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HEAT EXCHANGER-INGOT CASTING/SLICING PROCESS

Silicon Sheet Growth Development for the Large Area Silicon
Sheet Task of the Low Cost Silicon Solar Array Project

Third Quarterly Progress Report, April 1, 1976—June 18, 1976

F. Schmid
B. Reynolds

June 21, 1976

MASTER

Work Performed Under JPL Contract No. 954373

Crystal Systems, Incorporated
Salem, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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Third Quarterly Progress Report
by
Frederick Schmid and Blake Reynolds

Covering Period from April 1, 1976, to June 18, 1976
Date of Report: June 21, 1976

JPL Contract No. 954373

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MAN-HOURS AND COST TOTALS

<u>Previous</u>		<u>Current</u>		<u>Cumulative</u>	
M/Hr.	Cost	M/Hr.	Cost	M/Hr.	Cost
1,399	\$82,406	714	\$30,250	2,113	\$112,656

ABSTRACT

The object of this program is to demonstrate that large single-crystal ingots, 6-inch diameter by 4 inches tall, can be economically cast by the Heat Exchanger Method (HEM) and economically sliced into thin sheets, 0.008-inches thick, with a multi-wafer slicer.

The thrust of the experimental work during this quarter was to establish the proper seed meltback and to nucleate single-crystal growth off the seed. Proper seed meltback was achieved, but a distinct interface was present between the seed and the ingot. This interface may be due to too rapid initial growth off the seed, too steep temperature gradients between the seed and the liquid, or to contamination at the seed/liquid interface. The growth rate was slowed down by increasing the liquid gradient and decreasing the rate of decrease of the heat-exchanger temperature.

The temperature gradient in the liquid was increased by increasing the furnace temperature 5°C . To compensate for the 5°C increase, the heat-exchanger temperature had to be decreased 40°C . This high gradient in the liquid and solid produced very good directional solidification and almost totally eliminated cracking, but it did not promote single-crystal growth.

The strong influence of furnace temperature on seed melt suggested that seed meltback may have occurred during the melt-down cycle for earlier runs. A process change was made to prevent this. It also became apparent that the graphite support ring around the crucible puts the ingot into compression during cool down due to its high coefficient of thermal expansion. The support ring was slit to allow for the expansion mismatch during cool down.

An SiC deposit was found on the silicon in the bottom of the crucible. The deposit may have occurred due to a reaction between the silicon and the graphite dust which settles in the bottom of the crucible during furnace close-up and pump down. Current efforts are to reduce the temperature gradient and to eliminate the SiC in the bottom of the crucible.

During the reporting period, slicing tests were begun on the multi-blade wafering machine, using a newly fabricated sensitive feed mechanism and associated components.

Preliminary results suggest that silicon may be sliced with the present machine into three or four hundred wafers at one time, each with a thickness as small as 0.004 inch, and with a kerf loss also as small as 0.004 inch per wafer. In addition, a wafer surface texture appears possible which would eliminate the need for successive lapping operations

during surface preparation.

Blades used in the testing were 0.008-inch diameter wire, impregnated with 45 μ diamonds.

After 60 hours of testing with one set of blades and 40 hours of testing with a second set, no blades had broken. In addition, from a small sampling of blades which had been used for 60 hours, under 100 successive conditions, microphotography suggests that the new slicing approach may provide significantly longer blade life than was previously available.

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QUARTERLY PROGRESS

SILICON CRYSTAL CASTING

During the reporting period ten crystal-growth runs were made. The objective was to establish the proper seeding and growth conditions for growth of large silicon single crystals. The variables that influence seeding are the seed shape, heat-exchanger and melt temperatures: i.e., solid and liquid gradients. Variables that effect the growth rate are the rate of melt-temperature decrease and rate of heat-exchanger temperature decrease: i.e., changes in liquid and solid gradients. To nucleate the seed and maintain crystallinity during the growth cycle, the temperature gradients in the liquid and solid cannot be too steep or too shallow.

In the last Quarterly Report, it was pointed out that the molten liquid only melted into, and nucleated on, the upper circumferential edge of the seed, as is illustrated in Figure 1. Microscopic examination of the seed area revealed that two distinct interfaces are present on top of the seed. This is illustrated in Figure 2, a photomicrograph at 125X of the seed and initial growth. An epitaxial growth appears to have initially grown to a thickness of approximately 2 millimeters. A polycrystalline

FIGURE 1. Macro-etched cross section through the center of the seed of Run 16 at 5X.

INGOT
GROWTH

EPI
GROWTH

SEED

FIGURE 2. Photomicrograph at
125 X showing the seed on bottom
and two interfaces for Run 16.

second growth appears to have nucleated off this growth. Examination of the interfaces shows them to be void. These interfaces may be caused by insufficient melting into the seed, too shallow or too steep a temperature gradient, and/or too rapid growth from the seed. Table I is a tabulation of these variables for the ten runs, with remarks on the results. Parameters varied were furnace and heat-exchanger temperatures and the rates of decrease of the furnace and heat-exchange temperatures.

The initial emphasis was to achieve sufficient melting into the seed. For Runs 11 through 17, the furnace temperature was held constant at 10°C superheat (10°C above M.P.), and the heat-exchanger temperature was varied. The heat-exchanger temperature was decreased rapidly (13°C to 25°C per hour) for Runs 11 through 15 to assure that the temperature gradient was not too shallow.

Analysis of the crystals grown in these runs shows the common trend. At the surface of the seed there is an initial melting in and single-crystal growth. Sometimes the melting in is not complete. The single-crystal growth continues for a short period of time, and then the growth quickly changes to polycrystalline growth. This phenomenon is illustrated in Figure 3, a 16X photograph of the seed/ingot interface for Run 12.

In Run 13, the thickness of epi growth was approximately

Seed/Ingot Interface

Breakdown of Single Crystal Growth

FIGURE 3 . 16X Magnification of Seed/Ingot Interface

TABLE I

TABULATION OF HEAT-EXCHANGER AND FURNACE TEMPERATURES
FOR SEEDING AND GROWTH

<u>RUN</u>	<u>PURPOSE</u>	<u>SEEDING</u>		<u>GROWTH</u>		<u>REMARKS</u>
		FURN. TEMP. ABOVE M.P. °C	H. E. TEMP. BELOW M.P. °C	RATE OF TEMP. DECREASE H.E. TEMP.	FURN. TEMP.	
11	Improve seed melt back.	10	125	15°C/1st Hr. 138°C/6.5 Hr.	10°C/7.5 Hr.	Almost no melting into seed. Ingot polycrystalline, badly broken.
12	Improve seed melt back.	10	98	150°C/1st Hr. 112°C/5 Hr.	10°C/6 Hr.	Almost no melting into seed. Ingot polycrystalline, badly broken.
13	Improve seed melt back.	9	100	20°C/1st Hr. 139°C/4.5 Hr.	9°C/5.5 Hr.	Almost no melting into seed. Ingot polycrystalline.
14	Improve seed melt back. Slow initial growth.	11	92	13°C/1st Hr. 286°C/7.4 Hr.	11°C/8.4 Hr.	Lost seed. Ingot crumpled into pieces.
15	Improve seed melt back. Fast initial growth.	12	100	25°C/1st Hr. 138°C/4.5 Hr.	12°C/5.5 Hr.	Good melt into seed. Ingot polycrystalline.

TABLE I (Cont.)

TABULATION OF HEAT-EXCHANGER AND FURNACE TEMPERATURES
FOR SEEDING AND GROWTH

RUN	PURPOSE	SEEDING		GROWTH		REMARKS
		FURN. TEMP. ABOVE M.P. °C	H. E. TEMP. BELOW M.P. °C	RATE OF TEMP. DECREASE H.E. TEMP.	TEMP. DECREASE FURN. TEMP.	
16	Slow initial growth. Improve seed melt back.	10	102	9°C/1st Hr. 99°C/14 Hr.	10°C/15 Hr.	Almost no melting into seed. Ingot polycrystalline.
17	Slow initial growth. Improve seed melt back.	11	90	5°C/1st Hr. 190°C/18 Hr.	18°C/19 Hr.	Seed meltback to 1¼" diameter, 0.3" height. Ingot large broken single crystal.
18	Slow initial growth by increased liquid gradient.	17	112	3°C/1st Hr. 167°C/31 Hr.	32°C/32 Hr.	Seed completely melted out. Ingot large columnar grain. Cracking minimized.
19	Slow initial growth by increasing liquid gradient.	16	112	6°C/1st Hr. 90°C/14 Hr.	18°C/15 Hr.	Seed completely melted out. Ingot large columnar grain. Very good directional solidification. Almost no cracking.
20	Slow initial growth by increasing liquid gradient.	15	132	3°C/1st Hr. 78°C/15 Hr.	15°C/16 Hr.	Seed meltback to ¾" dia. by 0.2" height. Some seeding; mostly columnar grains. Good directional solidification.

0.76mm. The total growth time was 5.66 hours for a vertical growth of 38.1mm (1.5"). Assuming a uniform growth rate of 6.73mm/hr., the time required to achieve 0.76mm of single crystal was 0.113 hours, or less than seven minutes.

During the seven minutes in which the single crystal section developed, the heat-exchanger temperature decreased approximately 1°C, and the power input to the chamber remained substantially constant. At the end of ten minutes of growth time, the crystal was already in the polysilicon mode.

The growth rate during seeding can be slowed by decreasing the rate of heat-exchange temperature decrease and/or increasing the liquid gradient: i.e., the furnace temperature.

Run 14 was an attempt to achieve better melt in on the top of the seed. The heat-exchanger temperature was set at 1320°C, and the melt-point temperature was set at 1405°C. This was only an 8°C difference from the previous run. Nevertheless, the seed was completely melted out, causing a polycrystalline ingot to grow and to crack into many sections. The seed section in particular was badly shattered, and no sampling was possible. The critical nature of seed temperature was amply demonstrated in this run.

It appears that the seed temperature, as measured by the thermocouple in the heat exchanger, and the furnace temperature are very critical parameters. It is possible to

lose the seed completely if the temperatures are not tightly controlled or to induce polycrystalline growth by reducing the heat-exchanger temperature too quickly.

Several changes can be made to make seeding less critical. A larger seed will allow a broader heat-exchanger temperature range for seeding. The furnace temperature can be controlled more accurately by monitoring the temperature with platinum/platinum-rhodium thermocouples rather than with pyrometers. Both of these measures are being implemented to increase seeding reliability.

For Run 15 a heat-exchanger temperature of 1312°C and a slightly higher superheat temperature of 12°C was used. The total growth time was 8 hours, with a 25°C/hr. decrease in heat-exchanger temperature. It appeared that some melt in had taken place on the circumference of the seed since the seed diameter had been reduced to approximately 1.5", but the top of the seed was still totally intact. A distinct interface was apparent between the seed and the ingot even though complete seed melt in was achieved. To slow the initial growth even more, the gradient in the liquid and solid must be decreased at a slower rate. This will extend the growth cycle. For Runs 16 and 17, the superheat temperature was held at 10°C , and the heat-exchanger temperature was held at 1310°C and 1322°C respectively. The heat-exchanger temperature was decreased at 9°C and 5°C respectively for the

first hour, while the furnace temperature was decreased at 0.6°C and 0.5°C per hour.

Good seed melt back was achieved for Run 17 but, again, a distinct interface was present between the seed and ingot. It appeared that the growth rate would have to be slowed down even more to adequately nucleate single crystal from the seed crystal. To accomplish this, the gradient in the liquid could be increased by increasing furnace temperature and slowing up the rate of heat-exchanger temperature decrease.

On a previous run it was noted that SiC powder was deposited on the melt stock in the bottom of the crucible. Possibly the SiC powder was coming from scratches in the lapped bottom area of the crucible. To eliminate this possibility and reduce the roughness, the crucible bottom was etched with HF for three hours.

For Run 18, the furnace temperature was increased to 17°C above the melt point, and the heat exchanger was decreased to 1300°C, 112°C below the melt point. Unfortunately, the crucible was not centered over the heat exchanger, and the seed was completely melted out. The solidification was very good; large columnars extended from the bottom of the crucible to the top with very little cracking. The good directional solidification appears to be related to the higher temperature gradients: i.e., 15°C superheat.

Provisions were made to assure that the crucibles would

always be centered on the heat exchanger after loading. The bottom of the crucible was again etched with HF acid for three hours to remove roughness and contaminants.

Seeding of Run 19 was a repeat of Run 18. The growth cycle was changed by decreasing the growth time: i.e., decreasing the furnace temperature to the melt-point temperature in a period of 15 hours rather than in 32 hours. The temperature decrease of the heat exchanger in this period of time was 90°C rather than 167°C . The resulting crystal was one solid piece with no cracking through the center section. The ingot section could not be removed from the graphite retaining ring. The graphite ring shattered when a small nick was put on it while attempting to saw it off. (The graphite support ring was obviously putting the ingot into compression during cool down and possibly caused cracking in many of the previous ingots.) A crack formed in the ingot due to the sudden release of energy. A sectioned and polished section of the crystal revealed that the seed had completely melted out. Directional solidification was much better than for Run 18 even though both the growth time and solid gradient were only one-half as great. This run has made it clear that the gradient in the liquid must be very steep at the seed/liquid interface since a 5°C increase in furnace temperature causes the seed to completely melt out even with the higher gradient in the solid.

For Run 20, the furnace temperature was held at a 15°C superheat, and the heat-exchanger temperature was held at 1280°C , 132°C below the M.P., for seeding. The heat-exchanger temperature was decreased only 3°C for the first hour while the furnace temperature was held constant at 15°C superheat. The resulting ingot exhibited one crack through the center. The seed was still present; it had melted back from a $2\frac{1}{4}$ -inch diameter by 1-inch height disc to a $\frac{3}{4}$ -inch diameter by 0.2-inch high disc. Its shape, a right-circular cylinder, was clearly delineated by the interface between the seed and the ingot. The area around the seed was single crystal that was twinned with respect to the seed. The single crystal grew out to about a $2\frac{1}{2}$ -inch diameter hemisphere before it degenerated into large columnar grains. The directional solidification was very good. It is now apparent that very high gradients are required to prevent seed melt out. For example, increasing superheat from 10°C to 15°C has required a 42°C decrease in heat-exchanger temperature to prevent seed meltout. The high gradients may be causing poor nucleation on the seed. The strong influence of furnace temperature suggests that the double interfaces may be caused during the melt-down cycle where the temperature is allowed to rise from 15°C to 20°C above the melt temperature.

To prevent meltback of the seed during melt down, a process change has been made. This involves holding the heat-

exchanger temperature at 1280°C until the furnace temperature has been stabilized at the desired temperature. The heat-exchanger temperature will then be increased at 1°C per minute to the desired heat-exchanger temperature and held for one hour as usual to melt back into the seed.

Electrical Properties

Measurements of the electrical properties of the ingots indicate that they are "P" type with resistivities in the range of 20-25 ohm/centimeters.

Investigation of Silicon Contamination

During the last quarter, a crucible loaded with a silicon seed and melt stock was heated above the melt temperature and immediately cooled to room temperature. A yellow powder was apparent on the melt stock on the bottom of the crucible. It was also deposited on the outer fringe of the seed adjacent to the heat exchanger. X-ray diffraction patterns of this powder indicated it is beta Silicon Carbide, since there is a one-to-one agreement with the "d" spacings. The deposit of Silicon Carbide is quite heavy; it may be remnant Silicon Carbide powder remaining from lapping the bottom of the crucible or due to carbon falling into the crucible. This deposit is not apparent directly above the heat exchanger.

Investigation of the Seed/Crucible Interface

The nature of the interface between the quartz crucible and the seed was investigated since it is critical to the process. It is imperative that the seed remain affixed to the crucible and maintain that position throughout the growth cycle. Since the seed/crucible interface is within the melt, no cement or other foreign bonding agents can be used, and any adhesion of the seed to the crucible must depend on chemical reactions that may occur during the growth process.

It has been experimentally found that the seed does, in fact, tenaciously bond itself to the bottom of the fused quartz crucible after being subjected to a growth cycle. The nature of this interface bond has been investigated by means of optical microscopy and electron microprobe methods.

The seed/crucible interface obtained during Run 16 was typical of all other interfaces and consisted of a section of single-crystal silicon affixed to a section of the fused quartz crucible bottom. The silicon seed was initially placed on the flat portion of the fused quartz crucible bottom that had been lapped with SiC abrasive to provide a $2\frac{1}{2}$ -inch flat area for the seed.

After solidification of the charge, a small section of the seed/crucible interface was taken for examination. A photograph taken at 13X is shown in Figure 4. Enlarge-

SILICON
SEED

INTERFACE

QUARTZ

FIGURE 4. Cross section of silicon seed bonded to the quartz crucible at 13X mag. for Run 16.

ments of the interface at various points showed that in those areas where the silicon metal made physical contact with the crucible, a definite change in structure was noted. Typical areas along the interface are shown in Figure 5. The interface consisted of a zone between the silicon and the bulk quartz and suggested that silicon metal had diffused into the quartz. The interface consisted of small inclusions of silicon within a silicon-oxide matrix.

Any chemical analysis of the constituents present in the interface would be difficult since both sides of the interface are high in silicon. However, an electron-microprobe scan across the interface did show that there was some significant difference in the silicon content of the two sides of the interface. Figure 6 is a photograph of the sample current in the two sides of the interface. These same areas when scanned for Silicon K alpha X-rays or Oxygen K alpha X-rays (Figures 7 and 8) show that there is a significant difference in the concentrations of these elements in the two portions of the interface.

Previous measurements using X-ray diffraction methods have shown that silicon dioxide and silicon monoxide are present in the solidified melt, and such oxides do concentrate between the silicon metal and the crucible walls.

From the electron-microprobe scan it is apparent that

SILICON

INTERFACE

LAPPED AREA
OF QUARTZ

QUARTZ

FIGURE 5. Cross section of silicon seed bonded to the quartz crucible at 500X mag for Run 16.

SILICON
/
QUARTZ

FIGURE 6. Electron microprobe scan across interface with sample current at 500X mag.

FIGURE 7. Electron Microprobe scan with Oxygen K alpha X-rays at 500X mag.

FIGURE 8. Electron Microprobe scan with Silicon K alpha X-rays at 500X mag.

the interface bond between the silicon seed and the crucible is due to the inter-diffusion of silicon metal into the fused quartz (silicon dioxide) plus the formation of various forms of oxides of silicon.

Investigation of Ingot/Crucible Interface

The interface between the ingot and the quartz consists of a tenacious brown layer. It was difficult to obtain a representative sample of this powder since it tenaciously adhered to the wall of the quartz crucible and the solidified silicon. The sample could contain, therefore, silicon metal, the crystalline quartz from the crucible, devitrified quartz, or some oxides of silicon.

Debye-Scherrer X-ray patterns were obtained from this powder as well as for SiO purchased from Union Carbide.

The data from these types of material are best presented in graphical form.

Pattern from U.C. "SiO" Powder

3.13 4.26

Pattern from Light Brown Powder

It should be noted that the line at 4.26 is the characteristic line for cristobalite, as well as the

strongest line observed in the "SiO" material.

The cristobalite is a whit , colorless powder and the "SiO", when ground, is a brown powder. Hence, the light brown powder is most likely a mixture of cristobalite and the reported "SiO" form of the oxide.

Conclusions

1. A 5°C increase in melt temperature from 10°C to 15°C above the melting point requires very steep gradients in the seed to prevent melt out: i.e., the heat-exchanger temperature must be decreased 40°C to compensate for the 5°C increase in furnace temperature.

2. Good directional solidification is achieved at 15°C superheat, and cracking is almost totally eliminated.

3. The strong influence of furnace temperature on seed melting suggests that seed meltback may have occurred during the melt-down cycle. A process change has been made to eliminate this possibility.

4. The graphite support ring around the crucible puts the ingot in compression during cool down due to its higher coefficient of thermal expansion. The support ring must have a slit in it to allow for the expansion mismatch during cooldown.

5. The bond between the seed and the crucible bottom is due to the inter-diffusion of silicon metal into the fused quartz plus the formation of various forms of oxides

of silicon, such as SiO , at the interface.

6. The brown layer that tenaciously bonds the ingot to the crucible wall is a combination of SiO and cristobalite.

7. Silicon carbide powder deposits on melt stock in the bottom of the crucible during heat-up. Some of this is trapped adjacent to the seed.

SILICON CRYSTAL SLICING

Summary

During the reporting period the newly fabricated components for the multi-blade wafering machine were assembled, and slicing tests were begun. The new components included: a sensitive vertical feed mechanism, a rocking workpiece cradle, a cradle drive mechanism, a slurry recovery system, and a wire/blade-package assembly fixture.

The machine was tested for approximately 100 hours, under approximately 130 successive conditions.

From the earliest test conditions, whose data have been examined the most closely, some preliminary results have been extracted. Further data analysis is expected to reduce the ranges of uncertainty in the values given and to help establish cause and effect relationships.

Results and Conclusions

Experimental Conditions and Findings To Date

<u>Specimen:</u>	Silicon (111) single crystal, 1 $\frac{1}{4}$ in square cross section.
<u>Blades:</u>	25 ea., 0.008 in D wire, impregnated with 45 μ natural diamonds.
<u>Coolant:</u>	Water-ethylene glycol mixture, 50% - 50% High flow rate.

<u>Feed Force:</u>	0.02 to 0.24 lbf/blade
<u>Cutting Rate:</u>	2 to 20 μ -in/stroke
<u>Machine Limit:</u>	200 strokes/min.
<u>Projected Cutting Rate:</u>	0.4 to 4 mil/min at 200 strokes/min.
<u>Kerf Width:</u>	0.009 in., measured, using 0.008 in dia. wires with 45 μ diamonds.
<u>Projected Minimum Kerf Width:</u>	0.00325 in , using 0.003 in dia. wires with 8 μ diamonds (measured by others, whose data agree with ours so far).
<u>Surface Texture:</u>	Areas produced during continuous cutting under steady-state conditions resemble finely ground or polished surfaces. Changes in test conditions and machine geo- metry have prevented measuring the minimum variations possible over a total wafer surface.
<u>Wafer Thickness:</u>	Fractures of individual wafers have occurred after combined slicing, measuring, and handling, with measured thicknesses in the range of 0.001 to 0.015 in. Prolonged cutting has been observed where wafer thickness was well under 0.005 in.
<u>Projected Wafer Thickness:</u>	Unavailable, until continuous, steady- state slicing can be performed.
<u>Flatness and Parallelism:</u>	Unavailable, until blade wander is restricted. This was not incor- porated into the reporting period testing.
<u>Blade Life:</u>	Unavailable. During 60 hours of

testing, using one set of blades and 40 hours of testing using a second set, no breaking of blades or unacceptable degradation of cutting rate has yet occurred to indicate blade-life limitations. This will be an accumulating form of data.

Blade Photography

Microphotographs using visible light were obtained of: samples of used and unused wire blades (Figure 9), and of unused plain and diamond-impregnated wires (Figure 10).

If the cross sections in Figure 9 are representative, which they presently appear to be, then these photos together with cutting rate data indicate that one particular design objective was realistic. That is, with a sensitive feed mechanism and controlled interaction between blades and workpiece, blade life may be extended dramatically over previously obtainable performance.

While this conclusion is being further examined, other questions will be considered.

One such question is: how effectively can diamonds in the blade be replaced or reconditioned when they are no longer cutting economically.

Another question is: how much better diamond distributions and concentrations can be achieved, over present blade materials, hence reducing blade wander due to distribution, and increasing cutting rates.

0.001" Cu 0.006" D Steel 45 μ Diamonds

(a) Unused wire

(b) After 60 hours

FIGURE 9. Cross sections of 0.008 in.
O.D. diamond-impregnated wire (300X).

(a) Diamond impregnated (100X)
See Figure 9.

(b) Plain (70X)

FIGURE 10. Segments of unused
0.008 in O.D. diamond-impregnated
and plain wire.

Discussion

The variables being studied as experimental results and derivatives from experimental results are the following.

Dependent Variables

<u>Symbol</u>	<u>Units</u>	<u>Definition</u>
Y	mils	Workpiece position--read from a dial indicator and recorded as a function of time-of-day (T.O.D.)
$\dot{Y}_\mu$	μ -in/stroke	Cutting rate--determined as the slope of the curve of Y vs. T.O.D.
δ	mils	Workpiece deflection (vertical travel) during each cycle.
$\ddot{Y}_\mu$	$\frac{\mu\text{-in/stroke}}{10^4 \text{ stroke}}$	Cutting degradation rate.
Y vs X	mils	Cut profile for each condition of the machine.

The variables being studied as machine input parameters are the following.

Independent Variables

<u>Symbol</u>	<u>Units</u>	<u>Definition</u>
F_F	lbf/blade	Feed Force--the force against each blade by the workpiece--adjusted by increasing or decreasing the air pressure to the cylinder of the sensitive feed system.
S	strokes/min	Machine speed--the rate of single strokes of the blade carriage. Two "strokes" in different directions make one "cycle".
α	degrees	Rocking angle--the left and right

<u>Symbol</u>	<u>Units</u>	<u>Definition</u>
		angular motion of the workpiece and rocking cradle--measured $\pm$ from the vertical, centered position.
ϕ	degrees	Phase angle--the angle between the position of the workpiece cradle in its rocking cycle, β , and the position of the blade carriage in its reciprocating cycle, Ω . $\phi = \beta - \Omega$. See below.
τ	psi	Blade stress due to pre-tensioning, before cutting.
N	blades	Number of blades held in the blade carriage and cutting simultaneously.
W	inches	Cut length--workpiece dimension.

Phase Angle and Cut Profile

Figure 11 describes the motions of the blade carriage and workpiece cradle, which give rise to the phase angle, ϕ .

Figure 12 describes typical cut profiles obtained with different values of phase angle, ϕ . In Figures 12 (a), 12 (b), and 12 (c) can be seen flats on the cut profile, while the cut profile in 12 (d) is continuously rounded. A rounded cut profile is considered to be favorable to both higher cutting rates and longer blade life.

Preliminary conclusions from phase-angle testing to date include the following.

Phase angles, ϕ , of approximately 30° to 150° avoid conditions considered unfavorable to blade life.

$$[\text{Phase angle, } \phi = \beta - \Omega]$$

FIGURE 11. Motion of blade carriage and workpiece cradle.

FIGURE 12. Typical cut profiles.

A phase angle, ϕ , of approximately 90° minimizes deflection, $\hat{c}$, of the workpiece by the blades, and hence minimizes fluctuations in cutting force, F_F , and total blade stress, σ , due to inertia of moving components. This would be most important at the higher carriage speeds associated with production operation.

Current testing is expected to help better establish these relationships.

Test Program

From consideration of the number of input parameters (7 each) the need for judicious test planning and data interpretation is apparent. This can be further appreciated by considering the number of tests which would be necessary if each variable were changed by itself through a given number of different values, for each combination of settings of the other variables.

Number of values (X) for
each of seven variables

Number of separate
tests required (X^7)

1	1
2	128
3	2,187
4	16,384

The conditions under which the machine was run during the reporting period, without regard to the specific combinations, were approximately the following.

<u>Variable</u>	<u>Units</u>	<u>Values</u>	
F_F	lbf/blade	0.02	0.14
		0.04	0.16
		0.06	0.18
		0.08	0.20
		0.10	0.22
		0.12	0.24
S	Stroke/min	36	100
		60	125
		75	
α	degrees	± 6	
ϕ	degrees	30	80
		45	90
		60	120
		70	150
$\mathcal{T}_C$	psi	100,000	200,000
N	blades	25	
W	inches	1.5	

The effects of phase angle, ϕ , together with the other machine settings in producing different cut profiles, cutting

rates, and cutting degradation rates is currently under study.

A typical series of test conditions for this purpose, underway at the time of this writing, is shown in Figure 13.

S ~ $\frac{\text{stroke}}{\text{minute}}$	$\odot$ ~ deg	F_c ~ $\frac{\text{lbf}}{\text{blade}}$
100	40	0.18
↑	60	↑
	80	
	90	
	100	↓
	120	0.18
	90	0.06
	↑	0.10
	↓	0.14
↓	↓	0.18
100	90	0.22

FIGURE 13. Typical series of test conditions.

SCHEDULE OF MILESTONES--CRYSTAL CASTING

PAGE 1 OF 2

ITEM	DESCRIPTION	Month 1976											
		Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
1	A. Modify and calibrate	○△											
2	furnace/Purchases	●											
3													
4	B. Optimize refining		◐△										
5	conditions												
6													
7	** Design & Performance		○△										
8	Review			●▲									
9	C. Establish seeding con-			○				△					
10	dition for 6" Ø x 4"			●									
11	single crystal												
12													
13	D. Establish single crystal							○				△	
14	casting parameters for												
15	pure silicon melt stock												
16													
17	E. Establish single crystal											○	△
18	casting parameters for												
19	solar energy grade silicon												
20	melt stock												
21	F. Final Report												○△
22													

LEGEND: ○ Estimated Start △ Estimated Complete ● Actual Start ▲ Actual Complete

CRYSTAL SYSTEMS, INC.
CONTRACT # 954373

SCHEDULE OF MILESTONES--CRYSTAL SLICING

PAGE 2 OF 2

ITEM	DESCRIPTION	Month 1976											
		Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
1	A. Blade and equipment	○△											
2	modification and purchases	●▲											
3													
4	B. Slice silicon test piece		○			△							
5			●										
6	** Design & Performance		○△										
7	Review			●▲									
8													
9	C. Blade hardness varied and					○		△					
10	alternate blade systems					●							
11													
12	D. Particle size varied							○		△			
13													
14	E. Diamond type varied								○			△	
15													
16	F. Special effects on cutting											○△	
17													
18	G. Final Report												○△
19													
20													

LEGEND: ○ Estimated Start △ Estimated Complete ● Actual Start ▲ Actual Complete

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