ERDA/JPL/954344-75/1

Web-Dendritic Ribbon Growth

USC Solar Report No. Q-1

Quarterly Report for Period 10-1-75 to 12-31-75

Authors: R. B. Hilborn, Jr. and J. W. Faust, Jr.

Date of Publication: 12-12-75

JPL Contract No. 954344

Contractor: University of South Carolina
College of Engineering
Columbia, S.C. 29208

MASTER

This work was performed for the Jet Propulsion Laboratory,
California Institute of Technology sponsored by the National Aeronautics
and Space Administration under Contract NAS7-100.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

*This is
to ERDA
for PWR 1/16/76*

pkd

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.

TABLE OF CONTENTS

<u>SUBJECT</u>	<u>PAGE</u>
Technical Content Statement	1
Abstract	1
Man-hours and Cost Totals	2
Summary	2
Quarterly Progress	4
Table I	20
Table II	22
Table III	23
Fig 1	25
Fig 2	26
Fig 3	27
Fig 4	28
Fig 5	29
Fig 6	30
Fig 7	31
Fig 8	32
Fig 9	33
Program Plan	Attachment

Technical Content Statement

This report contains information prepared by the University of South Carolina under JPL subcontract. Its content is not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or the National Aeronautics and Space Administration.

Abstract

This is a report of the first quarter's work on the web-dendritic ribbon growth at the University of South Carolina. A brief description of the work initiated and carried out during this period to meet the program goals is given along with a copy of the Program Plan covering the entire period of the contract.

Man-hours and Cost Totals

<u>Previous</u>		<u>Current Quarter</u>		<u>Cumulative</u>	
Man-hours	Cost	Man-hours	Cost	Man-hours	Cost
—	—	1977	\$25,719	1977	\$25,719

Summary

The purpose of this investigation is to develop web-dendritic process methods that will: (1) minimize the cost of processing silicon into ribbons of solar cell quality with a terrestrial energy conversion efficiency greater than 10%, and (2) be suitable for large quantity production.

The goals for producing silicon ribbon by the web-dendritic process developed under this contract are:

Width	5.0 cms
Linear Growth Rate	5 cms/minute
Thickness	4 mils $\pm$ 1 mil
Dislocation Density	$< 10^4 \text{ cm}^{-2}$
Crystal Structure	Single Crystal

The work is largely experimental in nature, utilizing the results of thermal modeling analyses and empirically determined data from ribbon growth runs to determine the feasibility of the process methods.

The report for this first quarter (actually the first two and one-third months) describes the initiation of the program and presents the plan for the program for the full length of the contract.

Work is described on:

- (1) the procedures used to set up, calibrate and operate the web-dendritic growth furnace;
- (2) use of the furnace to grow dendritic seed crystals and single crystal ingots;
- (3) initial considerations applied for the thermal analysis of the web-dendritic growth system;
- (4) procedures and facilities being established for the structural and electrical characterization of web material.

The major result of this report period is the successful set-up and operation of the web-dendritic growth furnace and its use in growing dendritic seed crystals.

These results reflect that we are on target, if not slightly ahead, in regard to our time-phased program plan. The prime achievement to be realized during the first quarter of the contract was to make the web-dendritic furnace operational and we have achieved this to the point of being able to successfully grow the dendritic seed crystals needed to initiate the growth of the web. This represents the completion of the first step towards the satisfaction of the contract goals, i.e., the production of web-dendritic ribbon.

In view of the apparent progress being made towards the attainment of the program goals, no recommended changes in the initial program plan are offered at this time.

QUARTERLY PROGRESS

T.E. 1.1.1: Level, align, calibrate gas flow; measure physical/mechanical parameters

Before the start of the contract a special room, designated the Web Growth Laboratory, had been completed. By the start of the contract the furnace and r.f. generator had been installed in it and were approximately 90% complete. During the first month, the leveling and shock vibration mounting system was completed, tested and made operational. A manifold was constructed to hold the argon tanks. Valves, guages, and lines were connected for the argon protective gas system. The system including the furnace was tested for leaks and then calibrated. Final alignment was made on the pulling assembly, and a control system was designed, built and tested. A calibration curve, given in Fig 1, for pull rate versus motor speed was experimentally determined.

During the rest of the report period very little had to be done to the furnace with the exception of minor adjustments. One thing that was necessary, however, was a redesign of the assembly holding the r.f. work coil. This had been constructed from bakelite and held together with machine screws. Some arcing resulted at high power. A new design was drawn up (the drawing is reproduced in Fig 2) and constructed. It has not given any problems. During actual operation of the furnace, we found that the number 5 welding glass used on the heat shield for viewing purposes cracked. This is being replaced with infrared protective glass, and viewing will be done with hand-held welding glass.

The work during this first quarter, summarized above, is complete. During the running of the furnace, as summarized in 1.1.2, 1.1.3, and 1.2.1,

we have found no problems and thus anticipate nothing more than normal maintenance and adjustments in the next three-month period.

T.E. 1.1.2: Instrument melt temperature sensors, run furnace, and r.f. generator

The temperature of the melt is being controlled, at present, by an Ircon Modline temperature control system which is fed by an Ircon optical pyrometer sighted on the bottom of the susceptor. Initially the output of the controller was to feed a magamp to control the generator. Operation of the generator, however, showed the magamp to be defective. Rather than repair or purchase a new magamp, it was replaced with a Hewlett Packard 6299A D.C. programable power supply. This has necessitated the design and fabrication of an interfacing circuit, shown in Fig 3, to match the output of the Ircon controller directly to the input of the generator. In actual operation the furnace is brought up to temperature manually. The Ircon controller is used only to keep the temperature constant at a desired value. Temperatures read from the meter on the Ircon controller were found to be in good agreement with two independent optical pyrometers.

During this report period for this task element, the generator and furnace were run without any silicon in the crucible. Initially it was not possible to get the susceptor above 1200°C even with all but two turns of the tank coil shorted out. There was quite a bit of corona discharge and arcing. After several days of outgassing the susceptor, and tracing through the r.f. generator circuit, it was deemed advisable to have Lindberg send a man who was familiar with the generator. After two days he left with the generator checked over and in good order as per the schematics.

A temperature of 1570°C was reached the day he left. Within a few days it was apparent the generator was not doing the job it should. Capacitors and resistors were measured for leaks and parasitics. The time constant of the tank capacitor checked properly. Calculations were then made on the tank coil and circuit. The calculations indicated that for our working coil the capacitor for the generator was not correct. To get the desired LC, we obtained a smaller capacitor and put it in parallel with the one in the generator. This move proved correct. Not only were we able to get well above 1600°C (actually close to 1700°), but also solved the problem of arcing.

The susceptor we are using is made of Mo and is 4 inches in diameter. We tried a Mo susceptor that was about 2.5 inches in diameter. This proved too small for our work coil; it gave poor coupling even for the best tap position on the tank coil. Two graphite susceptors were tried. One was 3.25 inches in diameter; it gave very good coupling but was too long to couple enough power density to be raised to a sufficiently high temperature. The second susceptor was not as long. We obtained good coupling and about 1600°C . It appears obvious that if we should go to a graphite susceptor, it will be necessary to redesign our work coil to optimize the coupling.

Experiments were run to study the effect of the position of the susceptor in the work coil on the temperature. Studies of the effect of the Ar flow rate on the susceptor temperature and oxidation were also carried out. We used a 50 cfh rate during heat-up and cool-down, but lowered the flow rate to 35 cfh during pulling.

Twice the generator kicked off because of an unusual fluctuation in the water pressure. In each case it was toward the end of the day.

A separate distilled water cooling system independent of the city water supply has been designed, not only to make sure the water pressure does not become a problem, but also to protect the cooling tube bases from clogging from deposit build-up that is common locally with tap water cooling.

The above summary showed that this task element is complete. (The water pressure is not considered a problem, but will be completed before the time for the next quarterly report.) As will be discussed in Sections 1.1.3 and 1.2.1, the generator has given no trouble during the numerous runs made in the past month. Thus during the next report period we anticipate nothing more than the usual maintenance.

T.E. 1.1.3: Calibrate r.f. generator controls to melt temperature

Sections 1.1.1 and 1.1.2 summarize the work on the furnace and the r.f. generator. In these sections (particularly 1.1.2) it was necessary to summarize some of the r.f. generator control calibration that could actually have been given in this section. On November 5 the first melting was obtained; however, due to the generator problems discussed above, it was only a partial melting. On November 11, after the generator problems had been solved, the first complete melting of a charge was obtained. (The charge weight was 120 gms. The size of one charge to be used will be discussed in Section 1.2.1.) On very slow cooling we could see the "ice" form on the surface. It started from the approximate geometric center, indicating that the center of thermal symmetry was very close to that of the geometric center. Since that time we have had over 12 meltings, each with a specific goal.

Some SiO formation has been noticed. In an attempt to reduce or eliminate this the following have been tried: (a) checks for leaks, (b) variation of flow rate of Ar, and (c) trying three grades of bottled Ar. Periodic checks on the system have shown no leaks. Increased flow rate over that given in Section 1.1.2 gave no improvement. A bottle of presumably very high Ar (it cost approximately five times the cost of our regular gas) was tried as was a bottle of "better purity" Ar since it is only a dollar or two more expensive than our regular Ar. The SiO formation is not, however, excessive.

The fact that the temperature read with the Ircon optical pyrometer was in good agreement with those of two independent optical pyrometers was already noted in Section 1.1.2. Temperatures were taken at various positions on the heat shield and susceptor walls as well as of the melt itself. The Ircon optical pyrometer was initially sighted on the lip of the susceptor. It is now sighted on the bottom of the susceptor near the periphery. This gives us a lower temperature reading with little or no change in sensitivity or response time. Temperatures on the periphery of the heat shield, on the heat shield near the opening for pulling, and of the silicon surface itself were monitored during the first few runs. Final temperatures and thermal symmetry were checked by probing the melt with a single crystal seed.

After the first two melts where temperatures were raised and lowered very slowly, a routine was worked out of getting to growth temperature as rapidly as possible. The operating instructions for the generator and furnace are given in Table I. From the time the r.f. is first turned on, complete melting is obtained in approximately 30 minutes and the melt is down to pulling temperature in another 10 minutes. It takes approximately two hours to cool enough to get the crucible out of the furnace. Thus from

the time of ending one run, another run can be started in approximately three hours. While a melt is up to temperature, seeds can be taken out, changed, and other things done through the withdrawal chimney. On one run we kept the silicon melt at temperature for over five hours.

The information summarized above shows that both generator and puller are working well. In addition the work performed under this task has given valuable experience on the equipment, on the controls, on loading, unloading and many other operational aspects. This task is not listed for completion until the end of December; however, it is now complete.

Nothing more is contemplated on this task element in the next three-month period.

T.E. 1.2.1: Pull nominal web based on 1965 experience, establish measurements baseline

It was mentioned in Section 1.1.3 that over 12 crucibles of Si have been melted. Although initially a charge of 160 gms was used, most of the charges used have been between 110 and 125 gms. The size of the charge is based on the calculations given in Table II to be able to supply not only the minimum requirements of the contract but also the desired goal of 5 cm wide ribbon. A cylinder of polycrystalline silicon 7 cm in diameter and 1.3 cm high will give a charge of 116 gms.

The first charge of silicon was heated in the furnace without a heat shield. Although the temperature of the susceptor was high enough to melt silicon, no melting took place because of the radiation losses; this was expected. All melts have, understandably, required a heat shield. The heat shield used for the initial thermal probing of the melt, mentioned in Section 1.1.3, had a "large" opening - 1.57 cms across and 5.59 cms long. The single crystal seed was 5 mm in diameter. This probing was done to locate

more precisely the temperature of the melt and to check the radial thermal symmetry. These probings showed that the center of radial thermal symmetry was quite good. After the last probing with the single crystal seed, a single crystal "ingot" approximately 10 cm long was pulled by careful intermittent manipulation of the pull rate.

A twinned seed was then tried. With this seed (which had given questionable results in the past), no dendrites were grown. Growth did occur; however, the buttons were not faceted and pulled out in a somewhat symmetrical shape, indicative of too small a temperature gradient in the vertical direction and possibly too large an opening in the heat shield.

A heat shield was then placed on that had a width of 6 mm and a length of 47 mm. This, of course, changed the temperatures slightly and it was necessary to reprobe the melt. A new twinned seed was used. The seed was inadvertently put in upside down. A good growth button was obtained (see Fig 4) for a three twinned dendrite growing in the "wrong" direction (i.e., the $\langle\bar{2}11\rangle$). Two short dendrites grew out at the 60° angles. The seed and button were removed through the chimney without the necessity of shutting off the furnace. The seed was inverted. A number of good buttons were grown but only very thin short dendrites grew from them, indicating that the vertical temperature gradient was too low. We are now in the process of adjusting the susceptor in the work coil to get the correct vertical temperature gradients. Initial adjustments proved to be in the right direction. Several dendrites of about 1 foot in length have been grown using the maximum pull rate of the puller. Further adjustment is necessary.

As was mentioned previously it has been possible to remove and change seeds through the chimney - in fact, one charge was kept in use for over five hours. We have had some adjustment problems on the positioning fingers, but these are being taken care of. The dendrites that were grown were

purposely grown to add to our supply of seeds as well as to check the thermal gradients in the crucible.

The work done in this task element is essential to the contract. Without a thorough knowledge and understanding of the thermal conditions it is folly to attempt to pull web. The experience gained in changing seeds, removal of material, positioning of seeds, etc., was invaluable. Within a few days web pulling will begin.

During the next three-month period webs will be pulled according to our contract plan. It is expected, however, that we will spend several days to a week, sometime during this three-month period, on pulling primitive dendrites in order to get a variety of twin spacings for future experiments.

T.E. 1.3: Web growth analysis

A. Summary of the results

A thermal model is being developed to model the web growth. For analysis purposes the web is separated into two regions consisting of the web section and the supporting dendrites. The separation is performed for purposes in constructing the model; however, the complete model will necessitate the integration of the components of the model.

The temperature distribution in the web can be calculated from the heat flow equation with boundary conditions which involve heat losses from the ribbon and surrounding temperatures. Because the web is very thin, the temperature variation in the web can be considered one-dimensional and in the direction of the length of the web. The thermal interaction of the dendrites with the web at the edges of the web may require that the model be applied at various positions across the web width with the appropriate boundary conditions.

A thermal model of the dendrites which appears to most closely approximate the geometry and is analytically tenable is the elliptical paraboloid. This geometry has been used previously by Horvay and Cahn¹ to study single germanium dendrites with good success. Measured values of the two principal radii of tip curvature were used in the equation to predict growth rate and, therefore, additional study is needed to determine the parameters which affect the curvature so that the results can be generalized. It is expected that tip curvature is a strong function of twin spacing.

It is presently expected that the thermal interaction between web and dendrites can be treated as a perturbation of the separate models. Non-uniform temperature distribution in the melt due to crucible/heater configuration will be included in the model.

B. Interpretation of these results

The results will be used to determine the effect of the temperature on the growth rate and the quality of the web. Measurement of the temperature distribution within the melt at the accuracy required for determining growth mechanisms would be extremely difficult. Therefore, the analytical technique appears to offer the greatest possibility of success, at least for the present time. The thermal model could be used in assisting in optimizing the furnace design and control parameters.

C. A projection of activities to occur in succeeding three-month period

The assistance of a graduate student will be obtained in January, 1976. The basic thermal model should be finalized shortly and the mechanics solution will be performed. In addition, preliminary comparisons between

experimental and the analytical results should be performed.

References

1. Horvay, G., and J.W. Cahn, "Dendritic and Spheroidal Growth," Acta Met. Vol. 9, pp/ 695-705 (1961).

T.E. 2.1: Development of sampling strategy, prototype technique

While the key to crystal growth studies is characterization of the material, the key to material characterization is careful sampling. Because of the uniformity of the material from the web growth process, one is not trying to set up a scheme for truly random sampling with a large enough number of samples to have statistical significance. Instead what is desired is to take enough samples along the strip to catch any deviation or anomalous changes in the structural and electrical properties of the material, but not so many samples that material, time, and money are wasted.

During this first quarter of the contract, we worked out a strategy based on past experience with webs and solar cells, and in keeping with the requirements of this contract. It is anticipated that this plan will be useable over the entire length of the contract. The growth button (or, in the case of direct seeding from a web, the region of seeding) will be separated from the seed and the rest of the length of web, by careful scribing and fracturing perpendicular to the growth direction. A twelve inch length followed by two one inch lengths will be separated by fracturing. This will be repeated down the entire length of the pull. Each piece will be carefully identified as to its position from the seed. The twelve inch pieces will be stored and used to fill requests from JPL or for making twelve inch

solar cell strips. One of each of the one inch pieces along with the seed sample will be used for the structural characterization, and the other one inch piece will be used for electrical characterization and test solar cell fabrication. In case of pulls less than two feet, the longer lengths will be reduced from twelve inches accordingly. Should any of the one inch pieces show an unexpected change, other samples will be cut from the twelve inch piece, if indeed more samples are required. It is anticipated that this may well be necessary in the first six or so pulls. During "routine" pulling, experience may well show that it is not necessary to make the tests on each one inch piece. This will not, however, alter the sample cutting. If the measurements are not made every twelve inches, the samples will be kept in storage for future use. A history of each sample of each run will be kept.

This task element is complete with the exception of laying out standard test data sheets. Since the exact layout will in part be guided by test data, it is deemed advisable to wait until data is available on at least one run. Thus in the next three-month period we plan to finalize on standard data sheet layouts.

T.E. 2.2: Structural characterization

All of the equipment to do the structural characterization of silicon was already on hand before the contract started with the exception of a microscope that has phase contrast (or Nomarski) and a Lang camera for x-ray topography. At present we will need neither of these. Later on (possibly in 6 months) we may very likely need a Nomarski set-up. It seems highly doubtful that we will actually need a Lang camera since equivalent data is obtained from TEM and careful dislocation etch studies. The graduate students are all trained in the characterization techniques. They

received this training in their course work, and some of them have done these measurements on previous contracts.

During this first quarter, no web was grown. The time was spent in designing and building special equipment necessary for holding and preparing web samples for measurements involving optical microscopy and transmission electron microscopy.

Measurement of twin spacings, thickness, density of dislocations running down the web parallel to the two main faces, and spacing of twin lamellae between the main faces necessitate viewing the sample "end on" under an optical microscope. This requires very exacting alignment. Often it is desired to tilt the sample approximately 20° to examine one of the $\{111\}$ planes on the fracture cross-section. The sample holder itself shown in Fig 5 was fabricated from a $\frac{1}{4}$ inch diameter steel rod with one end machined flat and a wire spring attached so that the sample is held firmly against the flat. The rod is placed in a V cut in a small block of steel that is affixed on one side of a steel plate cut to the size of a microscope slide. A knob allows rotation of the sample.

Transmission electron microscopy is used to examine samples for dislocations and microdefects (vacancy cluster, dislocation loops, and microprecipitates). One-eighth ($1/8$) inch diameter samples must be cut to fit on the standard electron microscope sample grids. The samples must then be thinned to less than $2000 \text{ \AA}$. A tool was made for the ultrasonic cutter to cut $1/8$ inch diameter samples. Tests are being made to be sure that the cutter we use is not putting in damaged or additional dislocations.

Thinning of such small samples for TEM requires jet etching. Jet etchers for Si and Ge require special materials that can withstand HNO_3 and HF and also not introduce contamination. A jet etching apparatus

has been designed and constructed somewhat along the lines of several already reported in the literature. The first design proved to be too critical in adjustment and gave very uneven etching. A second one has been built.

With the new instrument and practice an operator can repeatedly produce successfully etched samples. The active nature of the etchant is a constant worry, but immediate clean-up of the etcher after use minimizes part wear. Parts that wear are the tip and the bottom cap of the nozzle which are made of quartz.

The following is a description of the modifications made on the etcher, and a detailed etching operation procedure is given in Table III.

As depicted in Fig 6, the nozzle body is made of teflon instead of quartz as used before. Since the CP4 etchant does not react with teflon, the problem of erosion is eliminated. The tip is made of a piece of quartz capillary with an inside diameter 1 mm. It is sealed to a holder which screws into the nozzle body. The holder is also made of teflon. The etchant does erode the tip and the bottom cap. If care is taken in thoroughly cleaning the nozzle after each etching operation, the tip and the bottom cap can last for many operations.

T.E. 2.3: Electrical characterization, web bulk silicon

At the start of this contract, facilities were already in operation for making the following electrical characterization measurements:

1. Hall effect - Van der Pauw
2. Four-point probe conductivity
3. Capacitance.

During this period work has been initiated on setting up a facility for making minority carrier lifetime measurements by the MOS Capacitance

technique. An analysis and evaluation of the works of Jund and Poirier¹ and Hofstein² have been made. As a result of this, a facility is being assembled and tested, based on the paper of Hofstein².

This task element is proceeding on schedule and it is anticipated that the lifetime facility will be completed prior to the end of December, 1975.

T.E. 2.4: Electrical characterization, web solar cells

In order to evaluate the web-dendritic silicon for solar cells, it has been decided that as a minimum the i-v characteristics and efficiencies of representative cells must be measured.

An Eppley pyrometer has been set up to measure the sun's insolation during the solar cell testing, which will be done by natural sunlight.

Work has been initiated on building and testing a circuit for making the i-v characteristics with a dynamic display of the results under loading conditions ranging from zero to infinity. A breadboard form of the circuit has been constructed and successfully tested. The circuit is shown in block form in Fig 7, and schematically in Fig 8. Two controls are available to the operator for setting the current amplitude and the offset bias. The output which is displayed on an oscilloscope is the i-v characteristic of the test solar cell under illumination.

Plans for the succeeding report period call for the completed construction of the final i-v characteristics facility with the inclusion

¹ S.R. Hofstein, IEEE Trans. on E.D., ED-11, 11, 785-6 (1967).

² C. Jund and R. Poirier, Sol. States Elec., 9, 315-9 (1966).

of a circuit for the automatic location of the maximum power point in the output characteristics. A proposed circuit to achieve this aim is shown in Fig 9.

Problems

No problems of significance exist in the program at this time. The work is proceeding on schedule.

Plans

No deviations from the program plan, as updated on December 11, 1975, are anticipated. Work will proceed as outlined in this program plan and as has been described under the progress reports for each of the task elements.

TABLE I
OPERATING INSTRUCTIONS FOR WEB FURNACE

Prestart-up

1. Check generator off button on generator.
2. Check filament off button on generator.
3. Check main breaker on rear of generator.

Start-up

Load and assemble the furnace. After this is complete, proceed as follows:

1. Check cooling water on furnace. Turn on both valves - one to furnace and other to generator.
2. Turn on argon flow to 50 cfh.
3. Turn on filament button on generator.

Note: After the above three items have been accomplished, wait 15 minutes. This will allow the chamber to be purged with argon, and the vacuum tube filaments in the generator to warm up.

4. Check controller Auto-Manual switch. Put it in manual position and have temperature control on zero.
5. Turn on power button on the generator.

Caution: Work coil is now HOT!

6. Adjust power to 5 kilovolts until susceptor glows (approximately a minute). Increase power to 6 kilovolts until outgassing stops (approximately 5 minutes). Increase to 8 kilovolts for 2 minutes to let the temperature stabilize. Then increase to 10.5 kilovolts until complete melting is obtained.

TABLE I (continued)

7. Decrease argon flow to 35 cfh.
8. Lower temperature to growth value. After the temperature has stabilized it is ready for web growth.

Furnace Shut Down

1. Flip the Auto-Manual switch to Manual.
2. Cut furnace temperature.
3. Turn the generator power button to off.
4. Wait 30 minutes for cool-down and proceed as follows.
5. Turn filament button off.
6. Turn off main breaker.
7. Turn off argon.
8. Turn off water valves.

TABLE II
CALCULATION OF Si CHARGE

Calculations based on 20 feet of web at the goal dimensions of 5 cm wide and 4 mils thick using a density of Si of 2.33 gms/cm³

Web

$$20 \text{ ft} = 610 \text{ cm}$$

$$4 \text{ mils thickness} = 0.01 \text{ cm}$$

$$\text{volume} = 610 \text{ cm} \times 5 \text{ cm} \times 0.01 \text{ cm} = 30.5 \text{ cm}^3$$

Edge dendrites (estimates)

$$20 \text{ mils} = 0.051 \text{ cm}$$

$$\text{volume} = 2 \times 610 \text{ cm} \times (0.051 \text{ cm})^2 = 3.2 \text{ cm}^3$$

$$\text{Total volume} = 33.7 \text{ cm}^3$$

$$\text{Weight Si} = 78.5 \text{ gms}$$

$$\text{leave in about } \underline{20.5 \text{ gms}}$$

$$\underline{99.0 \text{ gms charge}}$$

The charge for the same length of web on 1965 requirements
(i.e., 2 cm wide and 8 mils thick)

$$\text{Web vol.} \quad 24.4 \text{ cm}^3$$

$$\text{Dend. vol.} \quad \underline{3.2 \text{ cm}^3}$$

$$\text{Total} \quad 27.6 \text{ cm}^3$$

$$\text{Weight Si} \quad 64.3 \text{ gms}$$

$$\text{leave} \quad \underline{14.7 \text{ gms}}$$

$$\underline{79.0 \text{ gms charge}}$$

TABLE III
OPERATION PROCEDURES FOR THE JET ETCHER

PRECAUTION: Protective gloves should be worn during entire operating procedure

1. Insure that drain reservoir is properly connected to etcher drain and charged with the necessary $\text{CaCO}_3 + \text{CaCl}_2 + \text{H}_2\text{O}$ acid neutralizer.
2. Mount the sample to the holder with black wax. (Use toluene as solvent.)
3. Position the sample above the nozzle tip. The distance between the sample and the tip should be approximately 3 mm.
4. Place the top on the etcher. Assure that the sample can be observed from the viewing mirror.
5. Adjust the bottom of the etchant reservoir to a level approximately 5 cm above the nozzle tip.
6. Mix CP4 etchant. (To etch a 10 mil silicon sample, use 27 c.c. HF + 123 c.c. HNO_3 .)
7. Turn on rinse jet water.
8. Turn on the etcher light.
9. Turn off the room light.
10. Pour etchant into the reservoir.
11. When a dim red light is observed in the viewing mirror, reposition the sample holder so that the sample is directly above the rinse jet.
12. Turn on the room light.
13. Decant the residual etchant from the reservoir into a plastic beaker.
14. Disconnect the tubing from the reservoir to release the remaining etchant into the beaker.
15. Stop the rinse jet water.

16. Remove the sample holder and rinse it in water.
17. Disconnect tubing from the rinse jet.
18. Remove tubing from the drain reservoir.
19. Rinse the etcher with tap water.
20. Unscrew the nozzle tip holder from the nozzle body and rinse both parts thoroughly with water.
21. Remove the sample from the holder. (Dissolve wax in toluene.)
22. Rinse the sample in acetone.

REEL SPEED AS A FUNCTION OF
VARIAC SETTING (115 VOLT LINE)

FIGURE 1

★ 5" BETWEEN CENTERS IS THE CRITICAL DIMENSION

FIGURE 2

CONTROLLER TO GENERATOR INTERFACE CIRCUIT

FIGURE 3

GROWTH BUTTON FOR A THREE TWINNED DENDRITE GROWING IN THE "WRONG" DIRECTION

Rotating
Sample Holder
for

Metallurgical Microscope

11/12/75

Side View

Scale: 2:1

FIGURE 6

BLOCK DIAGRAM OF TESTER

Solar Cell

TESTER POWER SUPPLY

TESTER CIRCUIT

FIGURE 8

POSSIBLE MAXIMUM POWER INDICATOR SCHEME

PROGRAM PLAN

WEB-DENDRITIC RIBBON GROWTH

UNIVERSITY OF SOUTH CAROLINA

LEGEND: H - HILBORN
F - FAUST
R - RHODES
A - RESEARCH ASSOCIATE
G - GRADUATE ASSISTANT
S - SECRETARY

PERIOD: 1 OCTOBER 1975 - 1 MAY 1977
UPDATED 11 DECEMBER 1975

(Figures in columns represent man hours
committed)

RECEIVED BY TAC 6 1976

1. Web Growth, Growth Analysis

1.1 Set up web furnace

1.1.1 Level, align, calibrate gas flow, measure physical/mechanical parameters

1.1.2 Instrument melt temperature sensors, run furnace and RF generator

1.1.3 Calibrate RF generator controls to melt temperature, no web pulling

1.2 Web growth, manual batch

1.2.1 Pull nominal web based on 1965 experience, establish measurements baseline. (Instrument melt level measurement), correlate with crystallization kinetics and seeding requirements

1.2.2 Vary pull rate, measure effects, correlate with crystallization kinetics and seeding requirements

1.2.3 Vary RF heat transfer rate, measure effects, correlate with crystallization kinetics and seeding requirements

1.2.4 Couple RF heat transfer rate and pull rate variations, measure effects, correlate with crystallization kinetics and seeding requirements

1.2.5 Final experimental design

1.2.6 Final manual variation of manipulated variables, correlation with crystallization kinetics and seeding requirements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
F35 A87 G44																		
F31 H2 A86 G43	F30 H2 A86 G44																	
	F32 H2 A86 G43	F30 H2 A87 G44																
		F27 H2 A86 G43	F60 H2 A173 G87	F53 H2 A173 G87														
					F56 H2 A173 G87	F35 H2 A173 G87												
							F56 H2 A173 G174	F56 H4 A173 G174										
								F56 H4 A173 G173	F48 H4 A87 G44									
									F8 H2 A86 G43	F10 H2 A87 G44								
									F14 A86 G43	F25 H2 A173	F50 H4 A173	F50 H4 A173	F50 H2 A173	F50 H4 A173	F50 H4 A173	F50 H4 A173		
											G87	G87	G87	G86	G87	G87		

1.3 Web growth analysis

1.3.1 Develop semi-empirical multivariate static model from web growth manual experiments

1.3.2 Thermal web growth analysis

1.3.3 Correlate analysis, experimental data, and semi-empirical model

2. Web Characterization

2.1 Development of sampling strategy, prototype technique

2.2 Structural characterization

2.3 Electrical characterization, web bulk silicon

2.4 Electrical characterization, web solar cells

3. Documentation, Program Review

3.1 Documentation

3.1.1 Initial financial management report and program plan

3.1.2 NASA Form 533M MAR 73, JPL 3645, JPL
3645-1

[illegible]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
3.1.3 Monthly technical progress report		▼ H10	▽ H8		▽ H8	▽ H8		▽ H8	▽ H8		▽ H8	▽ H8		▽ H8	▽ H8		▽ H8	▽ H8	
3.1.4 Quarterly report		H8	H16		H8	H16		H8	H16					H8	H16				
3.1.5 Interim summary																			
3.1.6 Annual report											H12	H24							
3.1.7 Draft final report																	H12	H24	
3.1.8 Approved final report																			H69 F87 R42
3.2 Program review, work sessions																			
3.2.1 USC in-house review		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3		H3 F3 R3	
3.2.2 JPL program review	H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		H8 F6 R2		
3.2.3 Task integration sessions				H30			F30			H30			F30			H30			
3.2.4 Annual workshop												H36 F36							

4. General Administration

Incurring Cost (Thousands of dollars)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H22 S87	H16 S87	H16 S87	H12 S87	H16 S87	H16 S87	H16 S87	H16 S87	H16 S87	H16 S87	H16 S87	H4 S87	H16 S87	H16 S87	H16 S87	H12 S87	H16 S87	H16 S87	H16 S87
12.5	16.8	14.2	14.3	12.7	13.0	13.3	12.6	17.8	19.1	17.2	15.5	13.5	12.8	13.6	13.4	12.8	13.2	7.1