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DRD No. SE-5
DRL No. 139

LARGE AREA SHEET TASK

ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

Quarterly Report

January 1, 1981 to March 31, 1981

C. S. Duncan, R. G. Seidensticker, J. P. McHugh,
R. H. Hopkins, D. Meier, and J. Schruben

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Westinghouse R&D Center
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Pittsburgh, Pennsylvania 15235

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1. SUMMARY

Silicon dendritic web is a single crystal ribbon form of
silicon capable of fabrication into solar cells with AM1 conversion
efficiency in excess of 15%. This is the second Quarterly Report under
JPL Contract 955843 the objective of which is to demonstrate the technology
readiness of the web process to meet the national goals for low-cost
photovoltaic power.

During this quarter, design of the prototype automated web
growth furnace neared completion; layout and detailed drawings of the
mechanical components are 90% completed. Mechanical items which have
undergone design change to reduce cost include the growth chamber, frame,
web storage reel, reel drive, tape storage reel, growth chamber cover
plate, work coil positioner, laser and detector mount, and lower cover
plate. All designs follow functionally proven concepts.

Several changes to improve the electronic functioning of
subsystems have been implemented. A new melt level control system has
been implemented to provide stepless silicon feed rates from zero to
rates exactly matching the silicon consumed during web growth. Bench tests
of the unit were successfully completed and the system mounted in a web
furnace for operational verification. Tests of long-term temperature
drift correction techniques were made; web width monitoring seems most
appropriate for feedback purposes. We successfully tested a system to
program the initiation of the web growth cycle. With further develop-
ment the approach can lead to wider, controlled starts, less need for operator
intervention, and improved growth reproducibility. A low-cost temperature
controller was tested which functions as well as units four times as
expensive.

A design of a recessed growth lid combining features of improved growth speed plus improved starting behavior was experimentally operated for the first time. The predicted improvements were verified. Web crystals constant in width to a fraction of a millimeter were grown using passive width control techniques. Further growth was limited only by the lack of melt replenishment hardware on the furnace, a feature now being changed.

2. INTRODUCTION

This is the second Quarterly Report on JPL Contract No. 955843 entitled "Advanced Dendritic Web Growth Development." The overall objective is to demonstrate the technology readiness of the silicon dendritic web process to produce sheet material at a cost compatible with the DOE/JPL goal of $0.70 per peak watt of photovoltaic output power in 1986.

Silicon dendritic web is a ribbon form of silicon grown directly from the melt without dies or shapers and which produces solar cells with AM1 conversion efficiencies above 15%. Most of the technical requirements to meet the 1986 cost goals have already been demonstrated individually including area throughput rate, solar cell efficiency, melt replenishment with closed loop control, and preliminary design of furnace hardware.[1]

The thrust of this program is to combine these developments and to design, fabricate and operate a prototype automated web growth machine to demonstrate technology readiness. This will include identification of cost reductions in the mechanical and electrical hardware, system test, and web growth under automated control. A parallel study is underway to further increase web output rate to 35 cm^2/min benefiting in added product cost reduction. Periodic updating of economic analyses will be made to reflect new cost and technical information as it becomes available.

This report covers the first quarter of 1981, during which prototype furnace design and throughput-related development were dominant activities.

3. TECHNICAL PROGRESS

3.1 Prototype Web Growth Machine

A key objective of this program is to design, assemble and operate a prototype automated web growth machine and to demonstrate its technology readiness to meet the 1986 goals for low-cost solar cell material. At the end of this reporting period the overall design of the prototype web growth machine neared completion. The remaining detailed design drawings will be finished early in the next quarter and the entire set of drawings will be included in the next quarterly report. Highlights of the mechanical and electronic design and test effort during this reporting period are presented in the following subsections.

3.1.1 Mechanical Design

The mechanical design effort during this period was exclusively for the purpose of reducing the cost to procure the equipment specified by the design. The new design was in all instances a refinement of existing, functionally proven subsystems, with all functional features retained. Specific design refinements made included:

- Growth chamber. Changed to a thinner walled, standard dimension seamless tube instead of one rolled and welded from sheet stock. Simplified external flanges to require less machining time.

- Frame. Adapted to fit the modified growth chamber design. Reduced height to accommodate shorter operators.

- Web Growth and Storage Reel. Completely redesigned to be molded from high-density polyurethane rather than fabricated and machined from aluminum. Bearings and shaft redimensioned.

- Reel Drive Gearmotor. Mounting position modified to eliminate conflict with melt level detector mounting.

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- **Cloth Tape Storage Reel.** Redesigned to reduce machining cost.

- **Growth Chamber Cover Plate.** Simplified web guide position adjusters above and below cover plate. Web withdrawal duct simplified.

- **Laser and Position Detector Mounting.** Redesigned to simplify mounting, machining and aligning.

- **Work Coil XYZ Positioner Mount.** Identified lower cost positioner with improved position readout. Simplified bellows assembly.

- **Lower Cover Plate.** Modified to simplify machining, especially penetration of thermocouple and thermopile sensors. Modified to match growth chamber changes and mounting to frame.

- **All Parts.** Judicious relaxation of all dimensional tolerances as appropriate.

Layout drawings of all mechanical design changes have been prepared and are now being incorporated into detailed drawings. The detailed drawings will be completed early in the next quarter. Procurement of mechanical components and fabrication of mechanical parts has begun. All work in on schedule.

3.1.2 Electronic Design

The electronic design effort centered on improvements to the function of the silicon melt level control system, evaluation of approaches for long-term steady state temperature control, tests of a system to program the start of the web growth process, and the highly successful operation of a new low-cost temperature controller.

3.1.2.1 Melt Level Control System

A prototype laser-sensor system to provide automatic control
of the silicon melt level during dendriti web growth was built, success-
fully operated and reported during the previous phase of web growth
development.[1,2] More recently a concept for improved electronic control
circuitry for this system was developed under the current program.[3] The
improved circuitry has the advantage of accommodating a full range of
pellet feed rates from zero to the rate required for maximum web through-
put, and its operation is independent of laser beam intensity over
a wide range of signal level. During this quarter the gearmotor and its
controller, which are used to rotate the mechanical pellet feed mechanism,
were received from the vendor. Tests of the gearmotor and controller
confirmed that the pair work properly.

The gearmotor responded linearly over its full range (0.0 to
7.7 rpm) to a DC command signal supplied to the controller (0 to 5 V_{DC}).
With the DC command signal below the linear range (-15 to 0 V_{DC}) the
motor remained off, while with the command signal above the linear range
(5 to 15 V_{DC}) the motor maintained its maximum speed, as required. The
DC command signal is optically isolated from the remainder of the
control circuitry to avoid grounding problems.

The entire melt level control system was assembled and tested
on the bench. The system consists of a He-Ne laser, a silicon photo-
detector, a pre-amplifier, analog divider, amplifier, motor controller,
and gearmotor.[3] In the bench test, the photodetector received the
direct beam from the laser, rather than a reflected beam.

The observed gearmotor speed as a function of DC command
signal to the motor controller is given by the following expression:

$$\text{Motor Speed (rpm)} = 1.77 \text{rpm/volt} [V_{command}(\text{volt}) - 0.27 \text{volt}] \quad (1)$$

for $0.27V \le 4.65V$. The motor speed was ~ 7.7rpm for $V_{command} > 4.65V$ and
was 0.0rpm for $V_{command} < 0.27V$.

Since the silicon feeding mechanism is constructed to supply 4 pellets per revolution, and since the mass of the silicon pellets is about 0.03g, the rate of mass input as a function of DC command signal calculated from Equation 1 is:

$$\dot{m} \text{ (gSi/min)} = 0.216 \frac{\text{gSi/min}}{\text{volt}} [V_{command}(\text{volt}) - 0.27 \text{volt}] \qquad (2)$$

for $0.27V \leq V_{command} \leq 4.65V$. Some representative values are given in Table 1.

During the bench test the system performed as we expected, with the motor speed varying from zero to full speed in response to an effective change in melt level height of 3.3mm. Based on command signal fluctuations that were observed during the bench test, it is anticipated that the silicon melt level will be regulated to better than 0.1mm, consistent with the requirements for stable web growth.

TABLE 1

SILICON MASS INPUT RATE FOR VARIOUS COMMAND VOLTAGES

$V_{command}$	$\dot{m}$	$V_{command}$	$\dot{m}$
0.0V	0.000 gSi/min	2.5V	0.482 gSi/min
0.5	0.050	3.0	0.590
1.0	0.158	3.5	0.698
1.5	0.266	4.0	0.806
2.0	0.374	4.5	0.914

The electronic components for the complete improved system have been mounted on the RE growth furnace. The system will be evaluated under actual web growth conditions during the next reporting period.
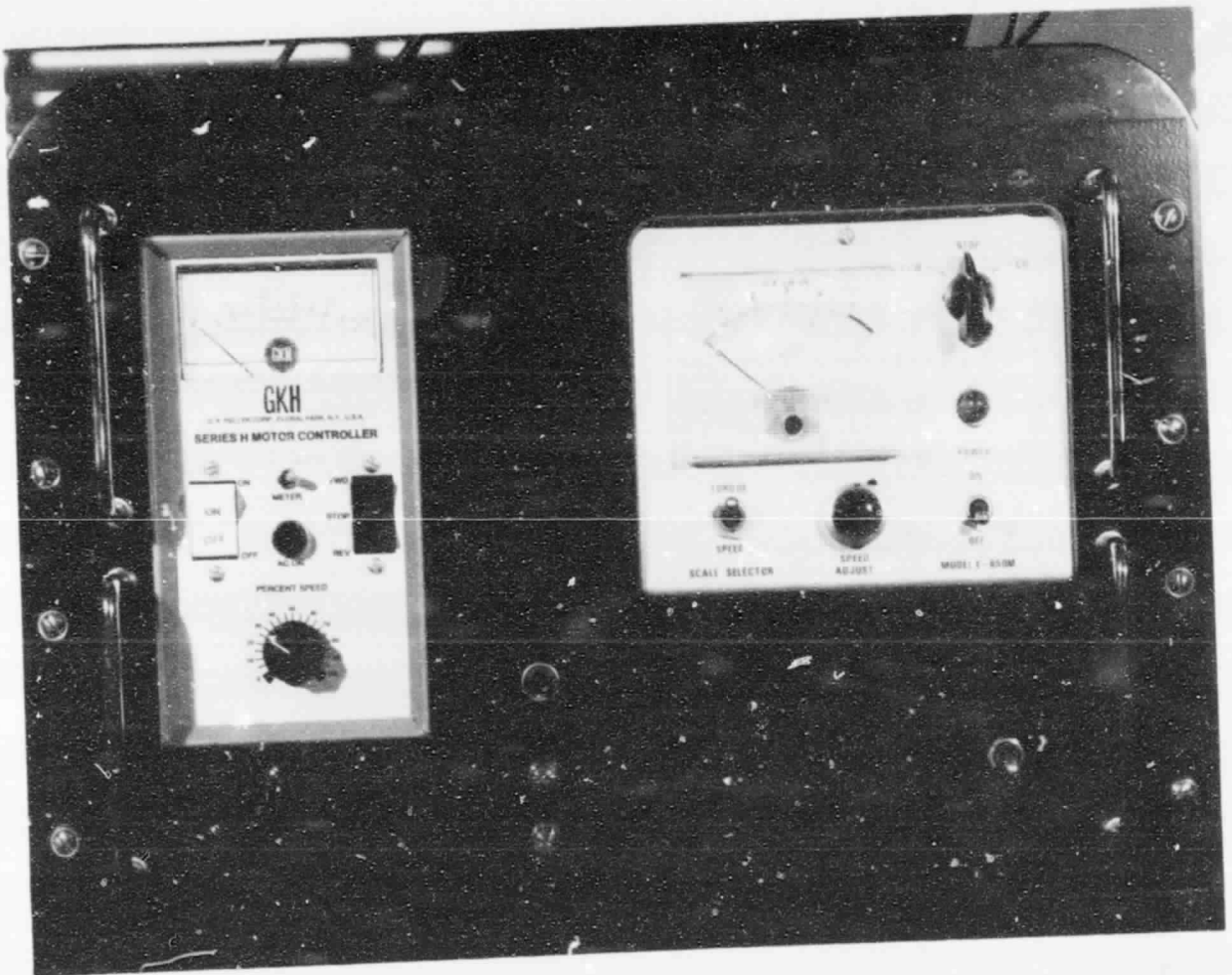
Figure 1 Control Panel for Improved Melt Level Control System (left side of panel) Mounted on RE Furnace.

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3.1.2.2 Long-Term Growth Stability

Unless compensated in some manner, a very gradual long-term temperature drift may occur during web growth. Without compensation, this temperature drift would eventually cause interruption of the web growth process, necessitating occasional restarting of the web crystal. Long-term drift occurs for at least two reasons: 1) gradual change of the temperature sensor calibration and 2) gradual change of the thermal properties of the system, notably the emissivity of heat shields.

We have tested two methods to sense and compensate the system for small thermal drifts, monitoring dendrite thickness and monitoring web width. Both methods work although we believe the latter approach offers some distinct advantages for control.

Dendrite thickness monitoring by visual observation has been in use for quite a while as a guide to adjust growth and is a sensitive indicator of the thermal conditions in the system. With the unaided eye or optical equipment, the dendrite is viewed edge-on; a thickening dendrite implies the liquid is too cold, a thin dendrite that it is too hot. Temperature adjustment can readily be made to compensate for drift due to sensor calibration change or heat shield emissivity variation with time. We recently attempted to quantify these observations by employing the use of a linear array of diode sensors coupled with an optical system to measure dendrite thickness.

EG&G RETICON manufactures such diode arrays and the associated circuitry and so was invited to Westinghouse R&D to demonstrate the equipment required. This equipment included the lenses needed to focus a magnified image of the dendrite on the diode array.

The demonstration was successful in generating a signal directly related to dendrite thickness. However, the light from the glowing melt was not adequate to obtain a well-defined image and an external light source had to be used. With external back-lighting of the web sample in the furnace, an image of the dendrite having good contrast was obtained. With front-lighting the image was discernible but the

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contrast was barely adequate. In both cases alignment of the optical system was quite important. Where back-lighting was used, the orientation of the web was critical. Further evaluation of this approach for monitoring dendrite thickness is underway and will include these alignment considerations along with system cost and practicality in a production environment.

An alternative, and we feel better method for temperature compensation, is to monitor and control web width. Here the web is viewed face-on, a geometrically more favorable technique. With a suitably designed lid/shield configuration, our experience has shown that web width can be maintained constant within a fraction of a millimeter so long as the temperature is constant (see Section 3.2). Thus, web width is a reliable indicator for temperature adjustments. Suitable optics can be used to enhance the width measurement.

Thus, we have concluded that width rather than dendrite thickness sensing is preferable for drift compensation. The method can be applied in the form of fully automatic closed loop control or, alternatively, can be applied in the form of infrequent operator adjustment as needed.

In the next reporting period, operator compensation of temperature drift will be evaluated during web growth with automatic melt replenishment. When the frequency of required operator action has been determined, an economic analysis will be prepared in order to evaluate the comparative cost of manual versus automatic control.

3.1.2.3 Programmed Start of Growth

Programmed start of the growth operation[3] has the potential for several important advantages compared to manual growth starts, including a) repeatable wide starts, b) reproducible high crystalline quality and c) less stringent operator skill and training. To evaluate programmed start of growth we have interfaced a Leeds and Northrup 1300 Process Programmer, Figure 2, with the speed and temperature control circuits of a web growth furnace. This programmer features two synchronized programs which are independently set to adjust pull speed and temperature.
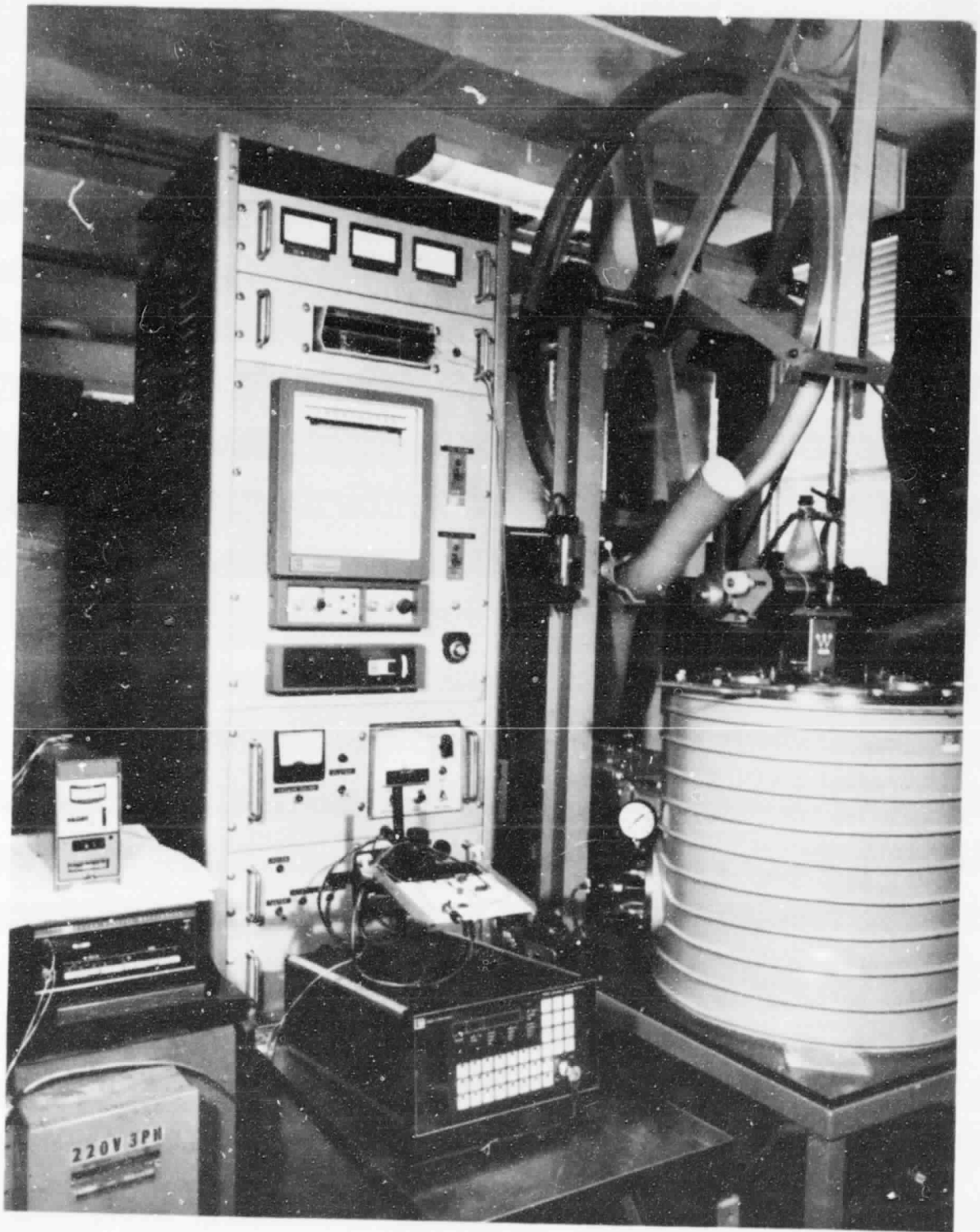
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Figure 2   Evaluation of Control Circuits
a)   Programmer for Start of Growth (center)
b)   Low-Cost Controller Modified for Web Growth (left)

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The system has been used to provide high-quality starts of growth with no operator input. The interfacing has been designed to allow synchronized ("bumpless") transfer from "manual" to "programmed" and back to "manual" status, thus permitting a single programmer to be transferred from furnace to furnace as required.

The circuits designed to accomplish the "bumpless transfer" between manual and programmed modes are depicted in Figures 3 and 4. In actual operation, the transfer from the remote or programmed mode to local, manual control is achieved by setting the voltage at V in each case to zero with the selector switch in remote. For temperature control, this is done by adjusting the alternate set point potentiometer to match the output of the local set-point potentiometer. In the case of pull speed, the local control potentiometer is adjusted to match its output to that of the interface amplifier. The local/remote switches can then be set to local and the crystal growth maintained in the conventional manner throughout the rest of the run.

Circuit modifications are being made to provide improved interfacing with the speed control system. When this change has been made, further laboratory evaluation of programmed starts will be performed.

3.1.2.4 Low-Cost Temperature Controller

Several comparatively low-cost, commercially available temperature controllers were evaluated for web growth application. The unit selected was a Leeds and Northrup Electromax controller (left side of Figure 2) which was factory modified to provide appropriate zero suppression and expanded scale. The unit shown has been used to grow web crystals and found to satisfy all the technical requirements of web growth. Its cost is less than one-quarter the cost of the more versatile equipment used during the web growth development program and has the added advantage of its small physical size.

3.1.2.5 Overall Control System

All electronic circuitry will be housed in a single console cabinet of modest size and convenience as compared to previous control
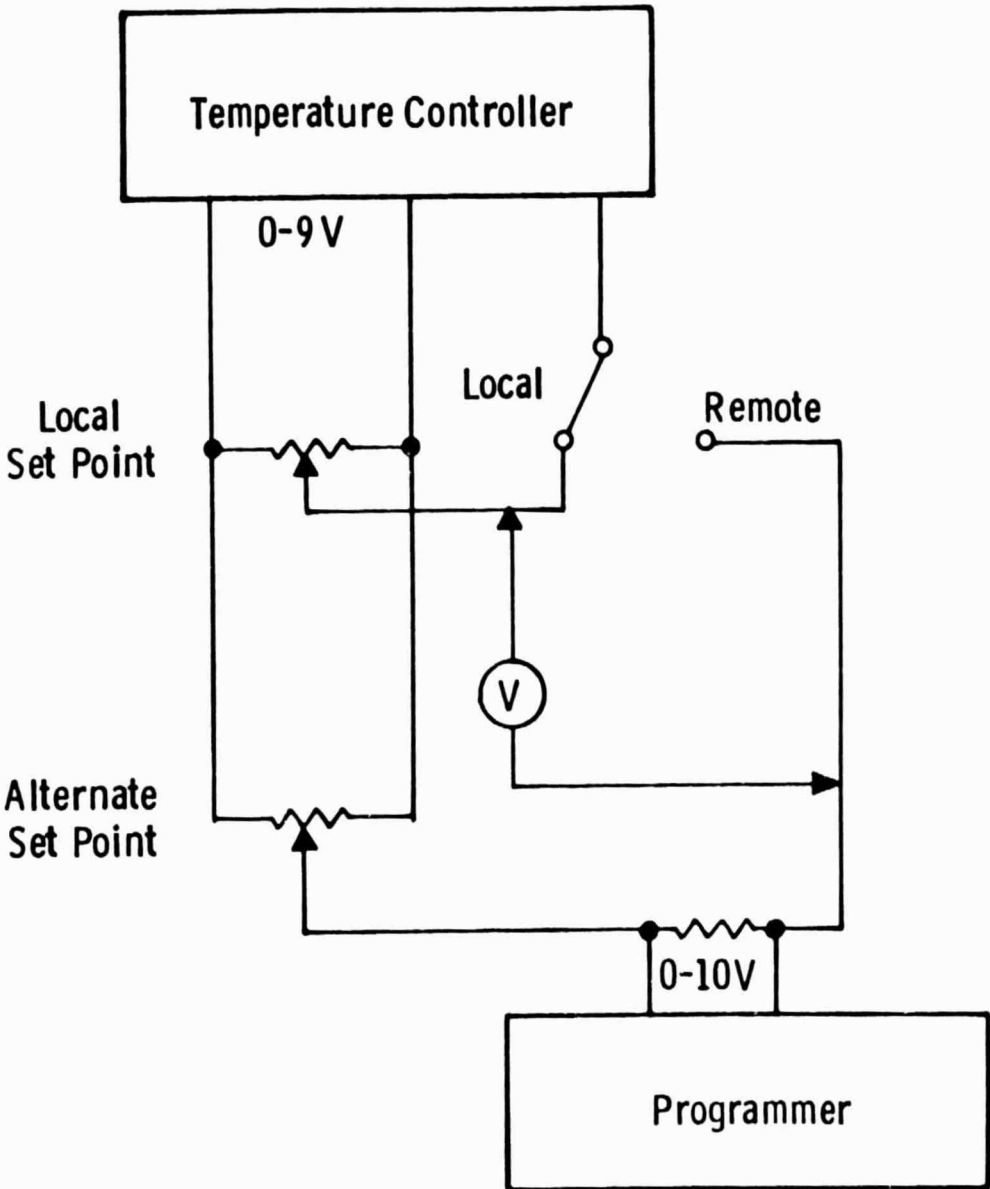
Figure 3   Temperature Control Transfer   Circuit
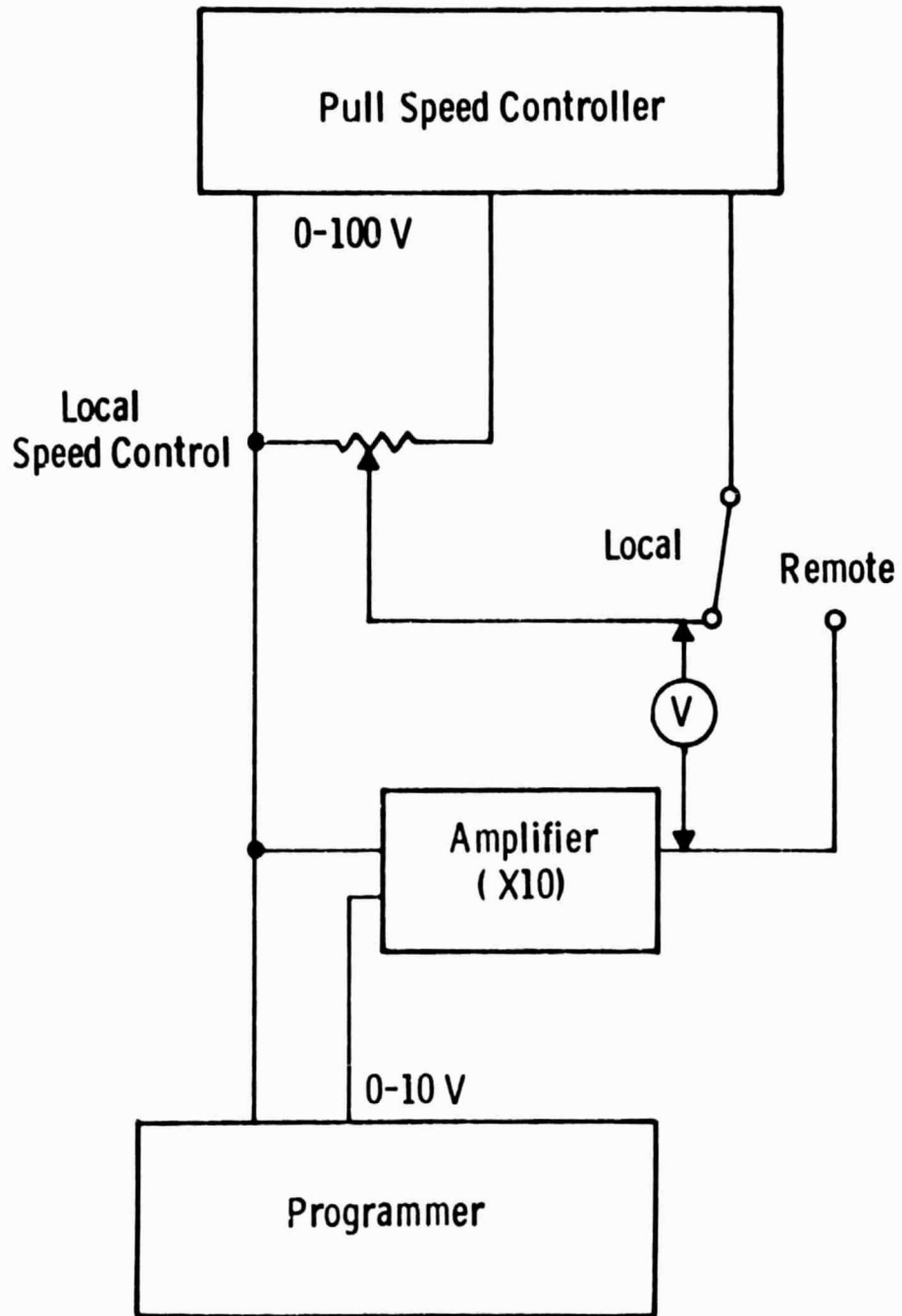
Figure 4   Pull Speed Transfer Circuit

equipment. Nearly all components have been ordered and construction and assembly will be performed during the next reporting period.

3.2 Advanced Throughput Development

The objective of this activity is to develop technology for achieving higher web throughput - up to 35 cm^2/min - and thus reduce the sheet cost even further. There are two aspects to this development: (1) developing lid and shield growth configurations giving higher speed growth at wider width and (2) developing the technology for steady state growth at high throughput for long times.

The first activity is concerned with the continued design and testing of growth configurations which will permit both high speed and low-stress operation, particularly low-elastic stress which presently limits width through deformation of wide crystals. The second activity not only involves the design and validation of automated growth equipment, but also includes the achievement of growth configurations which produce a constant, controllable ribbon width compatible with melt replenishment.

During this report, laboratory activities have been devoted mainly to continuing development of high-speed lids capable of growing high-quality material, and to development of techniques for width control. Melt replenishment work has also been reinitiated with improved equipment (Section 3.1.2) and the current work reemphasizes the importance of constant melt level to throughput as well as to steady state growth.

Modeling of buckling stresses has been initiated using the WECAN finite element code, and preliminary results will be forthcoming during the next period; as soon as design guidelines have been established, the laboratory development of configurations for wider growth will be underway.

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3.2.1 Enhanced Area Throughput

3.2.2.1 Speed-Related Studies

During the reporting period, laboratory activities continued to be directed toward increasing the speed of web growth through the modification of lid and shield design. In the previous quarterly report,[3] work on the use of thinner lids in combination with multiple heat shields was reported, and some speed enhancement was accomplished. In the course of these experiments, it was also discovered that the spacings of the elements were important for controlling such aspects of the growth as oxide deposition, "ice" formation, etc. Nonetheless, even with improved spacings and lids which had reasonably fast growth speeds, growth was not always easy. In some cases, the crystals would degenerate after some tens of centimeters of growth. Split width measurements showed that some of the crystals had considerable residual stress, even at the relatively narrow width of 20 mm or so. These factors indicated that the lid temperatures in the vicinity of the slot were too cool, even with multiple top shields.

Another approach to achieving the proper thermal geometry was then tried: a thick (9.6 mm) lid with a recessed center portion around the growth slot. Such a configuration would have a higher slot temperature since the higher thermal conductance of the thick lid would transport heat more readily and further, the thicker lid would couple to a greater extent with the work coil.

Several recessed lids with different thicknesses in the slot region have been investigated. The speed of these configurations are very similar to the speed of the flat lids of equal thickness, with the distinct advantage that the growth behavior is now better. With each lid configuration, a number of shield configurations have been tried. Two general types of configuration are shown in Figure 5. In the first configuration, flat shields are used, but in the second configuration, one of the shields is made of thinner material and bent over to reduce radiative heating from the sides of the recess. An
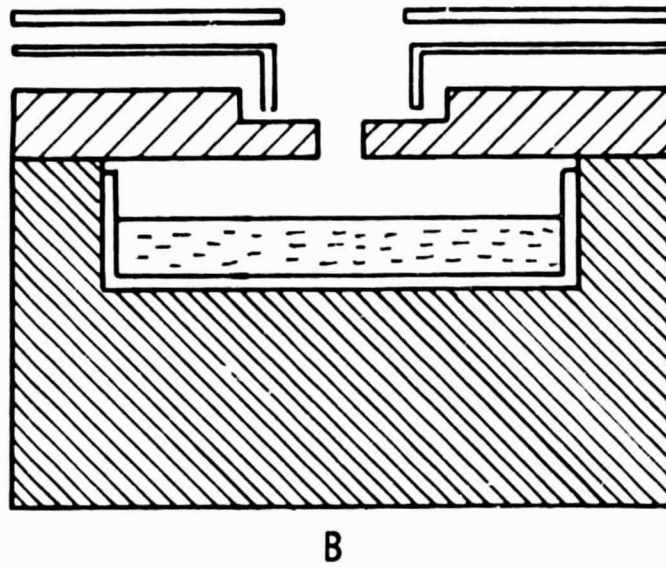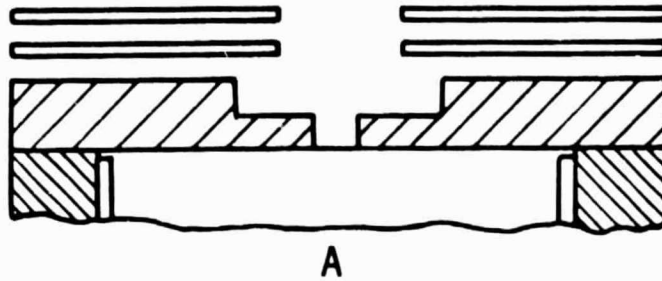
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Figure 5   Typical Cross Sections of Recently Tested Recessed
Lids for Growth Speed Enhancement.

advantageous configuration uses the bent shield together with a top shield which is slitted around the edge to reduce coupling.[1] This combination provided relatively fast growth with an acceptably low residual stress, although other configurations were nearly as good.

Although the shield configurations and the slot shape are very important in determining the speed of the system and its stress behavior, one of the most important parameters seems to be the melt height. Later in this section, data are given for the change in web thickness as a function of crystal weight (which is equivalent to melt height). Using the conversion that 20 gm of crystal is equivalent to 1 mm of melt height, it can be seen that significant speed improvement results when growth is maintained with high melts. Some of the configurations we tested have shown promise of such behavior, and this work is being continued. Shortly, melt replenishment will be used to augment the speed enhancement studies.

3.2.2.2 Analysis of Web Buckling

Web width has been limited to 4 to 5 cm by buckling of the ribbon. We are developing a model to correlate the thermal profile in the web with expected buckling behavior. The model output is then used to guide the design of lids whose thermal profile produce stresses in the web which are below those to cause buckling. Recent work on the stress analysis approach is described below.

Westinghouse has developed a finite element computer code, called WECAN, for performing complex stress analysis computations. This code has options for both thermal stress analysis and for buckling prediction and previously only the thermal stress option was used to model the dendritic web as a two dimensional ribbon.[1] In the present work, we are employing the full capabilities of the WECAN code to calculate the critical buckling stresses in a web crystal modeled as a three dimensional bar including the stiffening effect of the supporting dendrites. The required three-dimensional program uses nodal points at the intersection points of each of the finite element parallelepipeds and also at points midway between these. Further, for buckling analysis, each nodal point is allowed three degrees of freedom.

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To reduce computer time and cost, the grid size can be minimized by dividing the ribbon into only the number of finite elements needed for reasonable computational accuracy. While this number cannot be determined a priori, at least the placement of the finite elements should be arranged so as to have the finest grid structure in the region of maximum temperature and stress variation. For the dendritic web problem, this region is near the melt surface. A non-uniform grid can make the variation of stress across each finite element more nearly zero than can be done with a uniform grid. Although WECAN cannot handle large variations in grid spacing from one element to the next, it can accommodate a grid with element size varying as a geometric progression. Such a grid for the silicon web is shown in Figure 6; the elements next to the surface are one-eighth as long as the elements at the other end. A perspective view of a section of the mesh is illustrated in Figure 7 to show the modeling of the bounding dendrites.

In addition to the finite element grid, WECAN requires a temperature input for each nodal point. The temperature distribution along the ribbon cannot be measured easily but is obtained by integrating the heat conduction equation for a specific furnace lid and shield geometry.[4] The uniform step size used in the previous integration algorithm does not match with the geometrically varying grid used with WECAN, and modification to match the points led to numerical instabilities. A solution was finally obtained by interpolation of the results of the uniform step integration.

Actual buckling analysis will be conducted during the next quarter; as an intermediate step we have made a three-dimensional thermal stress calculation. Figure 8 shows the isostress curves generated by this routine; the results are in excellent agreement with previous two-dimensional calculations for the same thermal geometry of the growth system. The present calculations give a slightly greater difference between the maximum and minimum longitudinal stresses; however, this is accounted for by a slightly greater ribbon width and by the presence of the bounding dendrites which were not included in the previous model.

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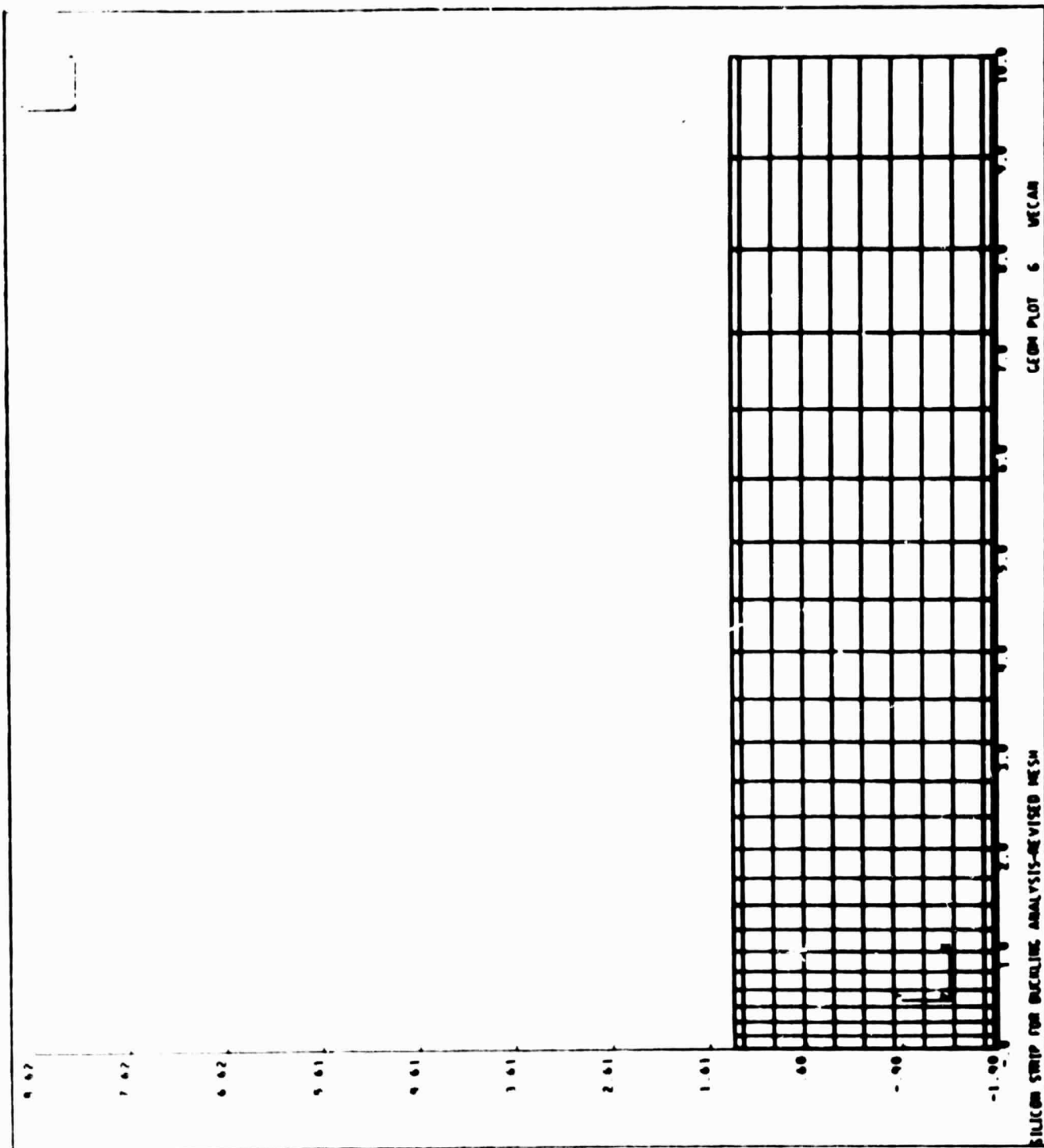
Figure 6 Grid Used to Model Silicon Web for Stress Analysis

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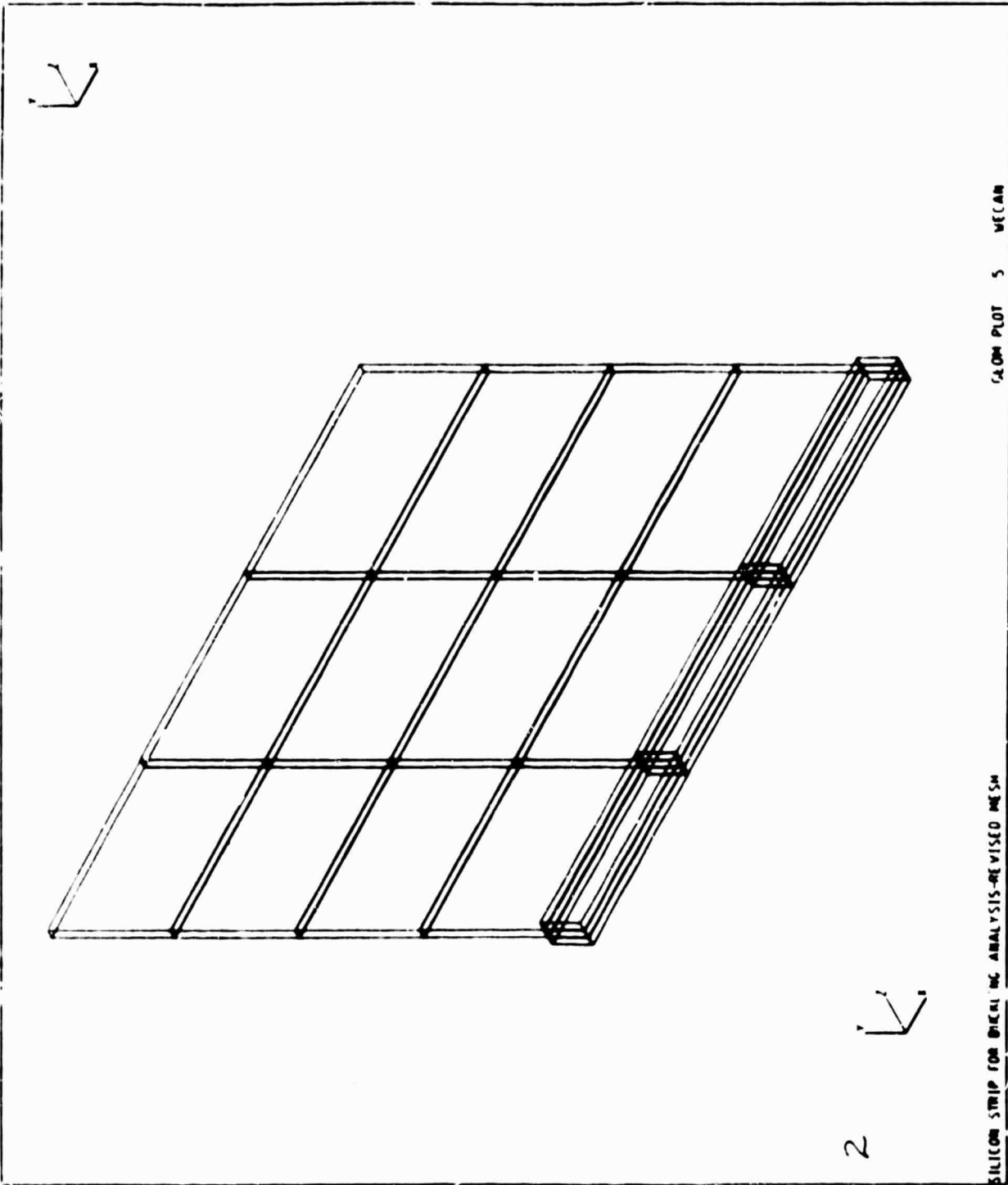SILICON STRIP FOR THERMAL ANALYSIS-REVISED MESH   FROM PLOT 5   MECAN

Figure 7 Perspective of Grid Used for Stress Calculation of Silicon Web.
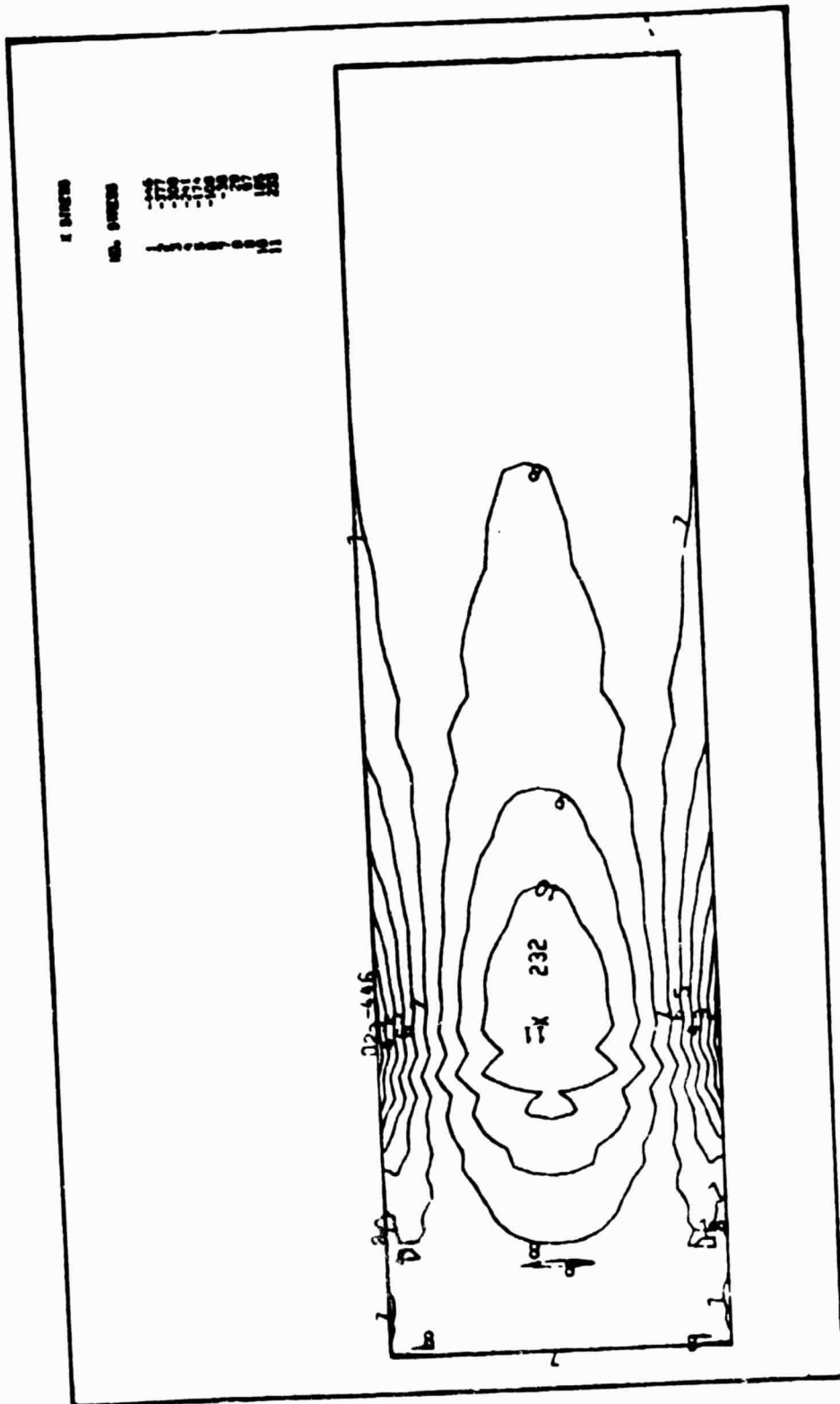Thickened Portion at Edge Represents Dendrite.

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Figure 8 Isostress Contours for Silicon Web in Baseline Furnace Geometry.

In the next report period, the full buckling analysis will be completed for the baseline furnace thermal system. Modifications of the thermal geometry will then be made and the effect of these on the buckling will be checked. Once the detailed critical parameters have been determined for buckling, it should be possible to utilize the simpler two-dimensional stress model to guide the design of the growth systems instead of the more complicated and expensive complete buckling analysis.

3.2.2. Melt Replenishment Experiments

During the later part of this reporting period, while awaiting the installation of the automated melt replenishment circuitry, melt replenishment experiments were reactivated using manually set feed rates to test various furnace components under operating condition. Growth configurations embodying the latest lid and shield designs in terms of width control and oxide control were adapted for melt replenishment by the addition of holes for pellet feeding and melt level sensing. Adjustable end shields were incorporated to maintain the crucible feed compartment at a sufficiently high temperature to insure melting of the feedstock pellets.[1,2] End shield positions were then adjusted so that stable growth could be maintained under the thermal conditions required for replenishment. Feed rates below the rate required for full replacement of the Si consumed by crystal growth were tested initially in order to verify the overall behavior of the new growth configurations as modified for replenishment. In a series of runs, pellet feed rates were incrementally increased until the feed rate and the silicon consumption rate for web growth were comparable, as shown by the small changes in crystal thickness at constant growth velocity. (As noted in Section 3.2.1, without replenishment a crystal thins as the melt level drops unless the growth rate is reduced to compensate. Thus, replenishment has a strong positive impact on throughput on an average daily run basis. Individual web crystals up to four meters long were grown with continuous melt replenishment.

Figure 9 illustrates the effects of melt replenishment on web thickness. The crystal grown without replenishment thinned to the point where the growth velocity had to be substantially reduced in
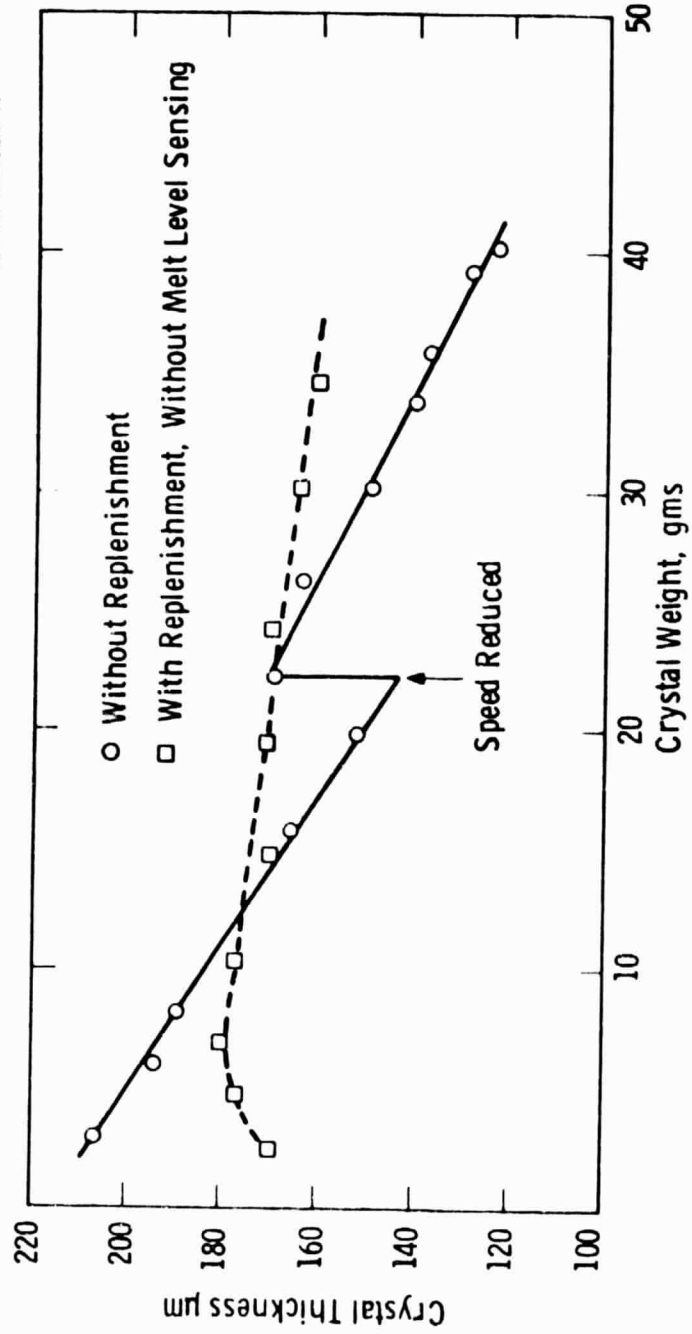
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Curve 727985-A

Figure 9 Change in Web Thickness with Amount of Crystal Grown Both With and Without Replenishment.

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order to continue growth in the desired thickness range. The crystal grown from a replenished melt was grown at constant speed. The desired feed rate was estimated empirically in this case and was slightly lower than the consumption rate. Nevertheless the crystal thickness was maintained in a narrow range throughout its approximately four-meter length.

By combining melt replenishment with high-speed lids such as those under development (e.g.,Section 3.2.1), throughput will be maintained at high steady-state values and constant thickness. During the next quarter, tests of the new automatic melt replenishment system (Section 3.1.2) will be carried out,thus making it possible to match exactly the pellet feed rate to the amount of web grown.

3.2.3 Web Width Control

Growth configurations have been developed by which we can grow a web crystal to a specified width, then hold that width more or less indefinitely with only very occasional attention from the furnace operator to adjust for any long-term temperature drifts.

In addition to targeting width to the requirements of a specific size solar cell, the crystal width is maintained below that at which stress-induced buckling might occur. Thus ,very long crystals can be grown with a majority of material useable for cell fabrication. Data from a crystal whose width was controlled to within a fraction of a millimeter by passive lid design techniques is shown in Figure 10. Recently, during the preparation of this report, we have grown crystals of controlled width over five meters long as part of an in-house effort. These results were obtained without melt replenishment and should improve substantially as melt replenishment techniques are blended with control technology.
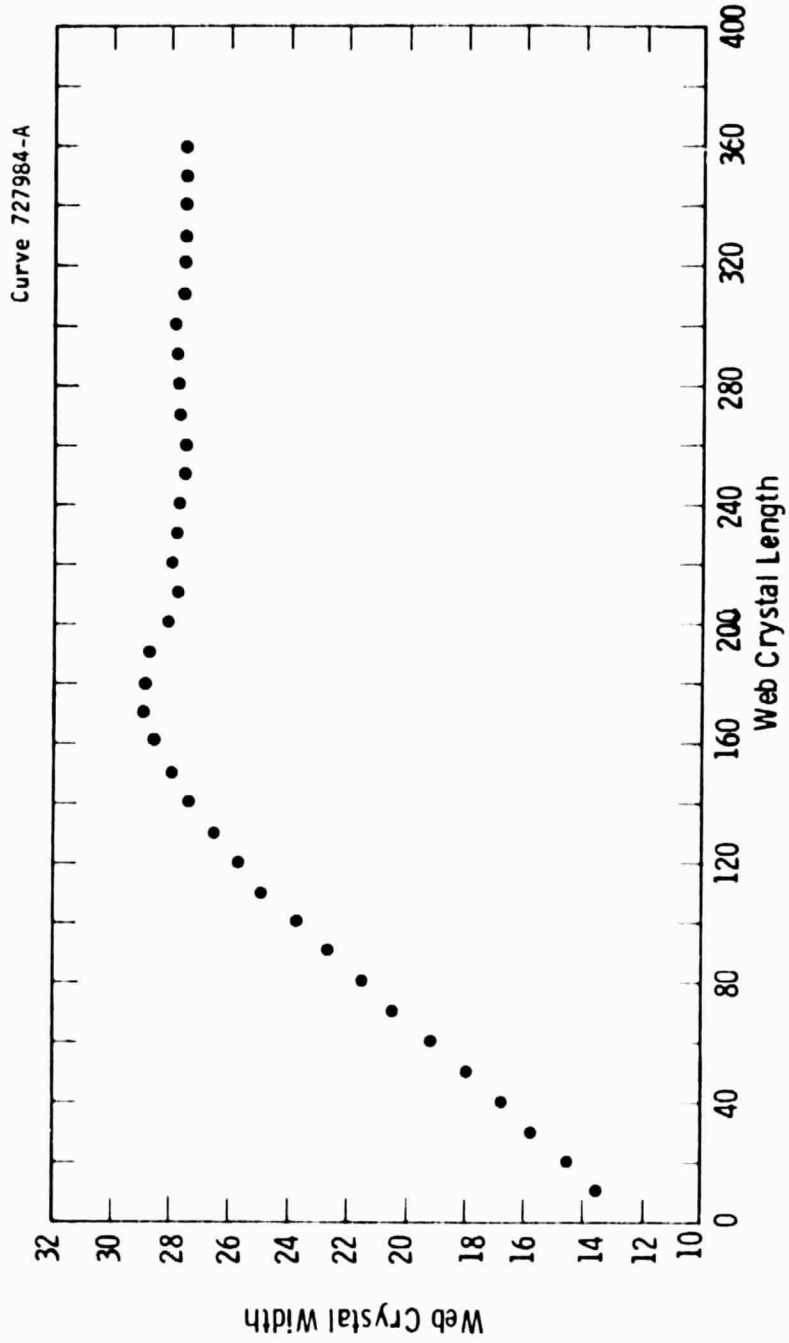
Figure 10 Variation in Web Width with Length of Crystal Growth for Lid Geometry Designed for Width Control

4. CONCLUSIONS

Mechanical design and layout of the prototype web furnace remains on schedule and should be complete within a month.

Bench tests show that newly designed melt level system circuitry functions as designed. The hardware has been installed on the RE web growth furnace for operational verification which will start shortly. Web growth initiation can be programmed using relatively simple circuits to interface the temperature and speed controllers to an L and N process programmer. Start-up and growth of several crystals were successfully accomplished. Of several low-cost temperature controllers which we evaluated, the L and N Electromax model appears to be the best combination of cost and function for web growth. Functionally, it performs as well as our sophisticated laboratory units while it costs about one-fourth as much. Web width measurement can be used to monitor system thermal conditions and provide feedback to correct for any long-term temperature drift in the system.

Growth lids with a recessed section to enhance radiative losses combine improved speed and ease of growth initiation and minimal oxide deposition. Further experiments are planned to assess their value for high throughput.

Preliminary computer runs indicate that the three-dimensional grid structure required for web buckling analysis provides stress calculations consistent with earlier two-dimensional approaches. Buckling analyses will be run during the next quarter.

Web widths constant to a fraction of a millimeter were produced over five-meter lengths of crystal using passive design and no melt replenishment.

5. PLANS FOR FUTURE WORK

During the coming quarter we will complete the mechanical design of the prototype furnace,and the fabrication and assembly of system components will be underway. Melt replenishment will be carried out using newly designed and installed circuitry,and tests of lid/shield configurations for enhanced throughput will begin under replenished conditions. The buckling model will be operated to identify lid designs which minimize stress and hence web deformation. Work on width control for high throughput will continue.

6. NEW TECHNOLOGY

No new technology is reportable for the period covered.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

9. PROGRAM SCHEDULE AND COSTS

9.1 Updated Program Plan

   9.1.1 Milestone Chart (attached)

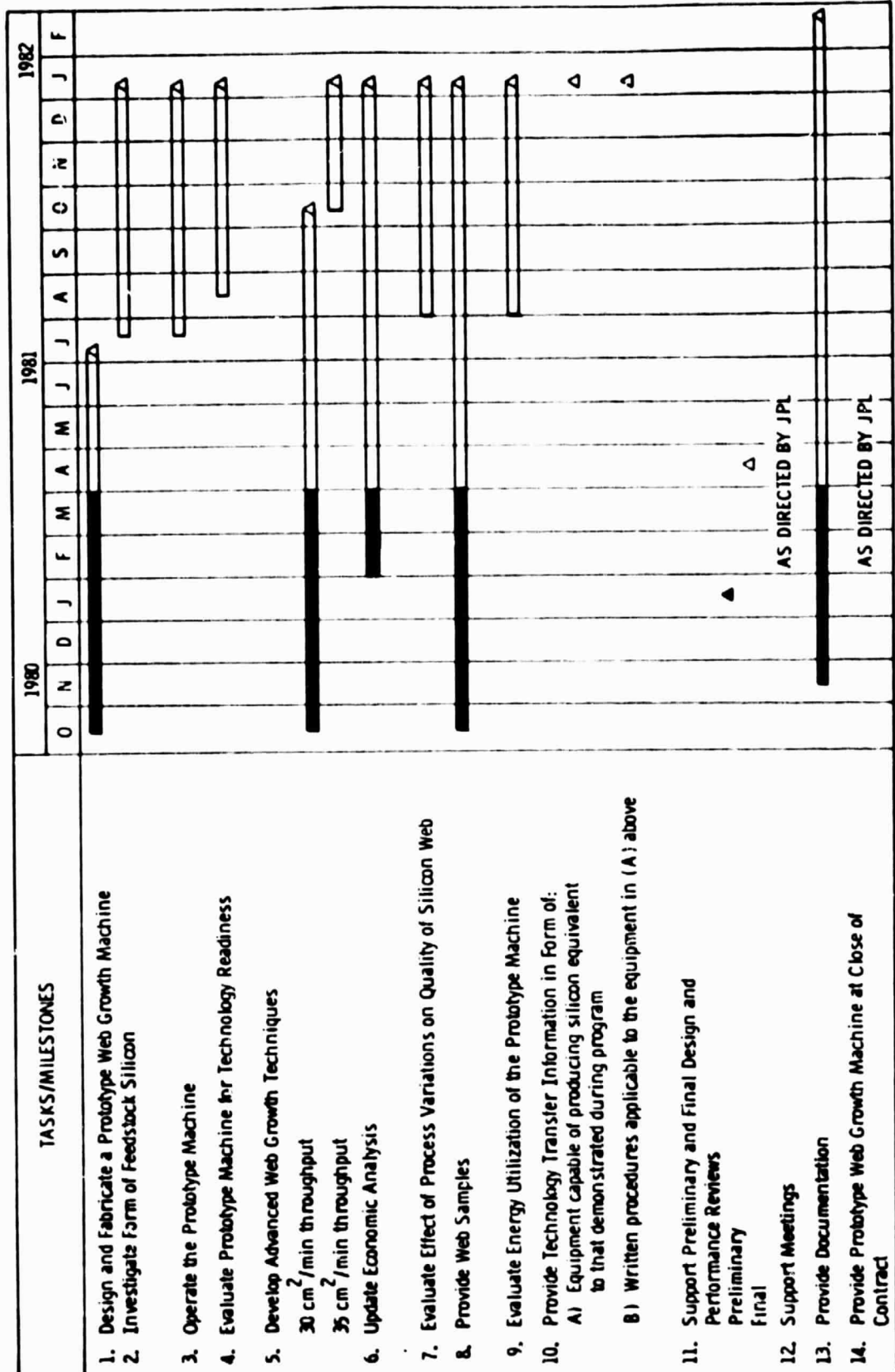   9.1.2 Program Cost Summary (attached Curve 725242A)

   9.1.3 Program Labor Summary (attached Curve 725243A)

9.2 Man-Hours and Costs
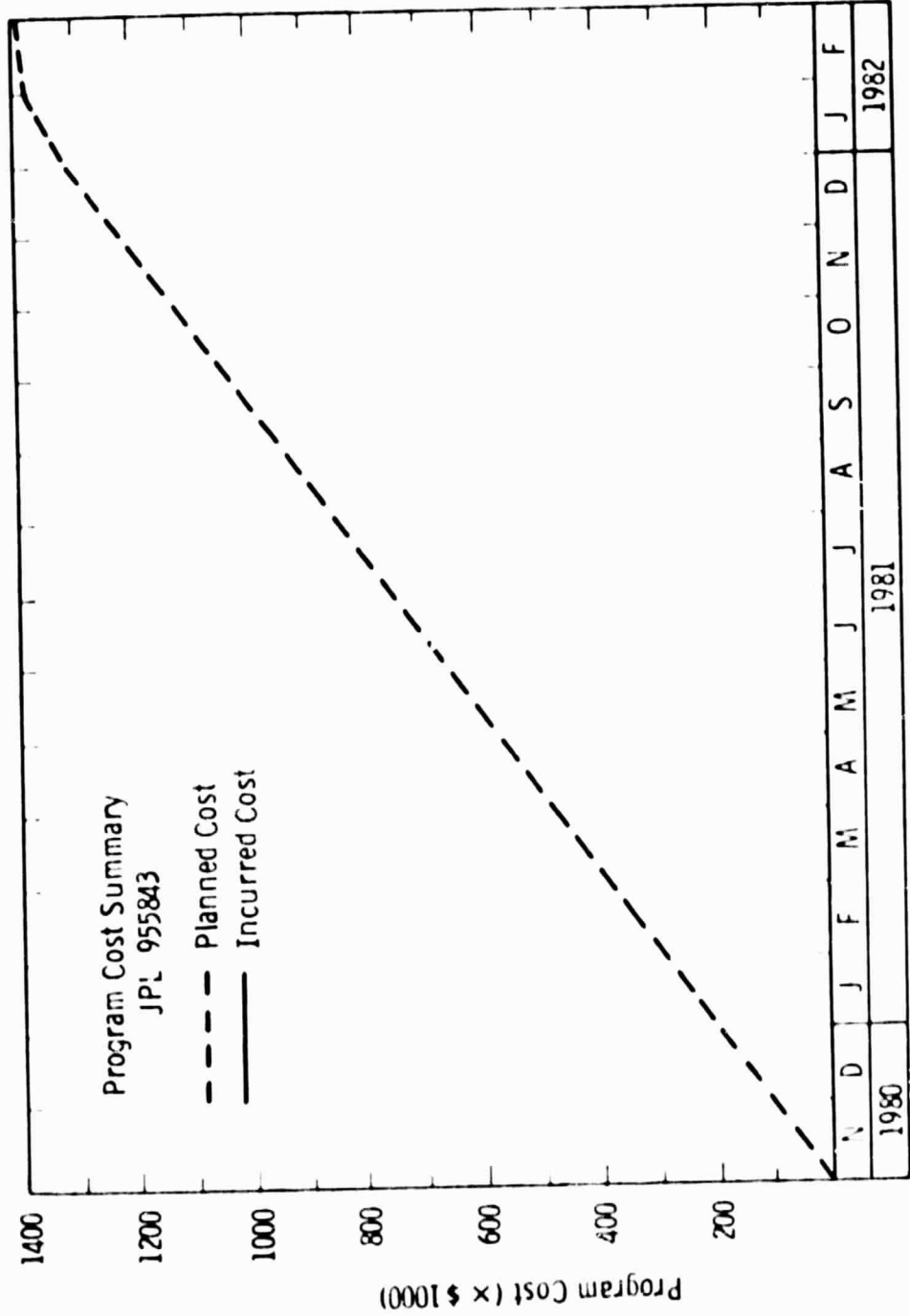
	Man-Hours		Costs
Previous	3613	Previous	$150,803
This Period	5048	This Period	$233,543
Cumulative	8661	Cumulative	$384,346

LSA PROJECT
LARGE AREA SILICON SHEET
ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT
MILESTONE CHART – JPL CONTRACT 955843

TASKS/MILESTONES	1980	1981	1982
	O N D J F M	A M J J A S O N D J	F

1. Design and Fabricate a Prototype Web Growth Machine
2. Investigate Form of Feedstock Silicon
3. Operate the Prototype Machine
4. Evaluate Prototype Machine for Technology Readiness
5. Develop Advanced Web Growth Techniques
   30 cm^2/min throughput
   35 cm^2/min throughput
6. Update Economic Analysis
7. Evaluate Effect of Process Variations on Quality of Silicon Web
8. Provide Web Samples
9. Evaluate Energy Utilization of the Prototype Machine
10. Provide Technology Transfer Information in Form of:
    A) Equipment capable of producing silicon equivalent to that demonstrated during program
    B) Written procedures applicable to the equipment in (A) above
11. Support Preliminary and Final Design and Performance Reviews
    Preliminary
    Final
12. Support Meetings
13. Provide Documentation
14. Provide Prototype Web Growth Machine at Close of Contract

AS DIRECTED BY JPL

AS DIRECTED BY JPL

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Program Cost Summary
JPL 955843

- - - Planned Cost
——— Incurred Cost

Curve 725242-A

Program Cost (× $ 1000)

1400
1200
1000
800
600
400
200

Contract Months

1980
1981
1982

34

Curve 725243-A

Program Labor Summary
JPL 955843

- - - Planned Hours
——— Incurred Hours

Direct Labor Hours (× 1000)

Contract Months

1980   1981   1982