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MASTER

LARGE AREA SILICON SHEET TASK

Silicon Web Process Development. Quarterly Report
for April-June 1980

By

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July 15, 1980

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

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Solar Energy

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Large Area Silicon Sheet Task

SILICON WEB PROCESS DEVELOPMENT

QUARTERLY REPORT

April 1980-June 1980

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Contract No. NAS 954654

July 15, 1980

"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."

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1. SUMMARY

Silicon dendritic web is a ribbon form of silicon produced from the melt without die shaping, and capable of fabrication into solar cells with greater than 15% AM1 conversion efficiency. This quarterly report describes the work carried out during the period April to June 1980, as part of Phase III of a DOE/JPL-sponsored effort to develop silicon web process technology compatible with the national goals for low cost photovoltaic output power.

We have successfully demonstrated eight hours of silicon web growth with closed loop melt level control, a key contract milestone. The result was achieved using a feedback system in which the change in output from a laser melt level sensor was used to control the rate at which silicon pellets were fed to replace the material frozen into web crystal. The melt level was controlled to about $\pm 0.1\text{mm}$, well within the range required for stable long term web growth. This is an important step toward the development of a fully automated silicon web growth machine.

A second major highlight of this quarter was the completion of an engineering design for a semi-automated web growth machine embodying all the desired features developed so far as part of this program (including e.g melt replenishment, level sensing and control) as well as some system simplifications. The completed design will serve as a basis for complete system automation; the detailed design drawings are not included in this report in anticipation of patent application.

2. INTRODUCTION

Silicon dendritic web is a ribbon form of silicon which grows directly from the melt without dies and produces solar cells with AMI 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 70 cents per peak watt of photovoltaic output power. This is the third quarterly report of the Phase III effort under JPL Contract 954654, Silicon Web Process Development.

In Reference 4 we presented a detailed description of the major technical results underlying the development of silicon web for low cost solar cells. Briefly, we had shown 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.

The central activities for this reporting period have been the assembly and testing of equipment for closed-loop melt level control and completion of the design of the semi-automated web growth machine. Further development of computer aided design and test of furnace hardware for enhanced web output rate also has been carried out.

3. TECHNICAL PROGRESS

3.1 Closed Loop Melt Level Control for Silicon Replenishment during Web Growth

During this reporting period, the major experimental effort was devoted to semi-automated melt replenishment. Having demonstrated 17 hours of manually-controlled continuous melt replenishment,⁴ equivalent to a one day growth cycle as defined in the economic analysis, work has been carried forward to provide the successful demonstration of a closed loop melt level control system. This step, a prerequisite for system automation, has been implemented on the RE furnace. The melt level control system has three major components: melt level sensor, pellet feeder (described in earlier reports) and a feed rate controller which closes the loop.

Recent development of melt replenishment had shown that feeding of the silicon pellets could be manually controlled to rates nearly equivalent to the rate of silicon removal during crystal growth. The output of a laser/detector level sensor¹ was fed into a chart recorder and the furnace operator made adjustments in the feed rate to keep the detector output, and thus the melt level, at a constant value. With experience, operators easily could maintain the melt level constant to within one millimeter. The next step was to close the control loop eliminating the need for any operator attention to the feed system.

To facilitate the operation of the closed loop control system, the laser melt level system was calibrated as follows; the output of the melt level sensor was fed into a strip chart recorder whose signal varied as a function of melt height. The change in melt height can be accurately determined by weighing the silicon removed from the melt following web growth.

During growth without feeding, the sensor output generates a sloped line on the chart, the slope being proportional to the rate of silicon removal (change in melt level). When pellets are fed to the liquid their feed rate can be adjusted until the chart slope is zero, at which point the melt level is being maintained constant. A higher feed rate reverses the slope of the chart trace. Once calibrated manually, the system could then be coupled with the feedback loop of the feed controller.

The completed feeder controller is pictured in Figure 1. The principle of operation is as follows: two independent feed rates are selected, one faster than the anticipated rate of silicon consumption during web growth and one slower than the use rate. When the output signal of the melt level sensing system indicates that the level is above a predetermined set point, the controller switches to the slower feed rate. If the melt level falls during growth, the controller switches to the faster rate. This oscillation between the two feed rates maintains the melt at the desired level consistent with the web output rate.

Near the middle of this reporting period the circuitry work for closing the loop between the melt level sensor and the silicon pellet feeder was completed and the general use and testing of the system was undertaken.

Numerous runs have now been made with the closed loop system and the results are very encouraging with respect to extended growth periods. The system has behaved functionally as expected. By monitoring the output of the melt level via the laser sensor we have demonstrated that the melt level can be held constant to within a few tenths of a millimeter, well within the range for stable long term melt replenished web growth. During the initial test period we grew under closed loop control for up to 3.5 hours with no difficulty in the melt level maintenance. Subsequent to this, silicon web was grown for 8 hours under closed loop control of the melt replenishment system during which time several web strips were grown, a total of six meters of material. (This demonstration fulfills the system objective for this contract).

Figure 1 Photograph of the principal components of the melt level controller.

A typical trace of the melt level sensor recorded during the eight hour run is depicted in Figure 2. The largest perturbations of the melt level detected by the sensor occurred after a crystal pull out. There was a brief deflection in the sensor output resulting from the passage a wave from the pull-out; this deflection has a negligible effect on the feed rate because it is brief in duration. (Following pull-out, the detector output levels out to a value about 2 millivolts lower than the output during crystal growth. This change equivalent to nearly 0.2mm of melt height, reflects the effect of how surface tension forces interact with the growing web.) During crystal growth the melt level remains constant, to within about 0.1 mm, i.e. only small fluctuations about the desired melt level occur.

These results clearly demonstrate the success of the melt level control system in meeting the following requirements:

- Must be compatible with web growth and the web growth apparatus,
- Must be accurate to within one millimeter or better, and
- Must be capable of both measurement and control

In addition, in both the recent 8 hour, automatically controlled feed run and the earlier, 17 hour, manually controlled feed run, the calibration appeared to remain steady. Furthermore, the components of the melt level control system are reasonably simple, and this can be reflected in the cost.

Some minor system changes have also been implemented to facilitate system operation. For example, one condition that recurred on occasion during these experiments was nucleation of silicon "ice" during feeding. During an inspection of the furnace parts we found a warpage of the lid causing misfit to the susceptor. This can cause uneven heating and oxide collection on the lid thus nucleating ice. The lid and susceptor were remachined and the most recent run produced a very

Figure 2 Example of melt level sensor output recording.

clean lid undersurface. Additional shielding was also added to facilitate pellet melting. Finally, the holes for the transit of the laser beam through the growth lid were opened to minimize any oxide accumulation there.

3.2 Dynamic Trimming for Melt Replenishment

Most of the work with the J-furnace was devoted to experiments aimed at further improvements to the thermal system for melt replenishment while maintaining good crystal growth conditions with the objective of increased area throughput. To this end, the J-furnace was configured so that melt replenishment could be carried out at any time during growth to test the ability of a specific lid and shield configuration to melt pellets at the required rates.

When replenishing the melt, it is necessary to maintain the feed compartment end of the crucible sufficiently hot to melt pellets as quickly as they are fed. Initially, fixed end shields^{1,4} were used for this purpose. While these could be configured to meet the requirements of a specific lid and shield geometry, the inability to change the amount of shielding during a run limited to their usefulness in terms of a development effort. The J-furnace was therefore fitted with adjustable shields at both ends of the susceptor. These can be raised or lowered during a run to vary the amount of shielding and thus the susceptor temperature, at each end independently. Thus, dynamic thermal trimming is provided.

When an end shield is used at the feed end of the susceptor, the shielding at the opposite end must also be adjusted to maintain thermal symmetry in the growth region of the melt, although the degree of shielding may not be identical at both ends. The heat of fusion required to melt the pellets, particularly at higher feed rates, requires that somewhat more shielding be employed at the feed end when feeding silicon. One of the advantages of the adjustable shields is that the thermal trimming can be adjusted for varying feed rates during the growth cycle.

At the opposite extreme, should too much end shielding be used, the hot susceptor ends will adversely affect the thermal profile in the growth region and cause thermal convection. Thus, for a given lid and top shield configuration, there is an optimum positioning of the end shields for growth.

Most of the experiments carried out this quarter used variations of the J-181 lid and shield configuration, adapted for melt replenishment. In a typical series of experiments, the growth behavior was first tested (ease of initiation, width of starts obtainable, growth stability, etc.). Adjustments to coil position and end shield position were then made as required until satisfactory growth was obtained. Melt replenishment was initiated and the system behavior observed during simultaneous web growth and feeding. If the crucible feed compartment was hot enough, the pellets melted readily and replenishment could be continued indefinitely. Periods of up to four hours have been demonstrated. (Note that the work with the J-furnace was directed at identifying system improvements to enhance output rate under replenishment conditions, not at long term replenishment). If the feed compartment was too cold the rate of melting was slower than the feed rate and the pellets would begin to pile up. On the basis of feeding behavior, further adjustments were made on the position of the end shields to either increase or decrease the susceptor and temperatures (and thus the crucible feed compartment temperature).

One outcome of the work was the determination that the use of the end shields for temperature management produces secondary thermal effects which must be compensated in the overall system. For example, with large amounts of shielding (>50%) there is an increase in the temperature gradient at the crucible sufficiently large to increase thermal convection in the melt. Under these conditions dendrites tended to be more uneven (choppy) on the side of the crystal farthest from the feed compartment, increasing the potential for pull out. Earlier work indicated that the feed end crucible barrier reduced convective effects. We therefore added a second barrier at the opposite end of the crucible. The result was smooth dendrites and very stable growth.

Another effect of the adjustable end shields was to change somewhat the lid and top shield temperatures by reduction in the heat losses from the ends. In effect, the lid tends to run slightly hotter for a given top shield configuration. This, in turn, causes a slight reduction in growth velocity for a given crystal thickness, clearly an undesirable behaviour. This effect has been eliminated by modifying to top shield configuration to run cooler, e.g. by using slitted shields, and by perforating the end shields in the region of the lid to increase heat loss in that region.

In conclusion, it has been demonstrated that the use of adjustable end shields for dynamic trimming can provide the thermal requirements for melt replenishment, provided some compensating adjustments are made in top shield configurations. Stable web growth has been achieved and further work will be to refine the concept for long term operation.

3.3 Thermal Modeling for Equipment Design

In a previous quarterly report, the velocity-thickness relationship of dendritic web was discussed in terms of an empirical relationship of the form:

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

were a and b are empirical coefficients and v and t are the growth velocity and web thickness respectively.¹ Although this empirical equation is a good representation of both the thermal modeling results and the experimental data over the range of thicknesses and velocities encountered in practice, it obviously cannot hold over a wide range of parameters since it implies that infinitely thick web will grow at a finite velocity. Recently, during an evaluation of lid and shield configurations, it seemed appropriate to re-examine the representation of both the modeling and experimental data to gain a better understanding with regard to the effects of various modifications in lid design.

Some guidance can be taken from the approximate analytical treatments of the heat loss from a moving ribbon. Several such treatments have appeared in the literature,^{2,3} and the results can be expressed in the form:

$$v = c + \frac{d}{t^{1/2}} \quad (2)$$

where the coefficients c and d depend on the details of the model, and again v and t are the velocity and thickness. Although this expression also contains a constant term, c , the value should be small and is related to external heat fluxes other than those related to the latent heat of fusion. In the case of dendritic web growth, for example, both the liquid in the meniscus and the web itself may have either a positive or negative heat flux from a surface element depending on the effective temperature of the surroundings.

Since the latent heat of fusion in dendritic web growth can be dissipated both to the ribbon and to the supercooled liquid meniscus, it is useful to associate "partial velocities" with each of the heat fluxes.⁴ If we associate a partial velocity v_w with the latent heat dissipated to the web and v_m with the latent heat dissipated to the liquid, then the real growth velocity is given by

$$v = v_w + v_m. \quad (3)$$

Further, if both of the partial velocities can be related to the web thickness by equations of the form Eq. 2, then the corresponding c and d coefficients of the partial velocities can simply be added to give the coefficients for the growth velocity and thus compared with the experimentally determined values.

Heat Lost to Liquid (Meniscus Losses). In practice it is not possible to measure the proportions of the latent heat dissipated to the web and to the liquid. In modeling, however, it is simple to calculate the two quantities. The thermal model of the meniscus is very similar to the thermal model of the web discussed in the Annual Report for 1978-1979.⁴ The computer code solves the moving frame thermal conduction equation with the heat flux at each element of the meniscus surface determined by the radiative transfer between the element and the ambient, the lid and slot and the liquid and growth cavity. The resulting temperature distribution shows a minimum which is assumed to be the melt undercooling. The heat flux from the growth front is then calculated and expressed as a velocity, the partial velocity v_m . This partial velocity can be calculated for several web thicknesses and the results fitted to Equation 2. These calculations were performed for a number of mechanical and thermal geometries and the resulting c and d values are given in Table 1. The agreement of the modeling results with an equation of the form Equation 2 was excellent; the rms of the residuals was less than 0.005 cm/min in all cases examined.

Rather surprisingly, Table 1 shows that the c and d coefficients of the melt partial velocities are relatively insensitive to the geometry of the system, but as expected are strongly affected by the melt supercooling. The implication of this result is that a single set of melt partial velocity coefficients can be used to represent a number of different lid/shield geometries with accuracy sufficient to analyze the experimental data. Further, the effect of melt supercooling can be relatively easily accounted for in any data analysis.

Web Heat Loss

As in the discussion of the previous treatment of velocity-thickness relation¹, the J181 lid/shield configuration was chosen as an example for analysis. As before, the analysis of Ref. 4 was used to calculate the web partial velocities for crystals of 100, 150 and 250 μm thickness, however the resulting data were analyzed in terms of Equation 2 rather than Equation 1. Based on the rms of the velocity residuals, the

TABLE 1

Coefficients for the partial velocity due to heat loss from the meniscus during dendritic web growth. $v_m = c + d/\sqrt{\tau}$. Lid temperature = 1623°K.

Lid Thickness	Slot Width	LIN*	ΔT	c_m cm/min	d_m $\sqrt{\mu\text{m-cm/min.}}$
10 mm	6 mm	2 mm	2°K	-.08	6.775
"	"	"	4	-.16	11.658
"	"	"	6	-.23	16.147
6	6	2	4	-.16	12.055
10	"	"	"	-.16	11.658
10	6	1	4	-.16	11.808
"	"	2	"	-.16	11.658

* LIN is the distance of the growth front below the bottom of the lid.

fit to the inverse square root model was even better than the fit to a simple inverse thickness model. When evaluating the model, measured lid and shield temperatures were used as discussed in Reference 1. Some of the results are given in Table 2 which shows the variation of the partial velocity coefficients c and d as a function of the interface position.

TABLE 2

Web partial velocity coefficients for J181 lid/shield configuration.
(LIN is the distance of the interface below the bottom of the lid.)

$\frac{LIN}{mm}$	$\frac{c_w}{cm/min}$	$\frac{\sqrt{d_w}}{\sqrt{\mu m-cm/min}}$
0	.47	13.90
1	.46	10.48
3	.33	7.58

Experimental Data

The experimental data presented in Table 3 of Reference 1 was reanalysed in terms of Equation 2 and is presented in Table 3 along with some more recent data. In parenthesis, below the experimental values of c and d are listed the calculated coefficients based on Tables 1 and 2. The calculated values are found from

$$c = c_m + c_w$$

and

$$d = d_m + d_w \quad (4)$$

The agreement between the experiment and model is remarkably good, with a major uncertainty being the interface position, LIN. A few measurements indicated that the melt position was about 6 to 7 mm below the bottom of the lid which would make $LIN = 0$ for a full 185 gm melt. The uncertainty in the measurement, as well as the variation in crucible dimensions would give at least a ± 1 mm uncertainty in LIN.

TABLE 3

Velocity-Thickness Coefficients for J181 Configurations

Crystal	Configuration (see notes)	T °C	c cm/sec	d $\sqrt{\mu\text{m}}$ -cm/sec	Remarks
J197-1	Std.	4.3	.16 (.30)	28.75 (26.63)	Full crucible LIN = 0
J198-2	M1	3.4	.18 (.38)	24.99 (22.38)	8 gm, grown LIN = .4 mm
J199-1	M1	5.0	.10 (.3)	26.90 (26.8)	5 gm grown LIN = .2 mm
J211-1	M2	3.6	.35 (.33)	22.97 (24.82)	Full crucible LIN = 0
J211-5	M2	3.7	.21 (.28)	21.74 (19.51)	45 gm grown LIN = 2.3 mm
J319-1	Std.	3.7	.47 (.35)	22.37 (22.77)	12 gm grown LIN = .6 mm

NOTES: The lid configurations are as follows:

Std. As in Figure 6, Reference 1.

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

M2 Added heavy shield; top two shields slitted to
reduce coupling to the work coil.

Numbers in parenthesis are calculated values

The agreement between the model and the experimental data gives a degree of confidence in the use of the calculations to design higher speed lids. In particular, it provides a means of parametric analysis to choose those parameters which have the greatest effect on the growth velocity.

3.4 Web Growth Furnace Design

One task of the Phase III effort was to design a semi-automated web growth machine. A completely new detailed engineering design has been prepared for such a silicon web growth furnace having all of the desired functional features thus far developed during this program. Major improvements over previous design include apparatus for melt replenishment, pellet feeding and melt level sensing. The design has also been simplified somewhat as compared to previous design. All detailed and assembly drawings, identified as Design Specification D903190, are excluded from this report in anticipation of patent application. The design is similar to Westinghouse furnaces shown in Figure 3. The earlier design shown in the photograph did not have melt replenishment or melt level sensing and was not capable of semi-automated web growth.

3.5 Solar Cell Characterization

A number of dendritic web crystals were characterized during the report period by evaluating diagnostic solar cells made on samples of the material. Table 4 has been generated from a new computerized data base of cell properties but is otherwise similar to tables of cell characteristics published in previous reports. The principal difference is that values of anticipated AR efficiencies for the cells are omitted; in previous tabulations the AR efficiency was calculated from the performance of the uncoated cells by the relation $\eta_{AR} = \eta_o \times 1.43$. Since the inclusion of an antireflection coating introduces another variable into an already sufficiently complex processing sequence, the diagnostic solar cells are uncoated and only this measured efficiency is stored in the data bank. As before, the data for each crystal represents the average value of (usually) four individual devices.

Figure 3 Westinghouse Web Growth Furnaces

TABLE 4

CRYSTAL NUMBER	WEB QUAL	THICK MIC-M	RHO OHM-CM	ISC MA	VOC VOLT	FF	EFF (uncoated) %	OCU MIC-S	NOTES
J163-1.4	WQ60	204	5.51	21.45	.545	.762	9.42	3.9	CP
J165-1.3	WQ60	285	6.86	21.85	.545	.753	9.48	6.2	CP
J187-3STD	WQ60	202	2.9	20.05	.539	.762	8.72	1.1	CP
J187-3STDA	WQ59	200	2.9	20.12	.545	.752	8.72	1.9	CP
J187-3STDB	WQ59	200	2.9	21.45	.570	.752	9.73	7.7	CP
J241-1.2	WQ60	318	7.23	22.05	.538	.749	9.41	8.6	CP
J292-3.3	WQ59	150	8.15	21.35	.564	.751	9.57	8.5	CP
J294-1.1	WQ60	215	8.03	21.70	.542	.749	9.33	5.9	CP
J294-2.3	WQ59	155	8.24	21.27	.560	.748	9.43	8.9	CP
J297-2.3	WQ60	200	3.8	20.12	.531	.740	8.38	1.5	CP
J297-4.2	WQ60	168	4.15	21.10	.546	.756	9.22	2.7	CP
J298-2.3	WQ59	140	3.89	20.25	.550	.753	8.88	2.9	CP
J298-3.3	WQ59	150	3.77	20.10	.550	.731	8.55	2.6	CP
J299-4.2	WQ60	168	3.59	20.32	.536	.749	8.63	1.4	CP
RE176-1.1	WQ59	220	8.11	20.95	.534	.738	8.73	4.5	CP
RE272-1.7	WQ59	220	7.11	19.60	.513	.732	7.78	.9	CP
RE275-2.4	WQ59	170	8.88	21.00	.542	.727	8.76	5.9	CP
RE286-2.4	WQ60	210	3.49	20.20	.532	.746	8.51	1.3	CP
W203-1.1	WQ59	250	.064	19.45	.590	.765	9.29	2.4	CP
W210-1.1	WQ59	160	2.67	21.10	.564	.756	9.51	5.2	CP
W211-1.2	WQ60	170	3.20	21.40	.562	.782	9.94	4.6	CP
W213-1.3	WQ60	130	3.15	21.10	.544	.699	8.50	2.1	CP
W214-1.1	WQ60	175	3.26	21.70	.544	.746	9.31	3.4	CP
W214-2.3	WQ60	112	3.16	.00	.000	.000	.00	.0	CP
WA30-1.3	WQ59	185	7.89	20.00	.518	.721	7.91	2.1	CP
WA30-1.3	WQ60	190	7.89	20.00	.515	.735	8.01	1.4	CP
WA63-1.3	WQ59	150	8.13	20.85	.535	.736	8.69	3.4	CP
WA63-2.2	WQ59	190	8.14	21.82	.557	.753	9.69	10.2	CP
WA63-4.2	WQ59	155	3.81	20.62	.556	.750	9.10	3.7	CP
WA84-1.4	WQ59	155	3.94	20.35	.551	.741	8.79	3.4	CP
WA87-1.2	WQ60	222	3.76	20.42	.541	.760	8.88	2.0	CP
WB54-1.2	WQ60	195	17.55	21.30	.519	.513	6.00	3.9	CP

5. PLANS FOR FUTURE WORK

Experimental work on this program will continue for a period approximately three weeks beyond that covered by this report. During this period additional semi-automatic web growth will continue. An additional month will be devoted to the writing of a final report covering the entire program.

6. NEW TECHNOLOGY

No new technology is reportable for the period covered.

7. REFERENCES

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9. APPENDICES

9.1 Updated Program Plan

9.2 Growth Run Summaries

9.1.1

MILESTONE CHART

JPL CONTRACT 954654

PHASE III

9.1.2 Program Labor Summary JPL 954654, Phase III

9.1.3 Program Cost Summary JPL 954654, Phase III

9.2 Growth Run Summaries

Experiments in the RE and J facilities have been dedicated to melt replenishment and thermal fine tuning to maintain good growth while feeding. Web output has been only a secondary consideration. The WA facility has been chiefly concerned with width control experiments.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE-264	Nonproductive			J-252 lid and shields. Oxide on the lid caused ice problems.
RE-265	Nonproductive			J-252 lid and shields; increased spacing between lid and lower shield. Again there was oxide on the lid and ice problems.
RE-265	2	475	31.3	Set up like RE-265. Some oxide and ice problems early in run. Feeding was successful; at end of run feed rate was approximately rate for full replenishment.
RE-267	4	273		J-181 lid, RE-1 type of shielding. Dendrites tended to be choppy; growth was difficult.
RE-268	5	494		J-181 lid and shields. Ice ended 2 crystals; others became polycrystalline.
RE-269	Nonproductive			J-252 lid and shields. Crystals pulled out for reasons other than feed-related problems.
RE-270	2	283		Repeat set up of RE269 crystals tended to pull out.
RE-271	2	180		J-181 lid and shields. Thermocouple behaved erratically. There were also several oxide and ice problems.
RE-272	3	517	40.2	Repeat RE271 set up. There were some oxide and ice problems in the morning. The end of the feed tube broke off during the run, preventing feeding in this run.
RE-273	Nonproductive			Repeat RE271 set up. Ice was a problem all day.
RE-274	Nonproductive			Repeat RE271 set up. Again ice prevented crystal growth.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE276	1	165	23.9	Repeat setup of RE271. Ice occurred in the morning, with and without feeding. Later feeding was successful at full replenishment rate.
RE277	3	394	22.4	Repeat RE276. Ice ended one crystal, about 3 hour of feeding with crystal growth were accomplished.
RE278	Short (max. 67 cm) web segments			J-181 feed/laser lid, moveable shields on both ends of the susceptor. Ice forced termination of crystals. First use of closed loop melt control; level maintained for 3.5 hours.
RE279	3	349	24.3	J-181 feed/laser lid, fixed shield on left end, moveable on right.
RE280	1	165	20.9	Repeat RE279. Compared effects of shield changes to crystal growth conditions.
RE281	Nonproductive			Repeat RE279. Varied moveable shields position; tried feeding, but ice occurred.
RE282	2	365	25.5	Repeat RE279. Several feed periods resulted in ice within an hour.
RE283	1	166		J-181 feed/laser lid and shields; fixed shield on left, fixed perforated shield and moveable shield on right. Ice occurred with and without feeding.
RE284	Nonproductive			Repeat RE283 set-up, again ice formation was a major hindrance.
RE285	2	223	23.0	J-181 feed/laser lid and shields, fixed solid shield on left, perforated on right. Ice occurred with feeding suspect it may have been the result of a gap between the crucible barrier and the lid.
RE286	2	364	33.3	J-181 feed/laser lid; no end shields. The susceptor was ground to have a flat top. As a result, of the better fit between the lid and the susceptor, the bottom of the lid was clean.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
RE-287	1	96	22	J-181 feed/laser lid and shields; solid shield on left; perforated and moveable on right. No feeding attempted.
RE-288	3	489	35.0	RE-287 setup. Ice occurred twice with feeding, once without.
RE-289	3	344	28.6	J-181 feed/laser lid and shields; solid shield on left; perforated on right. Examine shielding effects on growth behavior.
RE-290	5	681	30.0	J-181 feed/laser lid and shields; perf. shield on left; tab on right. No feeding: no ice.
RE-291	Nonproductive			Repeat RE290 set up. No feeding: ice occurred throughout run.
RE-292	5	644	33.3	J-181 feed/laser lid and shields; perforated shield on left and; moveable on both ends. Ice, with feeding, ended 2 short crystals. Once crystal grew over 1 1/2 hour with feeding.
RE-293	4	507	26.6	RE-292 set up. Test replenishment. Further feeding ceased after a shielding change resulted in a frozen feed compartment.
RE-294	4	531	25.2	RE-292 setup. Limited melt replenishment; no ice.
RE-295	3	237	25.0	RE-292 setup. Limited melt replenishment; ice once.
RE-296	5	504	21.2	RE-287 setup. Of 4 crystals grown with melt replenishment, one ended because of ice.
RE-297	6	609	24.1	RE-287 setup. Eight hours of melt replenishment using the closed loop for melt level control.
RE-298	Nonproductive			RE-287 setup. Crystals grown tended to third easily.
RE-299	2	209	22.5	RE-287 setup. Retest.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
J-292	Not Productive			J-252 lid, two short RE-1 top shields, one full. Test variations in coil height-consistent pull outs.
J-293	1	65		J-252 lid, standard RE-1 top shields. Growth difficult to initiate, pull outs. Dendrite probe showed asymmetric profile.
J-294	3	526	33.2	J-181 lid, feed configuration. Susceptor end shields, left solid, right perforated. Good growth most of day.
J-295	Not Productive			J-181 feed configuration. New movable end shields installed at both ends of susceptor. Vary positions of end shields and test behavior. Some control problems.
J-296	3	287	-	Repeat J-295. End shields not yet optimum. Underside of lid clean. No spalling.
J-297	4	394	26.7	Repeat J-295. Choppy dendrites. Continue test end shield positions.
J-298	3	558	33.9	Repeat J-295. Continue to move end shields higher. Better growth at higher shield positions.
J-299	4	382	25.5	Repeat J-295. Crystals terminated going poly.
J-300	1	241	29.7	Fourth slitted top shield added to J-295 configuration. Poor growth AM, good growth PM.
J-301	3	304	30.8	Repeat J-300, with end shields raised. Good growth in PM.
J-302	3	340	-	J-295 configuration. Early crystals terminated by pull out.
J-303	3	312	25.0	J-295 configuration. Test feeding. Crystals went poly.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
J-304	Short Crystals (30-100cm)			J-181 feed configuration, end shields. Crystals went poly.
J-305	No significant crystal growth			Slitted fourth top shield added to J-181 configuration. Poor growth. After run, shields and susceptor oxidized, crucible partially
J-306	5	460	27.3	Repeat J-305 configuration. End shields slightly higher. Test feeding behavior. Feed compartment not quite hot enough to accomodate feed rate of 6 pellets per min., and pellets began to pile up after ~ 20 min.
J-307	4	339	33.2	Repeat J-305 configuration. Lower end shields. Feed for 4 hours continuously, up to 8 pellets/min., no ice.
J-308	2	327	33.7	J-305 lid and top shield configuration. End shields with two rows perforations along bottom to provide gradient to shielding. Good growth, but some oxide in slot.
J-309	4	451	32.7	J-181 feed configuration. Feed 2 hours, no ice.
J-310	4	285	23.0	J-181 feed configuration. Test lower coil position. Vary end shield positions. Problems with pull out.
J-311	3	328	33.6	J-181 feed configuration. High end shield position. Good growth in P.M
J-312	3	299	26.6	Repeat J-311. Ice during P.M.
J-313	3	349	34.5	Repeat J-311. Wide starts Feed pellets began to pile up after 30 min. feeding. Not quite hot enough at feed compartment.
J-314	5	415	29.2	J-181 configuration less upper top shield. Faster than J-181 but web outcropped at narrower width.
J-315	2	220	23.4	J-181 with upper top shield slitted to run colder. Increased end shields. Reduced widening.
J-316	4	413	23.1	Repeat J-315. Ice during p.m. when attempting to feed.

GROWTH RUN SUMMARY

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
WA-70	2	115	-	RE-1 lid configuration. Some oxide problems.
WA-71	Several short crystals			J-259 lid configuration. Severe oxide problems forced pullouts.
WA-72	Several short crystals			J-259 lid configuration, change in top shield spacing to prevent oxide. Trouble with thirds and pull outs.
WA-73	No significant web production			Repeat WA-72. Control problems.
WA-74	5	430	-	J-252 lid configuration. No oxide.
WA-75	Several short crystals			Repeat WA-74. Some ice and thirding.
WA-76	1	82	-	Repeat WA-74 with change in top shield spacing. Smoother dendrites, but excessive thirding.
WA-77	2	165	-	Repeat WA-76. Choppy dendrites. Bottom shields were oxidized.
WA-78	No significant web production			Repeat WA-76. Choppy dendrites and pullouts. Measured melt profile with dendrite probe. Adjust coil for better thermal behavior.

GROWTH RUN SUMMARY

RUN	NO OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
WA79	2	391	-	J181 lid/shield configuration. Flat temperature profile required narrow buttons to start.
WA80	1	170	-	J181 lid/shield configuration. Coil adjustments made to improve thermal symmetry.
WA81	1	113	-	J181 lid/shield configuration. Temperature instabilities noted; will try lower melt level.
WA82	Several short crystals			J181 lid/shield configuration. Thickness-velocity data. Smaller initial melt tried, but resulted in poor wetting of crucible.
WA83	2	325	32.7	J181 lid/shield configuration.
WA84	1	150	-	J181 lid/shield configuration. Ice in melt.
WA85	No significant web material			J181 lid/shield configuration. Ice in melt.
WA86	No significant web material			J181 lid/shield configuration. Ice in melt.
WA87	No significant web material			J181 lid/shield configuration. Ice in melt. Molecular sieve trap installed in vacuum line to reduce system moisture level.
WA88	Several short web crystals			J181 lid/shield configuration. Asymmetric temperature distribution. Again tried a lower initial melt weight, but this caused dewetting of crucible.
WA89	No significant web material			J181 lid/shield configuration. Ice specks and pull outs.
WA90	No significant web material			J181 lid/shield configuration. Hydrox purifier placed in argon line. Experiment with coil positioning to generate symmetric melt profiles.

RUN	NO. OF CRYSTALS	LENGTH (cm)	MAX. WIDTH (mm)	DESCRIPTION/RESULT
WA91	1	94	19	J181 configuration. Oxide accumulation interfered with growth.
WA92	3	short		J181 Configuration with HYDROX gas purifier. RF power cable connection failed during run.
WA93	not productive run			Control instabilities
WA94	not productive run			Continued control instabilities
WA95	not productive run			" " "
WA96	not productive run			" " "
WA97	not productive run			Power failure in generator field supply
WA98	not productive run			Severe temperature drift
WA99	4	378	24	J181 configuration with HYDROX gas purifier. Thermocouple rather than light pipe used for control.
WA100	3	285	28	J181 configuration; no HYDROX purifier. Modified light pipe installation.
WA101	3	267	23	J181 configuration.

9.3 Design Specification D903190, Semi-Automated web Growth Furnace