pellets at an acceptable rate.

Following some modifications to the crucible barrier arrangement, a replenishment run utilizing the solid end shield produced the longest sustained period of web growth with replenishment to date, five hours. During this time pellets were fed at about half the rate required for full output rate replenishment. Three web crystals were grown, the longest for about two and a half hours. There were no feed-related problems throughout the course of the run.

Raising the replenishment/growth period beyond five hours has been hampered by two difficulties. First, melt dewetting like that previously described^{1,2} occurred during several subsequent runs. This behavior, apparently related to the hotter end temperature, has been eliminated by implementation of a new barrier design, C in Figure 10. The new design has operated successfully in the several runs since the inception of its use.

Figure 9 Perforated or solid shields were used to control temperatures at the feed end of the susceptor during web growth.

Dwg. 7709A08

(A)

(B)

(C)

Figure 10 New crucible barrier design (C) used to eliminate melt dewetting observed with hotter end shields. Older designs previously used, A and B.

A second difficulty has been the recurrent formation of floating silicon particles, or "ice",¹ in the growth chamber when pellets were fed into the replenishment chamber. Some of this has been traced to the spalling of oxide collected on the bottom of the growth lid. On other occasions the cause seems again to be carryover of particles from the replenishment chamber. The observations are complicated by the occurrence of ice recently even when no feeding was attempted, suggesting leaks in the RE furnace or the feed system itself. To prevent potential oxide carryover from the replenishment chamber, a higher crucible barrier, recessed into the growth slot will be fabricated. In the interim a thorough leak check of all systems components is underway.

In summary we have achieved a five hour period of growth with replenishment, the longest to date. Further extension of the replenishment period has been hampered primarily by "ice" formation due probably to a combination of furnace leaks and some particle carryover. We expect to correct these situations shortly and continue to extend the replenishment period.

3.3.2 Melt Level Sensing System

As this quarter ended, the melt level sensor system neared completion. The system uses a low power laser and solid state detector according to a concept devised earlier under this program.² Complete detailed drawings were prepared (See Appendix), components purchased, and all structural parts have been fabricated. Assembly has begun.

The need for maintaining a constant melt level for web growth has previously been established. The two principal parts of a system to maintain a constant melt level are a mechanized polysilicon pellet feeder and a melt level sensor. A mechanized pellet feeder for such a system has previously been developed and is in use.^{1,2} The melt level sensor, when completed, will first be used as a melt level indicator enabling an operator to determine the appropriate rate for feeding polysilicon pellets via the pellet feeder to maintain a constant melt

level. Ultimately the melt level sensor and the mechanized pellet feeder will be coupled in closed loop control to automatically maintain a constant melt level without operator input.

3.4 Solar Cell Evaluation

Nine solar cell processing runs were completed to evaluate silicon web crystals produced this quarter. In a few cases processing faults occurred which compromised the performance data. These crystals have been reprocessed and the data will be reported in the future. In general the characteristics of the web material were similar to those reported before; see e.g. reference 1. Cell efficiencies ranged from a high of 14.7% (AM1, AR coated) to a low of 10.2% with the average at about 13%. As usual, the cell data for each web crystal are compiled in the Appendix.

In addition to the data gathered by means of 10mmx10mm diagnostic cells described above, processing and evaluation were completed on thirty 16x40mm cells which have been sent to J.P.L. as deliverable items under the terms of the contract. All of the crystals used to fabricate these larger cells had been previously characterized by 10mmx10mm diagnostic cells. It is of some interest to see how well the diagnostic data represents the performance of the larger devices. Table 5 gives a comparison of the two types of cells arranged by crystal. In the case of the diagnostic cells $\eta_{AR} = 1.43 \eta_o$; for the 16x40mm cells, η_{AR} is the measured coated efficiency. The same efficiency data is compared graphically in Figure 11. It would appear that the correlation between the two sets of data is generally very good. The occurrence of several outlying points suggests that there is occasional process variation for both types of devices. More generally, however, the agreement is better than 0.5% in η_{AR} . One may conclude that the 10mmx10mm diagnostic cells are a valid predictor for the performance of a web crystal as a base material for solar cells, and that excellent cell performance is to be expected in the larger area devices.

TABLE 5

CELL DATA FOR 16x40mm AND 10x10mm
TEST CELLS MADE ON THE SAME WEB CRYSTALS

<u>CRYSTAL</u>	<u>16x40 mm CELLS</u>		<u>10x10mm QUAL CELLS</u>	
	η_{AR}	τ_{OCD}	η_{AR}^*	τ_{OCD}
W121-1	13.4	8	12.0	15
W125-1	14.2	11	13.7	13
W128-2	13.3	28	13.7	32
W135-1	13.4	8	13.6	19
W136-2	13.9	13	13.7	16
W138-2	13.1	9	12.4	7
W139-2	13.9	9	13.3	8
W140-1	14.9	14	13.2	8
RE78-4	12.3	3	12.4	9
RE105-3	12.9	4	13.3	6
RE141-1	13.3	5	13.2	10
J106-1	12.6	5	12.0	9
J115-3	12.0	3	14	20
J140-3	12.7	3	13.3	6

* η_{AR} is the projected value of the coated efficiency for the 10x10mm cells ($\eta_{AR} = 1.43 \eta_0$). The 16x40mm cells are coated during fabrication.

Figure 11. Comparison of cell efficiency for 16x40mm and 10x10mm solar cells made on the same web crystals.

4. CONCLUSIONS

Major advances in web area output rate and web width were accomplished during the time period covered by this report. An output rate of $27.1 \text{ cm}^2/\text{min}$, the highest value to date, was achieved. This is an important result for economic as well as technical reasons. The projected web cost when this output rate is sustained for prolonged operating periods via melt replenishment would fall below the 1986 JPL objective even with \$25/kg silicon.

The period of simultaneous web growth with replenishment by means of silicon pellets continued to improve. Growth for five hours, more than twice the previously reported high,² was accomplished with no feed related problems. We have designed, fabricated and are now assembling the laser melt level sensor system. This system provides a means to monitor the melt level in the growth system in real time so that the silicon consumed during web growth can be replenished at an appropriate rate for steady-state growth.

Thermal measurements coupled with determinations of web thickness and growth velocity have been used to validate the accuracy of the web growth model. Agreement was excellent between the model simulation of the behavior expected from a given susceptor/lid configuration and the experimental data. The model will be used in future work to guide the design of components for enhanced web output rates.

A good correlation was established between the 1 cm^2 diagnostic test cells used to characterize material and larger area devices. Web cell efficiencies on experimental crystals produced under a variety of conditions during this program continue to average 12 to 13% (AM1).

5. PLANS FOR FUTURE WORK

During the coming quarter three major activities will be emphasized: experiments to enhance web width and speed, melt replenishment technology development and the coupling of these two elements to provide for sustained high output rate web growth. Guidance for the design of new components to increase width and speed will come from the recently updated thermal model of the web growth process. We plan to introduce adjustable thermal trimming into the melt replenishment system so that the thermal ambient can be tailored to provide variable heat balance for both growth initiation and steady-state operation. The melt level sensor will be operated both to test its performance and to provide a control signal for the silicon feed rate during replenishment.

7. REFERENCES

1. C. S. Duncan, et al., Annual Report, Silicon Web Process Development, DOE/JPL-954654-79/2 April (1979).
2. C. S. Duncan, et al., Quarterly Report, Silicon Web Process Development, DOE/JPL-954654-79/3. July (1979).
3. C. S. Duncan, et al., Annual Report, Silicon Web Process Development, DOE/JPL-954654-78/2 April (1978).

8. ACKNOWLEDGEMENTS

We would like to thank P. A. Piotrowski, H. C. Foust, E. P. A. Metz, W. B. Stickel, J. M. Polito, A.M. Stewart, J. P. Fello, and C. H. Lynn for their contributions to the web growth studies and P. Rai-Choudhury, R. B. Campbell, E. J. Seman, J. B. McNally, W. Cifone, D. N. Schmidt, and H. F. Abt for the processing and testing of the web solar cells.

9. APPENDICES

9.1 Growth Run Summaries

Studies designed primarily to enhance web width were conducted in the J-furnace while all melt replenishment experiments were performed in the RE furnace. The major activities in the new WA furnace were shakedown and test of the equipment itself and initiation of studies to optimize web growth velocity for high output rate operation.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	MAX. VELOCITY (cm/min)	DESCRIPTION/RESULT
J-183	2	286	38.5	1.7	Repeat J181 configuration. Early starts tended to generate lines in crystals. Growth good later.
J-184	3	409	33.1	1.7	J-181 configuration. Similar to previous run.
J-185	3	431	33.5	1.7	J-181 configuration. Good crystal terminated by pull out.
J-186	3	266	28.0	1.7	To produce lower resistivity material for evaluation, (6×10^{17} total boron) J-181 configuration. Crystals terminated because of degeneration in quality.
J-187	4	513	33.4	1.6	Test new configuration. Insert additional 0.5mm thick full shield with slight bevel overlap into J-181 shield stack. Total 4 top shields. 6×10^{17} total boron. Growth behavior generally good. Crystals terminated by pull out.
J-188	No significant web production				Repeat J-187 configuration. Most of day spent video taping of growth initiation.
J-189	2	494	36.0	5.1	Repeat J-187 configuration. Reached thruput values of 15.8 and 16.6 cm^2/min .
J-190	5	525	30.1	1.6	Repeat J-187 configuration. Early crystals terminated by pull out or quality degeneration. Conclude this configuration not improvement over J-181 in terms of width capabilities.
J-191	3	378	33.9	6.6	J-181 configuration. Crystal quality poor early, good later in day.
J-192	3	534	36.0	5.2	J-181 configuration modified by addition of 0.5mm thick shield directly on top. Max thruput of $18.7 \text{cm}^2/\text{min}$.
J-193	Not Productive of Web.				J-181 configuration. Piece of oxide fell into melt early and attached to crucible wall, causing ice nucleation.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	MAX. VELOCITY (cm/min)	DESCRIPTION/RESULT
J-194	3	445	30.5	1.6	J-181 configuration. Crystals terminated by pull out. Attempt was made to minimize under-cooling during growth.
J-195	3	499	35.8	6.0	J-181 configuration. Max. thruput $21.5 \text{ cm}^2/\text{min}$.
J-196	2	421	35.7	7.6	J-181 configuration with additional thin top shield. <u>Reached record thruput of $27.1 \text{ cm}^2/\text{min}$.</u>

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	MAX. VELOCITY (cm/min)	DESCRIPTION/RESULT
J-197	2	202	19.7	3.3	Purpose: To measure lid and top shield temperatures of J-181 configuration. See text for results. Thickness velocity data. Doped to ~ 2 ohm-cm.
J-198	4	356	20.8	3.3	Test J-181 configuration with addition of 0.5mm thick shield spaced 1.5mm above upper thick shield. Doped to ~ 2 ohm-cm. Thickness-velocity data. Growth behavior generally poor.
J-199	3	260	19.9	3.3	Repeat J-198, with spacing of top most shield increased to 4.5mm. Thickness velocity data. Difficult to start and grow.
J-200	2	538	47.2	3.3	J-181 configuration. New width record. Thruput rate of $15.8\text{cm}^2/\text{min}$.
J-201	4	325	27.2	2.8	J-181 configuration. Some difficulty starting growth early in day.
J-202	3	338	29.1	1.8	J-181 configuration. Dendrites somewhat choppy.
J-203	2	463	39.2	1.7	J-181 configuration. Some starting difficulties early good growth during afternoon.
J-204	2	441	35.6	1.6	Test modification of J-181 configuration. Middle Top shield slitted around periphery to limit r.f. coupling. (See Text)
J-205	3	410	28.4	1.6	Another J-181 modification with slitted shield on top. Doped to ~ 2 ohm-cm. Crystals terminated by pullouts.
J-206	Not Productive of Web				Repeat J-205. Melt very unstable for no apparent reason.
J-207	2	167	24.1	3.3	Repeat J-205 configuration. Thickness-velocity data. Coil raised to improve dendrite penetration. Improved growth behavior, but crystal terminated when reel tape tension wire failed.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	MAX. VELOCITY (cm/min)	DESCRIPTION/RESULT
J208	2	470	33.7	1.6	J-181 configuration. Radiation shields below susceptor replaced. Nominal 175gm melt as opposed to standard 185gms to start at slightly lower melt level. Generally good growth behavior.
J-209	2	305	38.4	1.6	Modification of J-181 configuration. Two upper shields slitted around periphery. To minimize r.f. coupling and thus reduce temperature. Very stable growth.
J-210	3	696	38.4	1.6	Modification of J-181 configuration, extra top shield, upper two slitted to reduce r.f. coupling. Good growth behavior.
J-211	5	350	24.0	3.3	Repeat J-210 configuration. Thickness-velocity data. Growth behavior poor relative to J-210. After run, it was discovered that Si melt had not wetted one end of crucible, and pulled away further as run progressed.
J-212	3	586	32.9	5.0	Repeat J-210 configuration, except starting melt increased to 185gms. Thickness velocity data. Reached 16.5cm ² /min thruput.
J-213	4	432	32.0	5.2	Repeat J-210 configuration. Thickness-velocity data early and late in day. 16.6cm ² /min max. Thruput.
J-214	2	220	18.5	3.3	Test different to shield configuration. J-181 lid with RE-1 type shields, except upper slitted. Thickness-velocity data. Unstable melt. Poor growth behavior.
J-215	No significant web production				J-210 configuration with lid and topmost shield instrumented. Melt unstable. Thermocouple feed through evidently leaked, causing partial oxidation of side shields.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE165	3	351	18.6	Molybdenum blocks were placed on the ends of the wide growth slot to evaluate for use in width control. Oxide grew on the blocks and caused ice throughout the run.
RE166	2	420	18.6	This run was a repeat of the set up of RE165. Although oxide grew on the blocks, ice was not a problem. One of this run's crystals held a width within 2 mm for 90cm, a positive result for width control.
RE167	3	191	23.2	This was another run like RE165. Again oxide on the blocks caused ice and prevented good crystal growth.
RE168	2	275	19.0	To try to keep the lids blocks hotter, and oxide free, blocks were placed on the shields above the other blocks. The result was oxide along the slot of the shield as well as on the moly blocks.
RE169	NONPRODUCTIVE			Run aborted because of water pressure problems.
RE170	1	105	20.9	Wide grow lid and shields, with feeding. The feed tube was coiled to slow the pellets, to decrease the impact wave. Ice occurred when feeding was tried.
RE171	3	402	23.8	A lid with a long straight slot (no dogbone) was tried with the moly blocks to see if the gas flow would be sufficiently different. However, oxide on the blocks was as bad as with the dogbone lid.
RE172	2	260	26.4	Wide grow lid and shields for feeding, using a solid end shield on feed side. Feeding resulted in ice; experiment ended when pellets became stuck in feed coil. Enough web was pulled out that the melt shifted near the end of the day. Incomplete wetting of the quartz was evident in the feed chamber.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE173	1	147	29.4	Set up like RE172, using a different feed coil. A large amount of silicon was pulled before the recorded crystal was grown. This was necessary because the melt level was higher than normal, due to a failure of wetting in the feed chamber. Suspected cause: the arrangement of the polysilicon in the crucible.
RE174	1	92		Set up like RE172, except using the perforated end shield. The aspirator flow was varied throughout the day as about 10 crystals were started. This was done to find the flow which would be the most effective in the prevention of ice.
RE175	2	393	41.5	Wide growth slot in lid and shield. The lid had slots milled into the bottom. These slots act as aspirators, allowing the silicon oxide an alternative to the growth slot as an exit from the crucible region. With this lid the oxide deposited on the web was largely a hard oxide, but the bottom of the lid was perfectly clean.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE-176	7	546	32.6	J-181 configuration for feeding, perforated shield on left end. Oxide on the lid was the most significant problem, preventing long growth periods. One 40 min. feed period was achieved before the oxide caused ice.
RE-177	2	231	28.2	Set up like RE-176. Oxide again was a problem, but not as much as in RE-176. Ice occurred several times while feeding, but generally these particles could be melted while crystal growth continued on one crystal 1 hr 23 min. of feeding was achieved before ice ended growth.
RE-178	1	102	23.1	Set up like RE-176. There was no oxide on the lid, but ice was a problem. Feeding was not practicable this run because the feed end of the crucible had "dewetted" and held no silicon.
RE-179	Nonproductive of Web			An error in the furnace setup resulted in conditions that made crystal growth impossible.
RE-180	3	209	-	Set up like RE176. The thermal profile was peculiar; the ends of the crucible seemed colder than normal, relative to the center temperature.
RE-181	3	394	27.8	J-181 lid and shields for feeding; solid shield on feed end of susceptor to increase the end temperature. There was some oxide on the lid in the beginning of the run, but it was a temporary problem. When feeding was tried, this proved to be the most successful run yet. No feed related problems were encountered all day. Of the crystals grown, the longest grew for 2hr. 23min. with feeding. (Over 5 hours of feed time, 3 crystals were obtained without ice.)
RE-182	1	93		Repeat setup of RE181. This run was not successful; the feed chamber had dewetted and so held no silicon except the pellets which were added later.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE-183	1	170	33.6	Repeat set-up of RE181. A different coil position was tried in the meltdown, but again the feed chamber was empty.
RE-184	Nonproductive of Web			Repeat setup of RE181. A more extreme coil position was tried, successfully wetting the feed chamber of the crucible. However the other end of the crucible did not wet properly, and no good crystals were obtained.
RE-185	2	223	-	Repeat lid and shield of RE181. The barrier used had a 3mm ridge along the bottom of the crucible with a 3mm gap above the ridge. The furnace components were slightly oxidized during the run, affecting the thermal gradients. Ice occurred throughout the run.
RE-186	1	106	20.0	J-181 lid configuration perforated end shield; ice occurred with feeding.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE188	3	355		J-181 lid and shields, not set up for feeding.
RE189	1	204	21.8	J-181 lid and shields; solid end shield; "fence" barrier. Misalignment of feed tube resulted in ice when pellets rolled across the lid into the growth slot. Three crystals were grown for periods of up to 1 hr 15 min. with feeding with no other ice problems.
RE190	2		23.6	J-181 lid and shields, solid end shield. Ice was a problem in this run; the cause is uncertain.
RE191	1	90	22.2	J-181 lid and shields; solid end shield. Ice was a problem with and without feeding.
RE192	Nonproductive of Web			J-181 lid and shields for feeding; solid end shield. Ice was a problem with and without feeding.
RE193	1	96	23.1	J-181 lid and shields for feeding; solid end shield. Ice was a continuous problem; there was evidence of spalling on the lid.
RE194	Nonproductive of Web			J-181 lid and shield. This was not a feed run. Ice was a problem, generally occurring within an hour after a crystal was begun. Again there was evidence of spalling, despite the heavy sand blasting the lid received before the run.
RE195	Nonproductive of Web			J-181 lid with slotted bottom. Continual oxide growth on the lid prevented crystal growth. The probable cause of the oxide was an improperly cleaning of the lid.
RE196	Nonproductive of Web			J-181 lid for feeding, solid end shield. Whenever feeding was tried ice occurred. From the shape of the ice and from the varied times before ice appeared, oxide particles were the probable cause.
RE197	Nonproductive of Web			J-181 lid with milled bottom. Ice was again a problem.

GROWTH RUN SUMMARY

RUN	MAX. WIDTH (mm)	TOTAL LENGTH (cm)	DESCRIPTION/RESULT
WA-1	*	*	RE-1 lid configuration. Oxide from lid and shields caused icing problems. May have been due to melting down too rapidly and overheating. Lateral coil position adjusted until buttoning was symmetrical.
WA-2	*	*	RE-1 lid configuration. Initially difficult to get dendrite penetration. Coil raised to achieve dendrite formation and first web grown.
WA-3	*	*	J-181 lid configuration. Oxide and icing problems. Further coil adjustments to improve buttoning.
WA-4	*	*	J-181 lid configuration. Various coil heights tested obtained better growth initiation and dendrite penetration. Oxide deposition prevented significant web growth.
WA-5	*	*	J-181 lid configuration. Again, oxide interfered with web growth.

*First five runs primarily for leak check, coil test, controller and speed calibration.
Growth was secondary objective.

GROWTH RUN SUMMARY

RUN	MAX. WIDTH	TOTAL LENGTH (cm)	DESCRIPTION/RESULT
WA-6		112	Growing with vented lid in J181 configuration, to help eliminate oxide problems. Oxide was not a problem and growth was good. There was some polycrystalline growth and choppy dendrites until the melt was lowered by about 10 grams. Coil was adjusted for more symmetric growth.
WA-7		170	Using standard J181 configuration with a slower melt down to help prevent oxide development. This run was free of oxide and growth was good. Some additional coil movements were made to improve button symmetry and dendrite penetration.
WA-8		120	Standard J-181 configuration using normal melt down procedures. The more rapid melt down previously used seemed to be a cause of oxide formation. No long pieces were grown because of oxide falling in the melt causing ice.
WA-9		435	Repeat WA-7 using slow melt down to prevent oxide development. This run was again free of oxide, and oxide formation appears to be definitely related in part to melt down procedure. Growth was good with very few adjustments being required.
WA-10	Not Productive of Web		J-181 configuration being used for pull speed calibration. A more rapid melt down was used which resulted in oxide formation again. Future runs should be made with the slower melt down procedure. Oxide formation prohibited growth, but pull speed calibration was made, as intended.
WA-11	Not Productive of Web		Repeat WA-10 run, repeating pull speed calibration. Problems with melt down and lid preparation resulted in some oxide. Polycrystalline growth was a problem early in the run. Past experience suggests a lower starting melt weight will offset this difficulty.

GROWTH RUN SUMMARY

RUN	MAX. WIDTH (mm)	TOTAL LENGTH (cm)	DESCRIPTION/RESULT
WA-12	Not Productive of Web		Using J-181 configuration with a vented lid, repeat WA-6, to determine if vented lid will prevent oxide deposition. Oxide did not deposit on lid but did form on <u>shields</u> . Growth was prohibited by the oxide.
WA-13	24.7	184	J-181 configuration using slow melt down to control oxide deposition on components. Some oxide did form on upper shields this may be due to inadequate lid preparation. These lids will be prepared using the usual procedures and run in the J furnace to see if oxide forms. The oxide problem was not as severe as usual and some growth was possible.

GROWTH RUN SUMMARY

RUN	MAX. WIDTH	TOTAL LENGTH (cm)	DESCRIPTION/RESULT
WA-14	3.0 cm	109 cm.	J-181 configuration with 1/16" raised top shield. Clean and oxide free, raising shield helped prevent oxide. Problems were with polycrystalline growth, may be due to high argon flow rates.
WA-15	Not Productive of Web		Repeat WA-14 configuration. Clean and oxide free, raised shield appears to eliminate oxide. Lower argon flow appears to have corrected polygrowth problem, except at higher speeds.
WA-16	3.4 cm	160 cm.	Repeat WA-14, this run was clean and oxide free. Thickness velocity data for the J181 configuration was obtained. The melt weight was increased again to 185 grams but polycrystalline growth resulted early in the run.
WA-17	3.3 cm	150 cm	This run used a 30° beveled lid with a J181 shielding configuration to improve the radiation losses from the web. Growth was good and the run was clean. Thickness velocity data was taken and thickness was increased by 20% for a given pull speed as compared to the standard J-181 lid.
WA-18	Not Productive of Web		Repeating WA-17 configuration to get additional thickness-velocity data on the new lid. This run was again clean and oxide free. Sever short crystals were grown and thickness data recorded. The higher melt level is still resulting in polycrystal line growth early in the run.
WA-19	Not Productive of Web		Repeating WA-17, thickness velocity data was recorded for several short crystals and the thickness is still greater as compared to the standard J-181 configuration.
WA-20	3.8 cm	182 cm	Repeat WA-14 using J-181 configuration to get thickness-velocity data. This run was clean and free of oxide.

APPENDIX 9.2

AVERAGED SOLAR CELL DATA FOR WEB CRYSTALS

The tables in this appendix give the averaged solar cell performance for cells fabricated from the crystals listed. Each entry in the table represents the average value for approximately four cells. Measurement conditions were a simulation of an AM1 illumination at a power density of 91.6 mW/cm^2 as determined by a standardized solar cell. The cells were nominally $10 \times 10 \text{ mm}$ square (actual area 1.032 cm^2), and had an active area of about 92.5%. The cell efficiency with an anti-reflective coating η_{AR} , is an estimated value based on an average improvement factor of 1.43, typical of the results we obtain in practice with a $\text{TiO}_2\text{-SiO}_2$ coating.

SUMMARY OF DIAGNOSTIC SOLAR CELL DATA

J-, RE-, and W-Crystals

Crystal	Run	I_{sc} mA	V_{OC} Volt	FF	η_o %	η_{AR} %	τ_{OCD} μs	ρ Ω -cm	NOTES
J176-2.6	WQ30	21.1	.534	.752	9.0	12.9	6.5	8.0	
J181-2.4	WQ35	21.7	.55	.755	9.6	13.7	11.1	8.3	
J182-2.4	WQ31	18.4	.503	.728	7.1	10.2	1.0	8.3	
J183-2.1	WQ31	19.2	.511	.740	7.7	11.0	1.4	8.3	
J185-1.3	WQ33	22.6	.522	.695	8.7	12.4	4.8	8.4	
J185-2.4	WQ33	22.3	.506	.712	8.5	12.2	3.3	8.0	
J187-2.3	WQ33	21.8	.547	.750	9.4	13.4	4.6	3.1	
J187-3.4	WQ33	22.1	.555	.750	9.7	13.9	4.8	2.9	
J191-2.3	WQ35	21.6	.526	.737	8.9	12.7	2.8	8.9	
J194-3.4	WQ35	22.6	.543	.748	9.4	13.4	10.6	12.4	
J197-2.2	WQ36	20.8	.558	.723	8.9	12.7	2.4	1.4	
J198-2.5	WQ38	20.7	.556	.760	9.3	13.3	2.1	1.5	
J200-2.5	WQ36	21.2	.508	.730	8.3	11.9	.3	9.1	
J202-3.5	WQ37	21.2	.531	.769	9.2	13.2	3.1	8.6	
J203-2.5	WQ37	20.9	.522	.757	8.7	12.4	2.7	11.9	
J204-1.5	WQ37	20.6	.517	.759	8.5	12.2	2.2	11.5	
J204-2.5	WQ37	20.2	.504	.717	7.7	11.0	1.2	12.2	
J205-3.3	WQ38	18.1	.523	.753	7.5	10.7	.8	1.6	
RE155-1	WQ30	21.5	.531	.727	8.8	12.6	6.2	8.1	
RE155-2	WQ30	21.1	.540	.729	8.8	12.6	9.0	8.4	
RE157-1.3	WQ30	21.0	.534	.746	8.9	12.7	7.9	8.1	
RE161-1.6	WQ35	22.4	.558	.775	10.3	14.7	10.3	7.3	Feed Expt.
RE175-2.5	WQ34	20.7	.521	.749	8.5	12.2	1.7	7.0	
RE177-2.2	WQ36	21.6	.518	.719	8.5	12.2	3.1	6.8	
RE183-1.4	WQ37	20.3	.527	.763	8.6	12.3	1.2	12.2	
W180-3.7	WQ35	18.5	.589	.777	9.0	12.9	1.3	0.3	

9.3 Updated Program Plan

9.3.1

MILESTONE CHART

JPL CONTRACT 954654

PHASE III

TASKS/MILESTONES	1979											1980										
	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A					
1. Develop Melt Replenishment (MR) System With Liquid Level Sensor										Δ												
2. Develop Advanced Thermal Trimming With MR to Grow Wide Low Stress Webs at High Speed										Δ												
3. Combine the Developments of 1 and 2. Demonstrate Repeatable 25 cm ² /min Growth Output Rate											Δ											
4. Develop Closed Loop Controls for Semi-Automated (SA) Web Growth											Δ											
5. Operate the SA Web Growth and Evaluate Its Feasibility to Attain Throughput Goal																	Δ					
6. Prepare a Complete Design of a Totally Automated Experimental Web Growth Machine with all Functional Feature Assumed in Economic Analysis																	Δ					
7. Perform Characterization of Selected Web Samples and Demonstrate Solar Cells with Efficiency of 15% AM1																	Δ					
8. Provide a Minimum of 10 Solar Cells per month, with Data, Fabricated From Representative Web Ribbons																	Δ					
9. Provide an Average of 2 Meters per Month of Web Samples of 2.5cm or Greater Width																	Δ					
10. Update Economic Analysis not Later Than										Δ	Δ		Δ									
11. Provide Personnel to Support Required Meetings																	Δ					
12. Provide Documentation																	Δ

9.3.2 Program Labor Summary JPL 954654, Phase III

9.3.3 Program Cost Summary JPL 954654, Phase III

ROUTING	FIREPROOF VAULT				

DRAWING LIST

INDEX	TITLE OF DRAWING	DRAWING NO.	ITEMS OR STYLE NO.	CHECKED	DATE
1	LAYOUT	1290J11			
2					
3					
4	TOP COVER PLATE DET.	639F576			
5					
6					
7					
8	SENSOR SUPPORT DET.	8530086			
9	PORTHOLE FLANGE ASSY	8531007			
10	PORTHOLE FLANGE & WINDOW DETAILS	8531008			
11	LASER HOLDER WELDMT	8531009			
12	LENS & DETECTOR HOLDER WELDMT	8531010			
13	LENS & DETECTOR FASTENER DETAILS	8531011			
14	LASER VEE BLOCK & LID DETAILS	8531012			
15	OVAL SUSCEPTOR LID & SHIELD	8531055			
16	HEAT SHIELD	8531058			
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					
27					
28					
29					

GROUP ORDERED FOR DESIGN ON WHICH THIS DRAWING WAS BASED

NAME OF APPARATUS

SILICON WEE FURNACE (RE)

ENGR S. DUNCAN & M. HEIMLI

CHECKED BY AND DATE

TPG 10-4-79

DESIGN NO.

D 903133

WESTINGHOUSE FORM 6541 J

1 of 1

13.0711

11.0751

ALL DIMENSIONS SAME AS
ITEM-01 EXCEPT OPPOSITE HAND

SILICON AID FEMALE FBI BLOOD SPOOT DETAILS									
060 855520									
FILE	NO	DATE	TIME	TEST	TEST	TEST	TEST	TEST	TEST
01	1277	12/11/71	10:00	1277	1277	1277	1277	1277	1277
02	1277	12/11/71	10:00	1277	1277	1277	1277	1277	1277
03	1277	12/11/71	10:00	1277	1277	1277	1277	1277	1277
04	1277	12/11/71	10:00	1277	1277	1277	1277	1277	1277
05	1277	12/11/71	10:00	1277	1277	1277	1277	1277	1277

Westinghouse Electric Corporation

TITLE: S - CON WSB PLWACB (RE)
BENCH 5-0034- C5A-0

REV: 1

6530D86

NOTE:
1 - FURNACE BRATE ASSY V.T.

TITLE: SILICON WEB FURNACE RE-PORTHOLE PLANGE & WINDOW CETA-LS									
REV: 0531008									
REV	DATE	BY	CHK	APP	DESCRIPTION	REV	DATE	BY	CHK
01					WINDO PLANGE	01			
02					WINDO PLANGE	02			
03					WINDO PLANGE	03			
04					WINDO PLANGE	04			
05					WINDO PLANGE	05			
06					WINDO PLANGE	06			
07					WINDO PLANGE	07			
08					WINDO PLANGE	08			
09					WINDO PLANGE	09			
10					WINDO PLANGE	10			
11					WINDO PLANGE	11			
12					WINDO PLANGE	12			
13					WINDO PLANGE	13			
14					WINDO PLANGE	14			
15					WINDO PLANGE	15			
16					WINDO PLANGE	16			
17					WINDO PLANGE	17			
18					WINDO PLANGE	18			
19					WINDO PLANGE	19			
20					WINDO PLANGE	20			
21					WINDO PLANGE	21			
22					WINDO PLANGE	22			
23					WINDO PLANGE	23			
24					WINDO PLANGE	24			
25					WINDO PLANGE	25			
26					WINDO PLANGE	26			
27					WINDO PLANGE	27			
28					WINDO PLANGE	28			
29					WINDO PLANGE	29			
30					WINDO PLANGE	30			
31					WINDO PLANGE	31			
32					WINDO PLANGE	32			
33					WINDO PLANGE	33			
34					WINDO PLANGE	34			
35					WINDO PLANGE	35			
36					WINDO PLANGE	36			
37					WINDO PLANGE	37			
38					WINDO PLANGE	38			
39					WINDO PLANGE	39			
40					WINDO PLANGE	40			
41					WINDO PLANGE	41			
42					WINDO PLANGE	42			
43					WINDO PLANGE	43			
44					WINDO PLANGE	44			
45					WINDO PLANGE	45			
46					WINDO PLANGE	46			
47					WINDO PLANGE	47			
48					WINDO PLANGE	48			
49					WINDO PLANGE	49			
50					WINDO PLANGE	50			
51					WINDO PLANGE	51			
52					WINDO PLANGE	52			
53					WINDO PLANGE	53			
54					WINDO PLANGE	54			
55					WINDO PLANGE	55			
56					WINDO PLANGE	56			
57					WINDO PLANGE	57			
58					WINDO PLANGE	58			
59					WINDO PLANGE	59			
60					WINDO PLANGE	60			
61					WINDO PLANGE	61			
62					WINDO PLANGE	62			
63					WINDO PLANGE	63			
64					WINDO PLANGE	64			
65					WINDO PLANGE	65			
66					WINDO PLANGE	66			
67					WINDO PLANGE	67			
68					WINDO PLANGE	68			
69					WINDO PLANGE	69			
70					WINDO PLANGE	70			
71					WINDO PLANGE	71			
72					WINDO PLANGE	72			
73					WINDO PLANGE	73			
74					WINDO PLANGE	74			
75					WINDO PLANGE	75			
76					WINDO PLANGE	76			
77					WINDO PLANGE	77			
78					WINDO PLANGE	78			
79					WINDO PLANGE	79			
80					WINDO PLANGE	80			
81					WINDO PLANGE	81			
82					WINDO PLANGE	82			
83					WINDO PLANGE	83			
84					WINDO PLANGE	84			
85					WINDO PLANGE	85			
86					WINDO PLANGE	86			
87					WINDO PLANGE	87			
88					WINDO PLANGE	88			
89					WINDO PLANGE	89			
90					WINDO PLANGE	90			
91					WINDO PLANGE	91			
92					WINDO PLANGE	92			
93					WINDO PLANGE	93			
94					WINDO PLANGE	94			
95					WINDO PLANGE	95			
96					WINDO PLANGE	96			
97					WINDO PLANGE	97			
98					WINDO PLANGE	98			
99					WINDO PLANGE	99			
100					WINDO PLANGE	100			

.204 DIA.
4 HOLES SQ. SP. ON A
2.487 DIA. B.C.

.190-52 TAP
5 HOLES SQ. SP. ON A
2.487 DIA. B.C.

.204 DIA.
5 HOLES SQ. SP. ON A
2.487 DIA. B.C.

TITLE		SILICON WELD FURNACE (RS)		DATE		BY		REV	
LASSER HOLDER WELDING									
CNO 6651009									
REV									
REV	DATE	DESCRIPTION	QTY	UNIT	PRICE	TOTAL	TAX	NET	GRAND TOTAL
01		MOUNTING PL.	375	PC	30	11250			
02		CHANNEL	MADE FROM 1/2" AL.						

67

2011

Westinghouse Electric Corporation		(8)
TITLE SILICON WEB FURNACE (RE)		
LASER HOLDER WELDOUT		
Drawing No. _____		Rev# _____
DRAWN BY J. GRADISER	CHECKED BY _____	8531 D09
DATE 1-1-68	DATE _____	
Made at _____		

READ CAREFULLY: 1-10 INSTRUCTIONS FOR PREPARATION OF DRAWING

TITLE: SILICON WEB FURNACE (WB) OVAL SUSCEPTOR LID & SHIELD REV. 1					
ITEM	REV.	DATE	DESCRIPTION	BY	CHKD.
01			TOP SHIELD		
02			MIDDLE SHIELD		
03			SUSCEPTOR LID		
NOTE: 1- POLISH & REMOVE ALL SHARP EDGES.

01 02 SAME AS ITEM-01 EXCEPT AS SHOWN IN SECTION G-G

150 DIA. 8 HOLES MARKED "A"

03

SECTION D-D

SECTION E-E

SECTION G-G

Westinghouse Electric Corporation

TITLE: SILICON WEB FURNACE (WB)
OVAL SUSCEPTOR LID & SHIELD
REV. 1

8531 D55

72

FRONT

SILICON WEB FURNACE (RE)									
HEAT SHIELD									
REV. 1									
DMD 8551036									
REV. 1									
NO.	REV.	PART NAME	QTY.	MATERIAL REFERENCE INFORMATION		UNIT, MAT CODE PART NUMBER OF REV AND QTY. STK. NO.	GROUP NOTE	GROUP	
								1	2
21		HEAT SHIELD	875 DIA. OF .031 THK. 537 306			9408-0101			