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SILICON INGOT CASTING—HEAT EXCHANGER METHOD (HEM)
MULTI-WIRE SLICING—FIXED ABRASIVE SLICING TECHNIQUE
(FAST). (PHASE IV)

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

Quarterly Progress Report No. 2, April 1—June 30, 1980

By
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C. P. Khattak
M. Basaran

August 1980

Work Performed Under Contract No. NAS-7-100-954373

Crystal Systems, Inc.
Salem, Massachusetts

U.S. Department of Energy

Solar Energy

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CRYSTAL SYSTEMS, INC.

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Salem, MA 01970

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENT.	iv
ABSTRACT.	v
SILICON INGOT CASTING--HEAT EXCHANGER METHOD (HEM).	1
Square Shape.	6
Improvement of Crystallinity.	6
MULTI-WIRE SLICING--FIXED ABRASIVE SLICING TECHNIQUE (FAST).	12
Blade Development	12
Electroplated Wires	12
Impregnated Wires	22
ECONOMIC ANALYSIS	32
HEM Casting	33
FAST Slicing.	33
Band Saw Sectioning	34
Results	35
SUMMARY	37
REFERENCES.	39

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ABSTRACT

Silicon ingot size cast by HEM has been extended to 34 cm x 34 cm x 10 cm. A 20 kg ingot has been solidified at 3 kg/hr with no crucible attachment or ingot cracking problems. Another ingot of 26 kg weight has also been solidified. The heat treatment used to develop a graded structure caused cracking on the inside surface of the first large crucibles. The thermal conditions were altered to minimize high gradients and the cracking was eliminated. A high degree of single crystallinity has been maintained as the size of the ingots has been increased. A graphite retainer made out of flat plates was used to produce an ingot with flat sides and rounded curves.

It is now possible to electroplate diamonds only on the cutting edge of the wire. The advantages associated with diamonds on the cutting edge only are lower kerf, improved accuracy by improved seating in the support rollers, and less degradation of the rollers. This has resulted in less wander of wires and will reduce costs by using less diamonds and less degradation of rollers. The main failure mechanism of wires--diamond pullout--has been minimized by using filler diamonds

to prevent erosion of the nickel matrix. It has been shown that an electroplated wirepack can be used to slice three 10 cm diameter silicon ingots without significant diamond pullout.

IPEG analysis of value added costs of sheet formation using conservative and optimistic extension of HEM and FAST technologies yields $\$27.05/\text{m}^2$ ($\$0.191/\text{w}$) and $\$13.49/\text{m}^2$ ($\$0.095/\text{w}$), respectively. Assuming cost goals of other tasks are met, the projected costs are $\$0.654/\text{w}$, conservatively, and $\$0.539/\text{w}$, optimistically, for photovoltaic modules.

SILICON INGOT CASTING--HEAT EXCHANGER METHOD (HEM)

Emphasis during this quarter was on scaling up of the size of the ingot as well as on improving the square shape and the crystallinity of ingots. Significant advancements were made in both areas. Two 34 cm x 34 cm cross-section ingots weighing 20 kg and 26 kg were solidified. These are the largest silicon ingots made thus far by HEM and represent a cross-sectional area approximately 2.4 times that being routinely solidified. Details of experiments carried out during the quarter are given in Table I.

Scaling Up the Size of the Ingot

To scale up the size of the cast ingots, silica crucibles with a 34 cm x 34 cm cross-section were fabricated. During the heat treatment to develop the graded structure in the crucibles, it was found that the heat transfer characteristics are quite different because the crucibles are nearly three times as large. Cracking in localized areas occurred because of rapid cooling due to size. These cracks were welded; however, the high gradients developed during heat treatment produced stresses in the crucible and more cracks were seen on the

TABLE I. TABULATION OF HEAT-EXCHANGER AND FURNACE TEMPERATURES

RUN	PURPOSE	SEEDING		GROWTH CYCLE		GROWTH TIME IN HOURS	REMARKS
		FURN. TEMP. ABOVE M.P. °C	H.E. TEMP. BELOW M.P. °C	RATE OF DECREASE H.E. TEMP. °C/HR.	FURN. TEMP. °C		
41-13C	Improve square shape of ingot	14	-	-	11	34	Graphite box has held ingot to a square shape with flat sides
41-14C	Improve solidification	2			1	31	Profile does not show significant improvement across bottom
41-15C	Cast 34 cm x 34 cm cross-section ingot	14	-	-	4	6.5	First large 12-inch square ingot. No cracking.
41-16C	Cast 40 kg ingot	-	-	-	-	-	Run terminated as silicon leaked from crucible before start of growth cycle
41-17C	Test welded crucible	-	-	-	-	-	Run terminated during meltdown. Instrumen- tation malfunction.
41-18C	Test new plug design	39	-	-	1	27	No significant improve- ment in crystallinity
41-19C	Improve crystal- linity across bottom of ingot	40	-	-	2	30	No significant improve- ment in crystallinity

(cont.)

TABLE I. TABULATION OF HEAT-EXCHANGER AND FURNACE TEMPERATURES (cont.)

RUN	PURPOSE	SEEDING		GROWTH CYCLE			REMARKS
		FURN. TEMP. ABOVE M.P. °C	H.E. TEMP. BELOW M.P. °C	RATE OF DECREASE H.E. TEMP. °C/HR.	FURN. TEMP. °C	GROWTH TIME IN HOURS	
41-20C	Cast 45 kg ingot	45	-	-	33	8	Crucible leaked at crack in corner along wall. Final weight was 26 kg.
41-21C	Improve crystallinity across bottom of ingot	-	-	-	-	-	Run terminated during meltdown. Problems with cooling water system.

inside surface. During the heat treatment to develop a graded structure in the crucible, the inside is of high density, whereas the outside surface is low density. When the crucible is used in an HEM furnace, the outside surface sinters to full density during the meltdown cycle. Therefore, it was felt that the cracks on the inside surface may not be a problem to contain molten silicon as the outside surface will sinter to full density. Such a cracked crucible was used in run 41-15C to cast a 20 kg, 34 cm x 34 cm cross-section ingot. No problems were encountered during the run and a crackfree ingot was cast (Figure 1). The solidification rate achieved was 3 kg/hr; this is attributed to the larger size of the interface during growth.

Another 34 cm x 34 cm size crucible was heat-treated for run 41-16C. Control of heat losses during heat treatment prevented cracking of the crucible. A 40 kg charge was used in this run. During meltdown cycle molten silicon spilled from the crucible and the run was terminated. The bottoms of these large crucibles have a curvature; at high temperatures under a heavy load the crucibles deform and crack to spill silicon. A graphite plate with a curvature similar to the bottom of the crucible has been fabricated to support the crucible.

The bottom of the HEM furnace has been designed so that after spilling a 40 kg load of silicon, such as occurred during run 41-16C, the furnace can be brought into operation with minimum down time and replacement of parts.

Figure 1. A view of the 34 cm x 34 cm cross-section ingot weighing 20 kg cast in run 41-15C

In run 41-20C a 45 kg charge was used in a 34 cm x 34 cm size crucible. During the cycle a small crack occurred in a corner of the crucible just below the melt surface; consequently, some silicon dripped during the solidification period. The rest of the melt solidified as a 26 kg ingot. This is shown in Figure 2. More experiments are planned to cast such large ingots and prevent crack formation in the crucible.

Square Shape

It was reported previously¹ that a graphite box can be used as a rigid retainer to support the crucible. By this technique it was demonstrated that square shape ingots with sharp corners can be made in the crucibles fabricated by welding flat plates. An experiment, run 41-13C, was carried out to see if a molded crucible with rounded corners would deform at high temperatures to conform to the shape of the retainer. A 20 cm x 20 cm ingot was cast using a graphite box as a rigid retainer. Figure 3 shows the cast ingot. It can be seen that the sides of the ingot are flat; the corners, however, are still rounded. A significant improvement was not achieved when the melt was superheated to a higher temperature (run 41-14C).

Improvement of Crystallinity

Even though nearly single crystal structure has been

Figure 2. A view of the 34 x 34 cm cross-section ingot weighing 26 kg cast in Run 41-20C.

Figure 3. A view from the bottom of the ingot cast in a molded crucible using a rigid graphite box retainer (run 41-13C)

achieved in HEM cast ingots, the crystallinity breakdown is usually at the bottom of the ingot towards the periphery. In this area solidification initiates from the bottom of the crucible rather than off the solid-liquid interface. This is associated with heat flow conditions. The problem is compounded because the silica crucible does not have much strength at high temperatures and it is necessary to support the bottom with a graphite plate. The thermal conductivity of the support plate has a substantial influence on the gradient across the bottom of the crucible. This creates low temperatures in the bottom area; consequently rapid initial growth occurs from the crucible bottom rather than off the seed. This results in large grain formation in these areas. By changing the heat exchanger height in the zone, the outside diameter, the insulation around the heat exchanger, and furnace temperature, gradients can be controlled to grow a single crystal across the bottom of the crucible.

In run 41-14C the position of the heat exchanger was changed to increase the temperature at the bottom without changing the furnace temperature. No significant change was found in the crystallinity across the bottom for this condition.

Run 41-17C was the first run after the furnace was rebuilt following a spill of 40 kg silicon. In this run a crucible fabricated by welding flat plates was used. During the melt-down cycle silicon melt reacted with the graphite plug and the charge was spilled into the bottom of the furnace.

Examination of the crucible showed that the integrity of the welded joints was retained. The new graphite pieces and insulation put in the furnace prior to this run had changed the thermal profile so that the actual temperature of the melt was significantly higher than indicated by the instrumentation. This was confirmed in the following experiment.

In run 41-18C the heat exchanger was insulated by using a longer graphite plug. Thus radiation from the bottom graphite plate to the lower temperature heat exchanger was prevented. However, no significant improvement in crystallinity across the bottom was achieved.

In run 41-19C the melt was superheated to a higher temperature. It was felt that the high initial melt temperature would prevent the spurious nucleation from the bottom of the crucible. Figure 4 shows the crystallinity achieved. No significant improvement in crystallinity is evident.

Figure 4. Polished and etched cross-section of ingot 41-19C

MULTI-WIRE SLICING--

FIXED ABRASIVE SLICING TECHNIQUE (FAST)

During the second quarter of Phase IV, efforts in the area of Fixed Abrasive Slicing Technique (FAST) were concentrated on blade development. Significant progress was achieved. So far diamonds have been fixed in the cutting edge only in impregnated wires. It has now been demonstrated that this is achievable in electroplated wires as well. This feature combines the advantages of low kerf, high wafer accuracy, low materials costs and ability to use larger size diamonds. Details of the experiments are given in Table II.

Blade Development

Electroplated Wires. The wirepack used in run 413-SX was prepared by electroplating 45 μ m natural diamonds on a 5 mil, 0.124 mm diameter core wire. In the first run, as reported in the last quarterly report,¹ a very good yield (91%) was achieved. In the second run, run 414-SX, the yield was 70%. Examination of the wires under microscope after slicing has shown that the diamonds were still bonded to the wire.

This bladepack was also used for slicing a third 10 cm

TABLE II. SILICON SLICING SUMMARY

RUN	PURPOSE	FEED		AVERAGE		WIRE TYPE	REMARKS
		FORCE/lb.	BLADE/gn	CUTTING mil/min	RATE mm/min		
414-SX	Life test (2nd run)	0.069	31.60	2.0	0.050	5 mil, 0.125 mm diameter W wire. Co-deposited with 45 μ m natural diamond (Same as 413-SX)	70% yield. Diamond still bonded to wire.
415-SX	Life test (3rd run)	0.064	29.31	2.0	0.050	Same as 413-SX	44% yield.
416-SX	Test CSI impregnated wire	0.071	32.05	2.0	0.050	5 mil, 0.125 mm stainless steel core; 1.5 mil, 0.0375 mm copper sheath. 45 μ m diamonds, electroless nickel	53% yield.
417-SX	Test CSI impregnated wire	0.071	32.05	2.0	0.050	Same type as 416-SX	Run aborted after 7 hrs due to excessive blade breakage.
418-SX	Test CSI impregnated wire	0.059	26.96	-	-	Same type as 416-SX	Run was aborted after 4 hrs due to excessive blade breakage.
419-SX	Test CSI impregnated wire	0.073	33.14	3.0	0.075	Same type as 416-SX	55% yield.
420-SX	Test codeposited blade-pack	0.071	32.35	3.4	0.085	5 mil, 0.125 mm wire, co-deposited with 45, 30, 15 μ m diamonds	89% yield.
421-SX	Life test	0.071	32.55	2.7	0.067	Same as 420-SX	37% yield. Wire wander was observed.

(cont.)

TABLE II. SILICON SLICING SUMMARY

(cont.)

RUN	PURPOSE	FEED		AVERAGE		WIRE TYPE	REMARKS
		FORCE/BLADE lb	gm	CUTTING RATE mil/min	mm/min		
422-SX	Test CSI im- pregnated wire	0.071	32.35	2.0	0.05	5 mil, 0.125 mm stainless steel core; 1.5 mil, 0.037 mm copper sheath, 60 μ m diamonds, electroless nickel	Run aborted due to diamond pullout.
423-SX	Test CSI im- pregnated wire	-	-	-	-	5 mil, 0.125 mm stainless steel core; 1.5 mil, 0.0375 mm copper sheath, 45 μ m diamonds, electroless nickel	Run aborted as the diamonds were buried in the plating.
424-SX	Test CSI im- pregnated wire	0.070	31.97	2.7	0.067	Same as above except 45/60 μ m diamonds	64% yield.
425-SX	Test CSI im- pregnated wire	-	-	-	-	Same type as 423-SX	Run aborted due to diamond pullout.
426-SX	Test codepos- ited bladepack	0.071	32.35	3.0	0.075	Same type as 420-SX.	53% yield. Poor yield due to insufficient clearance of wires.
427-SX	Test CSI im- pregnated wire	0.071	32.55	1.7	0.042	Same type as 423-SX	43% yield. Wire wander was observed.
428-SX	Test CSI impreg- nated wire	0.046	21.06	2.7	0.067	5 mil, 0.125 mm stainless steel core; 1.0 mil, 0.0250 mm cu sheath, 45 μ m diamonds, electroless nickel plating.	Run aborted due to diamond pullout.

diameter ingot (run 415-SX). In this run, however, yield dropped to 44%. It was found that some of the breakage of wafers was not associated with wire wander, but with vibration problems in the present slicer.

SEM photographs were taken of wires located in different areas of a blade pack. Figure 5 shows a diamond electroplated wire from one side of the blade pack used in three runs, 413-SX through 415-SX. Diamonds are visible on only one side of the wire. Figures 6(a) and 6(b) are taken from the middle and the other edge of the wire pack, respectively. All of the wires show good diamond distributions. However, concentration of diamonds is higher in the middle section of the wire pack.

Under similar experimental conditions the electroplated wires have shown better performance than impregnated wires. This has been evident from slicing rates and wire life. Diamond electroplating technology, even though not practiced on wires, has been in production for a long time, for example, on I.D. blades. In comparison, the impregnated blades have been studied systematically for only one year.

One of the problems encountered so far was that the electroplated layer wrapped around the circumference of the wire. These wires do not seat well in grooved support rollers. Therefore, the wires are not guided accurately and the rollers are degraded.

The impregnated blades, on the other hand, had diamonds

(a)

(b)

Figure 5. SEM pictures of a wire used in runs 413-SX through 415-SX showing diamonds electroplated only on one side (300X). View (b) shows wire rotated 120° from view (a).

(a)

(b)

Figure 6. SEM picture of wires taken from different locations of the blade pack used in runs 413-SX through 415-SX: (a) from the middle; (b) from the right side

only in the bottom, whereas the central wires had abrasive over the entire circumference. Figure 7 shows three views of an unused wire from the side with diamonds in the cutting edge only. This wirepack was used in run 420-SX (Table II). During the run high cutting rates were achieved and slicing yield was 89%. SEM examination of the wire after this experiment shows that there appears to be no diamond pullout (Figure 8).

The second slicing test (run 421-SX) used the same wirepack and high cutting rates were maintained. However, the slicing yields were lower. It was found that wafer breakage was significantly greater in the central area of the workpiece where the diamonds were electroplated over the entire circumference of the wires. Examination of a wire in this area (Figure 9) showed that diamond pullout was not the problem. During slicing of the second ingot, breakage occurred in the area where the wires had electroplated diamonds over the entire circumference.

The improved performance of wires with diamond only on the bottom may be due to better seating of the wires in the support rollers or to the fact that the wire cannot cut laterally because it does not have diamonds on the sides.

Another concept adapted in this wirepack was to use a mix of diamond sizes. The slicing diamonds were predominately 45 μm size; the smaller sizes acted as fillers between the 45 μm diamonds. This prevented the nickel matrix from eroding during

Figure 7 . SEM photograph of unused wire at 120° rotation of wire. Wire was used in run 420-SX.

Figure 8. SEM photographs of a wire after first slicing test (Run 420-SX)

Figure 9. SEM photographs of a wire after second run (421-SX). This wire has diamond electroplated over the entire circumference.

the slicing tests. It has been seen that the major failure mechanism of wires--diamond pullout--has been essentially eliminated. Even after slicing two 10 cm diameter ingots, no diamond pull-out was seen (Figure 10).

A wirepack was prepared in which diamonds were electroplated over less than half the circumference of the wires. This wirepack was used in run 426-SX. Early breakage of wires was observed which accounts for the low yield, 53%. Even though blade wander was not apparent during slicing, the crystal vibrations were felt. Figure 11 shows three views of a wire rotated 120 degrees between photographs. It can be seen that there were insufficient diamonds on the wire for clearance which resulted in binding, abrasion and transmission of vibrations to the workpiece.

Impregnated Wires. For impregnation it was felt that the application of diamonds prior to impregnation was critical in achieving good concentration and uniform distribution of diamonds. Some of the variables studied were viscosity of suspension medium, concentration of diamonds, and pressure and time during spreading of the slurry. It was found that even these variables are interactive, e.g., when the viscosity was high, the diamond concentration had to be increased. With high concentration the pressure and time had to be increased accordingly. Once the diamonds were applied to the wires, they were impregnated under pressure. When

Figure 10. SEM photographs of wires after second run (421-SX) taken from different locations of wirepack.

Figure 11. SEM photographs of wire used in run 426-SX (300X)

the diamond application resulted in low concentration, very good impregnation was achieved; a higher concentration after application resulted in poor impregnation. This may be due to the fact that the pressure is transmitted over more diamonds and therefore the effective pressure on each diamond is reduced. Consequently, the diamonds are not pushed into the copper sheath. Further, the soft copper sheath is deformed, reducing the hold on the diamonds. The application and impregnation was also attempted in a single step operation, as was building up of concentration in a number of application-impregnation steps. Optimization over a number of experimental conditions led to satisfactorily impregnated wirepacks which were electroless nickel plated and tested on the high speed slicer.

During the current period some of the variables changed were the thickness of copper sheath, diamond size and the electroless nickel plating.

In run 416-SX a 10 cm diameter ingot was sliced with an average cutting rate of 2.0 mils/min, 0.050 mm/min. Good diamond impregnation was achieved in this wirepack; however, the concentration was non-uniform.

In runs 417-SX and 418-SX wire breakage occurred. Even though the diamond concentration was good, the diamonds were not impregnated deep into the copper sheath and were lost during plating. Because of diamond loss, the wires were rubbing across the workpiece during slicing leading to wire breakage. This

also resulted in wire breakage in run 428-SX, where a thin copper sheath, 1.0 mil, was used.

In run 419-SX a higher concentration combined with impregnation improved the cutting rate to 3.0 mils/min, 0.075 mm/min.

In order to identify whether diamond concentration is reduced because of severity of cleaning prior to nickel plating, wire samples were taken during each cleaning step. These samples were examined by SEM and are shown in Figure 12. Close examination of Figures 12(a) through 12(d) show that not an appreciable amount of diamond is lost during cleaning for good impregnation.

Run 422-SX was carried out using a 60 μ m diamond impregnated wirepack. Figure 13(a) and 13(b) show an unused and used wire, respectively. Considerable diamond pullout is seen, as the nickel plating was not sufficient to hold the diamonds.

Comparison of wires impregnated with different sizes of diamonds is shown in Figure 14. Wires impregnated with 45 μ m diamonds are shown in Figure 14(a), and 60 μ m size in Figure 14(b). Figure 14(a) shows that a higher and more uniform diamond concentration can be found in 45 μ m size. From the photographs it is not possible to see the depth of impregnation. Slicing experiments indicate that diamond pullout mostly occurred with 60 μ m size diamonds. On the other hand, nickel thickness had to be carefully controlled when smaller size diamonds were used. For example, in run 423-SX, an excessive amount of nickel

Figure 12. The effect of the cleaning baths before electroless plating: (a) first cleaning bath; (b) second cleaning bath; (c) third cleaning bath; (d) fourth cleaning bath

(a)

(b)

Figure 13. SEM photographs of impregnated wires (a) new and (b) used from run 422-SX.

(a)

(b)

Figure 14. Impregnated wires with different sizes of diamonds: (a) 45 μm diamond; (b) 60 μm diamond

plating buried the 45 μm diamonds; hence, the run was aborted. SEM examination of a wire confirms this result (Figure 15). In contrast, in run 425-SX, the small amount of nickel plating was not sufficient to hold the diamonds in their site.

Since diamond pullout in electroplated wires can be prevented by using filler diamonds, a similar approach was tried for impregnated wirepacks. With 45 μm diamonds used as abrasive, anything smaller in size would be buried completely in the copper sheath; hence only larger diamonds can be co-impregnated. For run 424-SX a mixture of 45 μm and 60 μm diamonds was used. Good cutting rates were achieved, but the yields were not very high. The low yields are attributed to non-uniformity of impregnated wirepacks.

Figure 15. SEM photograph of impregnated wire with plating burying the diamonds

ECONOMIC ANALYSIS

The economic analysis has been carried out to estimate the add-on cost of converting solar grade silicon meltstock into sheet by using the Heat Exchanger Method (HEM) of crystal casting and Fixed Abrasive Slicing Technique (FAST) of slicing. It is assumed that production will be carried out in 1986 on a large scale so that economies of scale will be effective.

It is intended to cast 30 cm x 30 cm x 30 cm ingots, section with a band saw into nine 30 cm x 10 cm x 10 cm bars and slice the bars into 10 cm square wafers.

Two types of analyses have been made using conservative and optimistic estimates of projections for 1986. The price calculations are based on 1980 dollars and use the IPEG equation:

$$\text{Price} = \{(0.49 \times \text{EQPT}) + (135.8 \times \text{SQFT}) + (2.1 \times \text{SLAB}) + (1.3 \times \text{MATS}) + (1.3 \times \text{UTIL})\} / \text{QUANTITY}$$

where

EQPT = total equipment costs

SQFT = working area in square feet

SLAB = direct labor costs

MATS = direct materials costs

UTIL = utilities costs

HEM Casting

It is intended to cast 30 cm x 30 cm x 30 cm ingots by HEM. The assumptions and projected add-on costs are given in Table III.

TABLE III. IPEG Analysis for Value Added Costs of HEM Casting Using Conservative and Optimistic Projections of Technology

	Estimate	
	Conservative	Optimistic
Ingot size	30 x 30 x 30cm	30 x 30 x 30cm
Equipment cost, \$	35,000	35,000
Floor space, sq.ft.	60	60
Labor, units/operator	10	10
Cycle time, hrs	72	48
Duty cycle, %	90	95
Material utilization, %	85	95
Expendables/run, \$	200	135
Average kw for cycle time	15	10
Add-on Price, \$/kg	10.66	6.73

FAST Slicing

It is intended to use a double-headed slicer so that two bladeheads will be used per run and two bars (30 cm x 10 cm x 10 cm) will be sliced simultaneously.

TABLE IV. IPEG Analysis for Value Added Costs
of FAST Slicing Using Conservative
and Optimistic Projections of Technology

	Estimate	
	Conservative	Optimistic
Equipment cost, \$	30,000	30,000
Floor space, sq.ft.	80	80
Labor, units/operator	5	10
Duty cycle, %	90	95
Set-up time, hrs	1.5	1.0
Slicing rate, mm/min	0.1	0.14
Slices/cm	22	25
Slices/wire	5	10
Yield	90	95
Expendables/run, \$	28	14
Motor power, h.p.	5	3
Conversion ratio, m ² /kg	0.85	1.0
Add-on Price, \$/m ²	13.13	5.9

Band Saw Sectioning

The 30 cm x 30 cm x 30 cm ingot cast by HEM has to be sectioned into nine 30 cm x 10 cm x 10 cm bars by a band saw using the following parameters:

Equipment cost, \$	20,000
Floor space, sq.ft.	80
Labor, units/operator	1
Cycle time, hrs/boule	4

Duty cycle, %	95
Motor power, h.p.	3
Expendables/boule, \$	5

The add-on price for sectioning is \$1.17/kg.

Results

The add-on price of HEM casting, sectioning and FAST slicing is summarized in Table V.

Table V. Value Added Costs of Sheet Formation
Using HEM and FAST Technologies

	Estimate	
	Conservative	Optimistic
HEM casting, \$/kg	10.66	6.73
Sectioning, \$/kg	1.17	1.17
FAST slicing, \$/m ²	13.13	5.59
Conversion ratio, m ² /kg	0.85	1.0
Meltstock-Sheet conversion, \$/m ²	27.05	13.49
\$/w	0.191	0.095
Meltstock-Sheet add-on goal, \$/m ²	36.3	36.3
\$/w	0.256	0.256

Assuming that all the other tasks meet the allocated goals,² (e.g., silicon meltstock is available for \$14/kg, cell fabrication is \$21/m², etc.), the effect of the conservative and optimistic

estimates of sheet conversion on the total cost of photovoltaic power will be as shown in Table VI.

Table VI. Strawman of HEM/FAST Sheet Fabrication for 1986 PV Power

	Estimate	
	Conservative	Optimistic
Silicon, \$/w	0.126	0.107
Sheet, \$/w	0.191	0.095
Cells, \$/w	0.141	0.141
Encapsulation materials, \$/w	0.098	0.098
Module, \$/w	0.098	0.098
Total, \$/w	0.654	0.539

SUMMARY

1. The first 34 cm x 34 cm cross-section ingot has been cast by HEM.
2. High solidification rates (3 kg/hr) were achieved for a 20 kg ingot and no crucible attachment or ingot cracking occurred. Similar results have also been achieved with a 26 kg, 34 cm x 34 cm ingot.
3. It was found that use of rigid graphite retainers with molded crucibles improved the flatness of the sides of the ingot; however, the corners are still rounded.
4. The loss of single crystallinity in the bottom of the ingots towards the periphery is associated with temperature gradients on the bottom of the crucible.
5. It has been demonstrated that no significant diamond pullout occurs when an electroplated wirepack is used to slice three 10 cm diameter ingots.
6. Some of the poor yields in slicing are associated with wafer breakage because of vibrations in the present slicer.
7. It has been possible to electroplate diamonds onto wires in the cutting edge only.
8. Wires with diamonds in the cutting edge only did not wander and produced high yields.

9. Smaller diamonds used as filler prevented erosion of nickel matrix and thereby minimized diamond pullout.
10. A conservative extension of HEM and FAST sheet technologies gives value added costs of $\$27.05/\text{m}^2$ ($\$0.191/\text{w}$) which fits with the strawman of $\$0.654/\text{w}$ for photovoltaic modules. A similar optimistic extension gives $\$13.49/\text{m}^2$ ($\$0.095/\text{w}$) to give a total cost of $\$0.539/\text{w}$.

REFERENCES

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2. R. W. Aster, "Price Allocation Guidelines, January 1980," DOE/JPL Publication No. 80-51, January 15, 1980.