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# CURRENT ECONOMIC AND SENSITIVITY ANALYSIS FOR I.D. SLICING OF 4" AND 6" DIAMETER SILICON INGOTS FOR PHOTOVOLTAIC APPLICATIONS

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## INTRODUCTION

This paper relates to the economics and sensitivities of slicing large diameter (≥ 4") silicon ingots for photovoltaic applications.

In order to arrive at economics which directly relate to the current low cost solar array activity, SAMICS costing methods were utilized. All economics are projected in 1980 dollars.

Currently, the manufacture of 6 inch diameter silicon ingots by the Czochralski process is a contract requirement of the LSA project. Ingot diameter does not present any technological problems to the CZ growth process. Indeed, diameters of up to 8 inches are considered feasible. However, it is considered that the slicing of silicon ingots in excess of 5 inch diameter at the required thickness and yield (25 slices/cm or 63 slices/inch) using current I.D. slicing techniques is unproven.

The current LSA slicing cost goals assume that 1 kg of silicon ingot will produce 1 meter$^2$ of wafer area. Failure to achieve this goal negates the assumption and thus will directly impact on the ingot add-on cost.

Kayex inhouse wafering of 6 inch diameter CZ ingot for solar cell fabrication indicated that the slicing of nominally 0.020 inch wafers was possible. It should be noted that the amount of wafering undertaken was minimal. In a photovoltaic manufacturing environment, only one slicing specification would be required. Standard semiconductor materials operations, although slicing to more difficult specifications, have the potential of utilizing the blade more adequately by progressively slicing less demanding specifications, e.g. smaller diameters, thicker wafers, etc.

Current economics and slicing add-on cost sensitivities have been calculated using variable parameters for blade life, slicing yield and slice cutting speed. All five standard SAMICS categories were calculated assuming fixed parameters.

It is considered that large diameter (>5") silicon ingot slicing by I.D. blade techniques for P.V. applications is still in a development stage. As such, the factors most likely to directly influence slicing add-on costs were chosen as the variables. It is appreciated that the standard SAMICS categories could also be calculated on a variable basis and directly affect slicing add-on costs, but to a lesser degree.

Data generated using the previously described variables indicate that cutting speed has the biggest impact on slicing add-on cost. This is followed by slicing yield and, to a lesser degree, by blade life as the blade life increases.

## DATA INPUT

Only a minimal amount of I.D. slicing of large diameter (nom. 6") silicon ingots was performed at the Kayex Corporation. The slices were used for conversion into solar cells. Approximately 10 slices were produced per ingot. Based on this work, routinely achieveable parameters were determined, e.g. slice thickness plus kerf of 0.034" (11.6 slices)/cm or 29.4 slices/inch).

Additionally, various I.D. slicing reports were analyzed to more fully determine the current "state of the art", such that projected techniques and related costs could be arrived at.

A DOE/JPL 1978 final report[1] by H.I. Yoo of Applied Solar Energy Corp. was used as a reference to simulate SAMICS FORMAT A to develop cycle times, projected labor and material costs for the I.D. slicing of 6 inch diameter silicon ingots.

A further DOE/JPL 1980 report[2] by M.H. Leipold, C. Radics and A. Kachare of JPL was used as a comparison to better qualify present day manufacturing capabilities and future projections.

## SAMPLE SAMICS ANALYSIS

Analyses were performed to realistically develop the cost of slicing of large diameter ingots in \$ per $m^2$ as a function of wafer diameter and wafer yield The approach differed from the Leipold et.al. wafering cost analyses, in that a total production quantity (wafer area) was not utilized as the starting point.

Determination of slicing cycle time was the initial parameter developed. The cycle times for the slicing of 4 inch and 6 inch diameter wafers is illustrated in FIG. 1 and FIG. 2.

Actual SAMICS cost analyses were performed for both 4 inch and 6 inch diameter silicon ingot slicing using the standard IPEG price equation. The 4 inch diameter costs generated are felt to be a reasonable approximation of present manufacturing achievements. The 6 inch diameter costs generated represent a projection of the cost of slicing using current "state of the art" techniques.

FIG. 3 shows an example of the SAMICS cost analysis for slicing of 6 inch diameter ingot. This example arbitrarily assumes a cutting speed of 1 inch/minute, a blade life of 1500 slices/blade, and a wafer yield of 75%. A series

**SLICING OF 4" WAFERS**

A. **Description of Slicing**

1. A Continuous Process

   Cut Rate: Two (2) inches/minute
   Wafer Yield: 94%

2. Average Slicing Cycle per Wafer

| | |
|---|---|
| Slicing Time: | 2.500 minutes |
| Machine Down Time: | 0.057 minutes |
| Total | 2.557 minutes/wafer |

3. Wafers per Operating Minute:

$$\frac{1}{2.500} = 0.4 \text{ wafer/operating minute}$$

4. Process Usage Time Fraction:

$$\frac{2.5}{2.557} = 0.978$$

FIG. 1

**SLICING OF 6" WAFERS**

A. **Description of the Slicing**

1. A Continuous Process

   Cut Rate: Two (2) inches/minute
   Wafer Yield: ~75%

2. Average Slicing Cycle per Wafer: 3.6 minutes

| | |
|---|---|
| Slicing Time: | ~3.5 minutes |
| Machine Down Time: | ~0.1 minutes |
| Total | ~3.6 minutes/wafer |

3. Wafers per Operating Minute:

$$\frac{1}{3.5} \cong 0.286 \text{ wafer/operating minute}$$

4. Process Usage Time Fraction:

$$\frac{3.5}{3.6} = 97.2\%$$

FIG. 2

**SAMICS ANALYSIS**
(Slicing of 6 Inch Diameter Silicon Ingots)

Process Parameters:

Cutting Speed - 1 inch/minute

Blade Life - 1500 slices/blade

Wafer Yield - 75%

| | | | |
|---|---|---|---|
| Equipment | C1 | \$57,322; 7 yr life x \$0.54/yr | \$ 30,954.00 |
| Space | C2 | 55 sq ft/saw x \$110.61/sq ft | 6,083.55 |
| Direct Labor | C3 | \$2.14/yr factor \$10,692 + \$78.19 = \$10,770.19 | 23,048.21 |
| | | (Operator's yearly salary = \$10.492; 3 operators for one 24 hr day/1 operator for 3 saws) | |
| | | Maintenance Mechanic II \$15,576 yearly salary | |
| | | Time required 50 minutes/cycle x 49.84 cycles/yr = 41.53 hrs/yr/saw | |
| Direct Mats | C4 | \$1.23/yr | 8,309.14 |
| | | 49.84 blades/yr x \$110/blade = \$5,482.40 + 1,273 = \$6,755.40 | |
| Utilities | C5 | \$1,350 x 1.23/yr | 1,660.50 |
| | | | \$ 70,055.40 |

It costs approximately \$70,055.40/yr to produce 56,070 good wafers.

Therefore, add on cost = \$1.25/wafer or \$70.74/$m^2$

FIG. 3

**Batch Cycle Times - ID Slicing of 6" Diameter Silicon Ingots**

Process Parameters:

Cutting Speed - 1 inch per minute

Blade Life - 1500 wafers/blade

Wafer Yield - 75%

| | |
|---|---|
| Total Slicing Time per Wafer = 6.6 minutes | |
| Therefore, one batch of 1500 wafers requires | 9900 minutes or 165 hrs |
| Add machine down time per blade | 67 minutes |
| Total Batch Cycle Time | 9967 minutes or 166.12 hrs |

Total hours available per year = 345 days x 24 hrs = 8280 hrs x 60 = 496,800 minutes
Therefore, Total Cycles per Year = 49.84

Total Wafers Cut per Year = 74,760 x 75% yield = 56,070 good wafers

Total $m^2$ of good wafers per year - 1 wafer (150 mm) = 0.0176625 $m^2$/wafer x 56,070 wafers = 990.34 $m^2$ production capability per year

FIG. 4

of calculations were then made by varying these three parameters. This was done to measure the sensitivity of the parameters on add-on cost.

For the purpose of calculation, the following three SAMICS parameters were held constant:

a) Equipment (C1) at $57,322
b) Space (C2) at 55 sq.ft.
c) Utilities (C5) at $1,350 per year.

Direct labor and direct materials were varied only to allow for varying blade life.

Since batch cycle times are directly influenced by blade life, a series of calculations were made to determine these relationships. An example of batch cycle time related to a specific blade life is illustrated in FIG. 4, together with total cycles per year, total wafers cut per year, total wafers produced after the wafer yield factor is applied and the conversion of good wafers produced into total surface area ($m^2$).

## ADD-ON SENSITIVITY ANALYSIS

As a result of the calculations made during the SAMICS cost analysis, the effects on the ingot slicing add-on costs as a result of varying the blade life, slice yield, and cutting speed factors are illustrated in Tables 1, 2, and 3. The overall sensitivities are also expressed graphically in FIG. 5 and FIG. 6.

The intent of the data generated is not to produce a specific silicon ingot slicing add-on cost, but rather to illustrate the effects of varying specific process parameters as they relate to slicing add-on cost per wafer and to the slicing add-on cost per meter$^2$.

It is realized that variation of some of the SAMICS factors that were held constant could also obviously affect the slicing add-on costs. Indeed, a calculation was made showing the effect of utilizing 1 operator for 10 saws. An add-on cost reduction, in terms of dollars per meter$^2$, of 23% can be achieved as illustrated in FIG. 7.

## COMPARISON OF 4" AND 6" DIAMETER SLICING ADD-ON COST

Defined process parameters were used to calculate the add-on costs for both 4" and 6" diameter wafers as follows:

- Slice yield of 94%
- Blade life of 1500 slices per blade
- Cutting speeds of 2"/min. and 3"/min. respectively.

The completed slicing add-on costs in both cost per wafer and cost per meter$^2$ for the slicing of both 4" and 6" diameter ingots are illustrated in FIGS. 8 through 11.

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TABLE 1

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 1 INCH/MINUTE)

| CUTTING SPEED (INCHES/MIN) | BLADE LIFE (SLICES/BLADE) | WAFER YIELD (%) | ADD ON COST $/M$^2$ | ADD ON COST $/WAFER |
|---|---|---|---|---|
| 1.0 | 250 | 75 | 107.78 | 1.90 |
| | 500 | | 85.55 | 1.51 |
| | 750 | | 78.14 | 1.38 |
| | 1,000 | | 74.43 | 1.29 |
| | 1,500 | | 70.74 | 1.25 |
| | 2,000 | | 68.88 | 1.22 |
| 1.0 | 250 | 85 | 95.09 | 1.68 |
| | 500 | | 75.48 | 1.33 |
| | 750 | | 68.95 | 1.22 |
| | 1,000 | | 65.68 | 1.14 |
| | 1,500 | | 62.42 | 1.10 |
| | 2,000 | | 60.77 | 1.07 |
| 1.0 | 250 | 95 | 85.08 | 1.50 |
| | 500 | | 67.54 | 1.19 |
| | 750 | | 61.69 | 1.09 |
| | 1,000 | | 58.76 | 1.02 |
| | 1,500 | | 55.85 | 0.986 |
| | 2,000 | | 54.37 | 0.96 |

TABLE 2

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 2 INCHES/MINUTE)

| CUTTING SPEED (INCHES/MIN) | BLADE LIFE (SLICES/BLADE) | WAFER YIELD (%) | ADD ON COST $/M$^2$ | ADD ON COST $/WAFER |
|---|---|---|---|---|
| 2.0 | 250 | 75 | 78.98 | 1.39 |
| | 500 | | 56.76 | 1.00 |
| | 750 | | 49.52 | 0.87 |
| | 1,000 | | 45.65 | 0.81 |
| | 1,500 | | 41.95 | 0.74 |
| | 2,000 | | 40.10 | 0.71 |
| | 3,000 | | 38.24 | 0.675 |
| | 4,000 | | 37.32 | 0.659 |
| 2.0 | 250 | 85 | 69.69 | 1.23 |
| | 500 | | 50.08 | 0.88 |
| | 750 | | 43.69 | 0.77 |
| | 1,000 | | 40.28 | 0.71 |
| | 1,500 | | 37.01 | 0.65 |
| | 2,000 | | 35.39 | 0.62 |
| | 3,000 | | 33.74 | 0.596 |
| | 4,000 | | 32.93 | 0.58 |
| 2.0 | 250 | 95 | 62.35 | 1.10 |
| | 500 | | 44.81 | 0.75 |
| | 750 | | 39.10 | 0.69 |
| | 1,000 | | 36.04 | 0.64 |
| | 1,500 | | 34.12 | 0.58 |
| | 2,000 | | 31.66 | 0.56 |
| | 3,000 | | 30.19 | 0.53 |
| | 4,000 | | 29.46 | 0.52 |

TABLE 3

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 3 INCHES/MINUTE)

| CUTTING SPEED (INCHES/MIN) | BLADE LIFE (SLICES/BLADE) | WAFER YIELD (%) | ADD ON COST $/M$^2$ | ADD ON COST $/WAFER |
|---|---|---|---|---|
| 3.0 | 3,000 | 75 | 28.66 | 0.506 |
| | 4,000 | | 27.73 | 0.49 |
| 3.0 | 3,000 | 85 | 25.29 | 0.447 |
| | 4,000 | | 24.46 | 0.432 |
| 3.0 | 3,000 | 95 | 22.62 | 0.40 |
| | 4,000 | | 21.89 | 0.387 |

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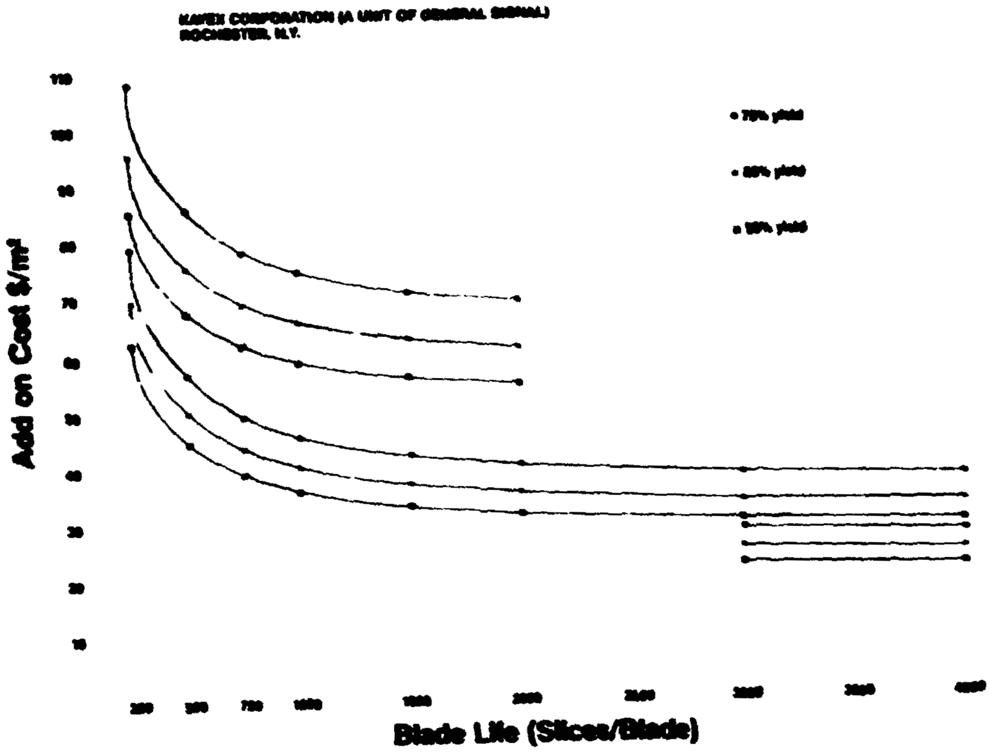


Fig. 5 Sensitivity Analysis of Add on Cost for I.D. Wafering of 6" Diameter Silicon Ingots

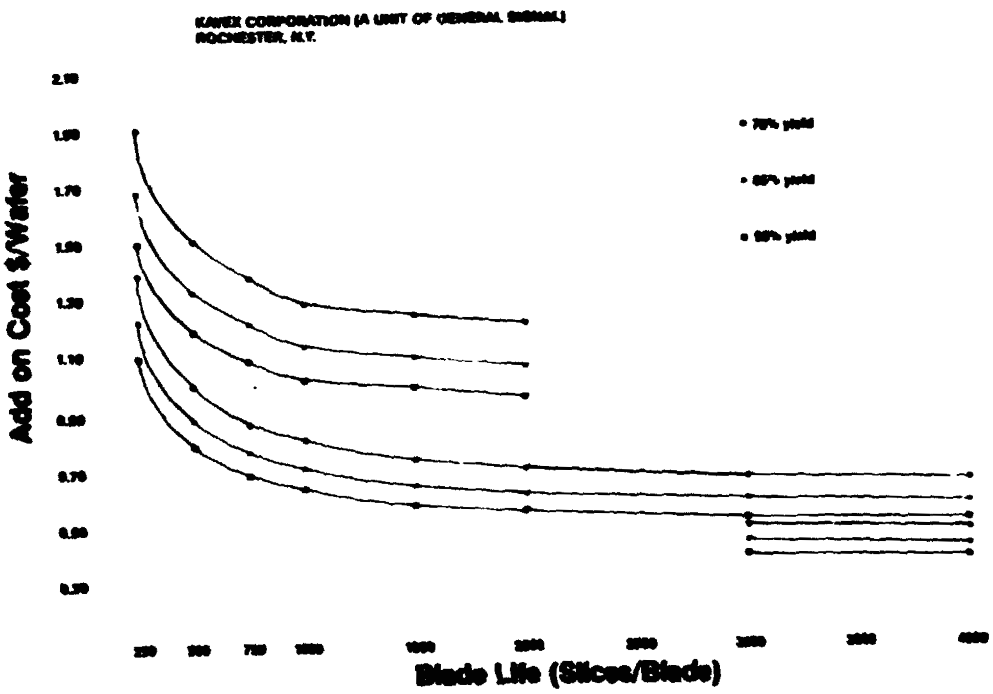


Fig. 6 Add on Cost in $/wafer for ID Wafering of 6" Diameter Silicon Ingots

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LABOR VARIATION COMPARISON (PARAMETER C3)

(1 Operator for 10 ID Saws)

Direct Labor change from one operator for three (3) saws to one operator for ten (10) saws

| Cutting Speed (in/min) | Blade Life (Slices/Blade) | Wafer Yield % | Add on Cost/m$^2$ (1 op/3 saws) | Add on cost/m$^2$ (1 op/10 saws) | % Reduction |
|---|---|---|---|---|---|
| 3 | 4000 | 75 | 27.73 | 21.36 | 23 |
| | | 85 | 24.46 | 18.87 | 22.9 |
| | | 95 | 21.89 | 16.89 | 22.8 |
| 1 | 1500 | 75 | 70.74 | 54.57 | 22.9 |
| | | 85 | 62.42 | 48.15 | 22.9 |
| | | 95 | 55.85 | 43.08 | 22.9 |

FIG. 7

SAMICS ANALYSIS

(Production Slicing of 4" Dia Si Ingots)

Cutting Speed = 2"/min

1500 slices/blade (94% yield)

| | | |
|---|---|---|
| Equipment | C1 = $0.54/yr ($57,322) | = $ 30,954.00 |
| Space | C2 = $110.61/sq ft (55 sq ft) | = 6,083.55 |
| Direct Labor | C3 = $2.14/yr (1.0 op for 4 m/cs = $8019/m/c) + $212.6 | = 17,615.67 |
| Direct Mats | C4 = $1.23/yr 130.33 blades/yr x $110 + 1273 = $15,609.3 | = 19,199.44 |
| Utilities | C5 = $1.23/yr Approx $1350 | = 1,660.50 |
| | Total | = $ 75,513.11 |

It costs $75,513.11 to produce 183,765 good wafers/mc/yr

Therefore, add on cost = $0.41/wafer or $50.54/m$^2$

FIG. 8

SAMICS ANALYSIS

(Production Slicing of 4" Dia Si Ingots)

Cutting Speed = 3"/min

1500 slices/blade (94% yield)

| | | |
|---|---|---|
| Equipment | C1 = $0.54/yr ($57,322) | = $ 30,954.00 |
| Space | C2 = $110.61/sq ft (55 sq ft) | = 6,083.55 |
| Direct Labor | C3 = $2.14/yr (1.0 op for 4 m/cs = $8019/m/c + $287.07 | = 17,774.99 |
| Direct Mats | C4 = $1.23/yr 176.05 blades/yr x $110/blade + 1273 = $ 20,638.5 | = 25,385.36 |
| Utilities | C5 = $1.23/yr Approx $1350 | 1,660.50 |
| | Total | = $ 81,858.40 |

It costs $81,858.40 to produce 248,230.5 good wafers/machine/yr

Therefore, add on cost = $0.33/wafer or $40.50/m$^2$

FIG. 9

SAMICS ANALYSIS

(Production Slicing of 6" Dia Si Ingots)

Cutting Speed = 2"/min

1500 slices/blade (94% yield)

| | | |
|---|---|---|
| Equipment | C1 = $0.54/yr ($57,322) | = $30,954.00 |
| Space | C2 = $110.61/sq ft (55 sq ft) | = 6,083.55 |
| Direct Labor | C3 = $2.14/yr (1.0 op. for 3 m/cs = $10,692/m/c) + $162.52 | = 23,185.87 |
| Direct Mats | C4 = $1.23/yr 90.87 blades/yr x $110/blade + $1273 = $ 11,268.7 | = 13,860.50 |
| Utilities | C5 = $1.23/yr Approx $1350 | = 1,660.50 |
| | Total | = $75,744.42 |

It costs $75,444.12 to produce 128,126.7 good wafers/machine/yr

Therefore, add on cost = $0.59/wafer or $33.34/m$^2$

FIG. 10

SAMICS ANALYSIS

(Production Slicing of 6" Dia Silicon Ingots)

Cutting Speed = 3"/min

1500 slices/blade (94% yield)

| | | |
|---|---|---|
| Equipment | C1 = $0.54/yr ($57,322) | = $30,954.00 |
| Space | C2 = $110.61/sq ft (55 sq ft) | = 6,083.55 |
| Direct Labor | C3 = $2.14/yr (1.0 op for 3 m/cs = $10,692/m/c) + $196.32 | = 23,30[illegible].01 |
| Direct Mats | C4 = $1.23/yr 125.23 blades/yr x $110/blade = 1273 = $15,048.3 | = 18,509.41 |
| Utilities | C5 = $1.23/yr Approx $1350 | = 1,660.50 |
| | Total | = $80,508.47 |

It costs approximately $80,508.47 to produce 170,574.3 good wafers/machine/yr

Therefore, add on cost = $0.46/wafer or $25.81/m$^2$

FIG. 11

Analysis of the data generated indicates that a lower add-on cost per wafer can be achieved when slicing 4 inch diameter ingot; however, significant reductions can be made to the cost per meter$^2$ when slicing 6" diameter at comparable cutting speeds, yields and blade life.

## CONCLUSIONS

A cost analysis, using the SAMICS FORMAT A indicates various sensitivities that affect slicing costs.

Based on the analysis of the data generated, it is considered that:

1. Cutting speed has the biggest impact on I.D. slicing add-on cost, particularly as blade life is optimized.

2. Slice yield has a significant bearing on I.D. slicing add-on cost, but to a lesser degree than cutting speed.

3. Above 500 slices per blade, blade life has the least impact on I.D. slicing add-on cost.

It is also apparent that potential cost improvements to the slicing add-on cost can be gained as the diameter of the ingot to be sliced is increased. This also impacts on equipment throughput capability.

## REFERENCES


1. H.I. Yoo, Applied Energy Corporation. DOE/JPL Contract No. 954830 Final Report, February 28, 1978.

2. M.H. Leipold, C. Radics, A. Kachare, Jet Propulsion Laboratory. DOE/JPL - 1012-37, February 15, 1980.

3. Jet Propulsion Laboratory. LSSA Project SAMICS Workbook Publication Number 5101-15, September, 1977.

DISCUSSION:

WCLF: Since you didn't include the cost of the lost silicon, I think you came to somewhat the wrong conclusion. I think the yield probably is the more important one, once you include the silicon cost.

ROBERTS: As I say, all of the calculations we did were on slicing add-on cost alone.

WOLF: Right. But I think that by itself can mislead you.

DAUD: In your analysis you had three speeds, 1-inch a minute, 2-inch a minute, and 3-inch a minute. That would roughly take you anywhere from 10 hours to 30 hours for an ingot of 30-centimeter length. What would the operator do? Don't you think the guy would be just sitting there for hours and hours?

ROBERTS: No, not reallv. Somebody has got to mount the ingot, somebody has got to change blades and if you can honestly tell me that that one operator can run 10 saws, can mount his own ingot, can change his own blades, then you have got a pretty damn good guy in there. What we are saying is the blade has to be changed, the time has to be allowed for, and that is why we put it in. How you utilize the operation is up to yourself. We are not specifically saying this guy is only going to be in there changing the blade for 40 hours a year and the remainder of the time he is going to be sitting down. It is a way of getting the time into the analysis.

DAUD: Have you in your analysis ever considered, as it was suggested some time back, cutting more than one ingot at a time?

ROBERTS: I think a lot of people are having a lot of difficulty cutting one ingot at a time. We haven't got an active ID slicing contract ongoing at the moment, these are just projections of how we see the situation. Personally, I'd be somewhat skeptical of ganging of ingots, particularly above 4-inch diameter.

ILES: Could we get the experts to tell us why it is so difficult to gang ID saws? I know the problems in translating, but is it an insuperable job? It would be very nice to get 3 blades running in parallel instead of one.

FARBER: Monsanto holds a patent on slicing more than one slice at once. If you throw a slice it is almost impossible to get it out from the blade. That is basically the disadvantage.

DYER: We have at least three saw manufacturers here. Would they care to comment on this?

BOUJIKIAN: I reiterate what Jeff said. There is no way you can take out a wafer when it breaks between the two blades. There is no way you can get it out of there even if it is a small piece of silicon. Even the slurry between the two blades, when it gets in there, is almost impossible to remove. If you were cutting one wafer it would be all right.

**YOO:** How about making the blades far apart so you can still put the hand down inside and take out the broken wafers?

**AHARONYAN:** I think what Henry said could work out very well in that you would be able to slice and you would have room in there to get rid of coolant and slurry and so on. But, from a machine design point of view, and from some of the things we want to do in terms of controlling the blade, getting optimum loads on the blade, etc., it would be a very difficult thing to do. If one blade is not cutting well the other blade is limited by it. It just becomes a very tough thing to control.

**FARBER:** Did you have a minimum thickness of slice in mind when you did all of your calculations?

**ROBERTS:** Yes, we used a 20 thousandths-slice thickness and 14-thousandths kerf for a total of 34. We kept it constant throughout all of the calculations that we made.

**FARBER:** Do solar-cell manufacturers have anything against the 10-mil, or 11-mil or 100-mil slice?

**ROBERTS:** The question is being able to utilize the materials so that the basic assumption of one kilogram of ingot being equivalent to one square meter is achieved.

**KOLIWAD:** It disappoints me when I hear "no way can it be done." Those of you who have been in the semiconductor industry probably know, in '65, when people proposed growing 3-inch dislocation-free ingots, there were a lot of people in the ECS meeting who said "no way." Today the same people, the same manufacturers, claim that they can produce 6-inch ingots, dislocation-free. I think that like Bill Yerkes was saying, we should attempt to project the technology and look at the various possibilities.

**DYER:** Re the difficulty of getting the broken slice out between the blades: is this a design problem, is it that no one has sat down and designed a solution? Or has someone considered it for a long time and decided that it is just impossible to design something that would stop the saw, force out a piece and get it going again? Or is it just one problem and there are 20 others?

**OSWALD:** It is very difficult to mount one blade and tension it properly and keep it concentric. I don't know how in the world you would do two.

**DYER:** Dr. Yerkes brought up the question of "is it a lubricant, is it a coolant?"

**BOUJIKIAN:** I am not in the lubricant manufacturing business and I don't handle one and I don't recommend one. However, the primary purpose of the lubricant or the coolant additive, as you call it, is to break down the surface tension of the water and to wet the diamond and the grinding action between the diamond and the silicon. The main objective again is to minimize the surface tension. Now that, as everybody knows, is just plain simple detergent that is available in the market. Now obviously simple detergent is not going to work in your operation because you have other defects such as algae forming for which you throw some chlorine in it or some other swimming pool stuff and then you have a rust inhibitor so the blades on the machine don't rust. In some cases they put wax remover in it because you have some epoxy and wax surrounding your ingot. A coolant, really, is nothing but a 50 cents a gallon detergent and some additives in it which you can buy in a swimming-pool supply house, add some rust preventive in it and you have got the best coolant in the market.

DYER: Can we have a comment now from someone who would like to speak from the lubricant industry?

HEIT: I wish to take exception to the last series of remarks. There is of course a necessity to have a surface active agent present in a composition. There is no doubt that a contribution is made by a choice of a suitable surfactant to wet the surface of the work so that you get a good spread of coolant water and you can absorb through that water the energy released in the cutting operation. We incidentally do not bother most of the time to put in an algaecide or a biocide. Most systems are used heavily enough that you don't require the action of a biocide to suppress biological activity. However, if the composition of the additive to the water does not contribute toward a prolongation of the life of the saw, then you have a problem. The batting average of a particular composition with which ACE Lube is associated is high in terms of prolonging the life of a blade. This was measured some time ago by measuring the nickel, not the diamond, that emerges in the effluent. It required a painful accumulation of the runoff from the operation and correlation with the throughput of the water used to cool the blade. We found out that the amount of nickel per run time in hours was on the order of magnitude of micrograms. We had to measure fractions of parts per million of nickel by atomic absorption spectrophotometry. This is a sophisticated effort. I wish to advise that there is more to it than meets the eye about formulating a properly constituted coolant.

DYER: Would you say the liquid going into the saw kerf slot is mainly a lubricant or a surface tension agent or a coolant, or is it all three?

HEIT: One of the things that we developed was choosing a certain anionic phosphorated derivative which adds extreme pressure effects, something that was not mentioned and that you will not get out of a conventional detergent, either [illegible]onic or nonanionic. There is an extreme pressure juncture at which [illegible] the right material is not used, you get a ripping action. The net result of our particular blend is a great prolongation of the life of the blade and a great freeing of the surface of the work from the kind of blemishes I've heard comments on from the floor before.

FRIZELL: I would like to point out to you some of the problems that develop when you don't have the right coolant. We found over years of working with this material that you can get a great decrease in your output and quality of your wafers and in the results of all of your sawing if you don't have the proper coolant-lubricant. We know that yields have gone up tremendously in just changing from one type of coolant to another. They have dropped off dramatically when errors are made in the amount of coolant that is in the water. People forget the importance of this in their operations at times. If you don't keep your mixtures right and you don't keep your rate of flow proper you are going to lose your slices like everything. It is a very important factor and I think it is one that is badly overlooked by almost everyone that does the work in this room today.

DANYLUK: I would like to give a different point of view on the effects of fluids on surfaces. Our opinion is that the effect of lubricants is a chemoabsorption effect, it is an absorption phenomenon that occurs in the cutting process that can drastically affect surface mechanical properties of nonmetals. In fact, this phenomenon has been known for quite a long time, which surprised me when we first starting working this area. We too have had preliminary experimental results that show that there can be significant reductions in surface hardness of silicon with fluid absorption.

LANE: Some time ago we were attempting to cut quartz with ID saws and we concluded that the only coolant lubricant to use was oil. It didn't work with water. Naturally when you have a saw running and you have silicon ingots in the plant you look at silicon too. We did quite a bit of slicing with silicon and the wafers that came off were dramatically different in surface finish. The finish was much smoother. The surface of the wafers was iridescent, suggesting totally different surface characteristics. We were told by our marketing people who were serving the semiconductor industry that what we desired there was an apparently lapped surface and this iridescent colored surface was undesirable, it did not have the right appearance. It looked to us like there was a dramatic difference in the resulting surface and probably in the damage to the wafer but we don't have any data on that.

SALTZMAN: We are sawing quartz; as I told you, we are not in the silicon sawing business per se. These people were actually running that experiment for me and possible other customers and as a result of their success in using oil I purchased one of their machines. Since that time we have gone into a technique that is not even discussed in this meeting. It is called band slicing. We have band saws with very low kerfs that are sawing large cross sections up to 9 inches square using Greenlee Diamond blades (a Division of DoAll). We had never been successful with this sawing process until we switched to 100% oil. We now end up with a very long blade life, sawing hours of somewhere between 300 and 400 hours. So my comment is yes, coolants are very important. Coolants are just as important to the process as the blades themselves and the machine. They are very highly interrelated and must be taken into consideration.

KOUNDAKJIAN: I manufacture ID blades. Most of our experimental runs are probably 12 or 20 pieces. We really would like to get some cooperation from the users. When we sell any blades we don't get the full information on what's the problem they have. Whether it's the coolant, or the tensioning, or this or that, because we are not in the slicing business. If we have to improve ID blades we'd really like to cooperate with the slicer. Mostly they blame the problem on the blade. We could try softer-bound, harder-bound, different things, but we are scared to send any blades that are new. If they don't work out we could cut out our business. Actually, if we have the full cooperation of the slicing department, we think we could improve this ID blade life. We could do it with nickel. Probably we could do it with other plating, but we never had the chance to get real cooperation, to have some real manufacturer willing to test the blades six months or a year.

DYER: How do you view the main influence of the fluid as it comes in?

KOUNDAKJIAN: If you want the truth, we get it from here and there and that is the whole thing. We don't have it really pointed out which lubrication works well. We know somehow certain lubrication helps in clearing out the nickel but we don't have full information from the slicers in it.

DYER: For those who don't know, I point out the fact that in an ID saw, the water can come in anywhere you want it, but generally you use one stream of water coming into the kerf slot and then after the blade passes through the kerf slot, you use another stream of water. You may use other streams to clear out any trash that collects in the blade housing.

BOUJIKIAN: I did not say that the coolant is not important, the coolant and the distribution of coolant. The additive coolant is very very important and it is an absolute necessity. Anybody who tries to go from tap water or any other deionized water is going to be very badly surprised. The coolant is very essential and very important.

The other comment I would like to make is on ID blades. Mr. Aharonyan mentioned in his lecture that they are working on the design of saws, and also mentioned that there is room for improvement in diamond blades. Now I can take the last 10 years and statistics show that in diamond-blade performance, not including the kerf loss gain, there is something like 30 times, 3000%, improvement in the diamond blade life. Today in the international market or worldwide market, the number of diamond blades is approximately the same as it was 10 years ago. At the same time, the number of square inches or square meters sliced today is about 30 times larger. So there has been improvement in the diamond blade. This isn't all credited to the diamond blade, however. We know for a fact that sometimes the saw manufacturers credit the diamond blade life with 10% improvement or 15% improvement. I can show you customers who have blades that cut 1000 slices, and blades that cut maybe 80,000 slices. So the bladelife is in there, it is designed into the blade. The diamond, the blade, the nickel, never wears if everything goes properly. It is a combination of blade manufacturing, machine usage and application, with the cooling and dressing being parts of it.

KUAN: I have done some work on the effect of lubricants. My results seem to indicate that the lubricants act as lubricant, coolant and also surface catalyst for breaking silicon bonds. I can say that because I have tested different kinds of lubricants including oil which is chemically not active with silicon.

AHARONYAN: We also manufacture blades. I wanted to comment on a statement that John Boujikian made. We can take several blades from a single batch where we know that all of the processes have been the same, we can take the blades and put them on the machine exactly the same way and think they were running without variation from blade to blade and we get different lifetimes, we got different results. There are a lot of influences on it but I think the blade, the machine, and the operator come into play. You can't point your finger at one particular parameter and say this is the problem. We have made progress in the equipment. We make better blade mounts, better machines today. You can't make the statement that the blade mounts today are the same as they were 10 years ago.

WERNER: I don't have special experience in ID sawing of rigid hard material like silicon, but I can refer you to a recent ASME Session on metal-working lubrication, where the stress was on metal. My contribution to that points out that in any grinding process, an ingoing cut perpendicular to the work material, without having the ingot rotating, generates a rather long contact zone, much longer than in conventional grinding processes. ID sawing basically is a grinding process, it has a rather small grinding wheel, same as stone cutting with a saw blade is also a grinding process. This, together with the fact that rigid hard material ground by diamond results in relatively high frictional forces rather than chip removal or chip formational forces, requiring the application of a lubricant rather than a coolant, because in this case, where frictional forces and frictional energies are relatively high, the active reduction of energy by lubrication is more important than the out-flux of energy in the form of a cooling effect. However, in practice, as I learn here, the application of oil in silicon grinding or silicon sawing is not the state of the art. I believe that is the reason why removal rates and cutting speeds in terms of the tangential cutting speed of the saws is limited.

(The recording tape was replaced at this time and part of the discussion was lost. --Ed.)

....and is just removed and if you even very suddenly stop your grinding process you never see those layers of restructured graphite type of carbon atoms, but at 20 to 50 contacts, with high flash temperatures, per second you really wear down your crystal rather fast. Whenever you have high contact temperatures, or frictional conditions, these flash temperatures occur, you have that kind of wear. If you increase your grinding speed and your in-feed rate, you come to a point where the high surface energy that is affecting your diamond is such that your diamond crystal wears rapidly. In this case, the only way out is to apply a lubricant, not a coolant, because a coolant can only have an effect after the single crystal left the contact zone. So, cooling means removing of energy that was established and lubrication means avoiding an energy to be established or to be transformed from mechanical into thermal energy. If you have a high degree of friction, and I think we have that, if you have a higher than normal cutting rate and removal rate, then I think an oil type of lubricant would be the best answer.

YERKES: Looking at the chart that was put up this morning about the various kinds of saws, you saw the higher speeds, linear speeds and higher pressures in the ID saw. But there is also apparently some bandsaw work over here that apparently could be the same. Do you think these speeds can be increased, where do we fall in the context of high-speed grinding on things like this?

WERNER: High-speed grinding is a very controversial issue. About five years ago, or a little more, the grinding world was thinking that higher speeds is the answer to the higher demand for increase of removal rates. There are areas where high-speed grinding, 100 m/s and more, for example and fluting of drilling tools, resulted in tremendous removal rates. In this fluting of drilling tools, the removal rates are 20 to 100 times higher than in milling and at the same time you cut into hardened material without visible thermal effect on the work surface. Now that would be nice if that would be true for all materials. It is only true for certain materials which have what I call a very good thermal-related grindability. That means, while I grind with increased removal rates my thermal level does not go up, but remains at the same level. That is only true for those materials that show a clear drop of cutting forces if you increase the grinding speed, the circumferential speed of the wheel. There are other materials that do not show this beneficial drop of forces if you increase the circumferential speed. Those materials have a relatively high frictional portion of the energy in the cutting process and I suspect that silicon belongs to those materials. Therefore, I would be rather careful in increasing the circumferential speeds for a given machine tool and material. However, I think it might make sense to experiment a little bit by applying a coolant that goes more into the direction of a lubricant.

BOUJIKIAN: I would like to make a comment first on the diamond. There are hundreds of papers written on so-called wear of the diamond, including in ID blades and OD blades and there are three types of wear reported. One, the thermal disintegration at flash point; two, the cracking of the diamond--the diamond will actually break because of an already existing crack that will fall apart, and three, the whole diamond pulling out of the matrix, which in ID blades is more severe than in OD blades because you have the tension. According to hundreds of papers, over 90% of the wear of diamond is attributed to thermal disintegration, or carburization, as it was referred to. This morning, Prof. Wolf presented charts where the pressure or the speed is directly proportional to the wear of the grind. This is correct up to that point, but when you disregard the fact that you are using diamond as a wear factor, this is not correct because the diamond will start disintegrating at a much faster rate as the speed increases. If you look at those curves, they will flatten out and start coming down as your speed increases. This is why every material that you are cutting, being GGG or silicon or any other material, has an optimum cutting speed, in surface speed per minute, at your point of contact. The silicon case happens to be somewhere around 3300 surface feet per minute. Now if you try to go 5000 surface feet per minute, as per that chart, you would increase your efficiency, which is not correct. You will decrease your efficiency all the way down.

AHARONYAN: I would like to make one comment on the wear of the diamond. It is very rare that a diamond blade is discarded because the diamonds have completely worn off of it. We have taken cross-sectional samples of many blades that have cut a few thousand slices each and almost the full amount of diamonds that was originally plated on that blade still remains. The number for a 22-inch blade may be 10 or 20 thousand slices per blade before all of the diamonds are worn off. Usually we found that the main problem has been the weakening of the core and we think that has to do with rubbing of the crystal and the wafer. Diamond wear has never really been a big problem. We had a paper just a while ago where Dr. Chen discussed the difficulties with silicon slicing in terms of the fracture of the silicon. A lot of what we have been talking about here is shear and also shear of the diamond or at least conversion to graphite, etc. Do we have someone here who is in the materials area who might make a comment or analyze for us just what is it we want in the silicon? Do we want the shear or the fracture or what? Particularly, I know that Dr. Schwuttke has done some work in previous years in this area. What would you say we want mainly, the fracture or the shear?

SCHWUTTKE: Actually, to be honest, I don't know what we want today. I think what you want today is the fastest cutting action and then the next question is how can this be achieved in silicon? The basic mechanism to separate silicon is the shear loop; that means a dislocation loop that is put into the surface by abrasion. If you have a pileup of such shear loops in silicon, you form splits, cracks, and then you separate the silicon because the pileup of shear loops in silicon will put the surface in tension and that will open up a crack. That is the basic mechanism. What I would say is, based on this, you have to strive to get the best possible abrasion process if you want to separate silicon. This may relate directly to how you put in your fluid, your coolant, whatever you name it to get the best possible abrasion of silicon.

CHEN: As far as I know, there are no data available on the shearing strength of the silicon. For brittle material, normally we're talking about No. 1 type, that is, an opening-mode fracture. That's direct opening of the crack. In a shearing crack, it is relatively difficult. The shearing strength should be higher than the tensile strength that caused the opening of the crack for crack propagation.

SCHWUTTKE: That is basically correct, but I said what you need is a pileup of shear loops. You surpass the tensile strength of the silicon very easily this way, and this is normally what happens.

CHEN: This is a different mechanism. Dislocation is due to the shearing stress and therefore localized plastic deformation. However, the crack propagation of the brittle material under the shearing is relatively higher.

SCHWUTTKE: I think the very surprising thing is that in silicon you introduce shear loops at room temperature, which is generally not known. There is no plastic deformation. For instance if you have plastic deformation, you would have cracks in silicon surrounded by dislocations at room temperature. This has never been observed and actually does not occur. Plastic deformation of silicon is a very special and complicated thing and a lot of information in the literature is not correct.

YERKES: You know, I am getting real confused again. It seems to me people were talking about 10-mil or 12-mil-wide grinding holes or slots in the silicon and that has got to have millions or tens of thousands of little molecular cracks and things that Dr. Schwuttke is talking about. It seems to me that right down there where all of these diamonds are impacting the silicon, and where these hydraulic forces are, and the lubrication and the steam and whatever else, it is a very wide track with thousands of events occurring. The poor silicon doesn't know where to crack, and how to proceed next. So it is a very statistical kind of a thing. I liked what Peter (Iles) said earlier about whacking this thing and just having it cut like bologna because if the bologna makers lost half their stuff they would be out of business now. So we really ought to be looking at these very thin shearing effects.

WOLF: I wonder how well you can slice your bologna once you cool it in liquid nitrogen?

HEIT: I have notes bearing on the development work that we did in connection with this coolant surfactant composition. This goes back to '76. We found, in three separate samples, 0.3% to 0.4% silicon. We measured 0.31 to 0.38 parts per million of nickel in those samples. We didn't find the diamond, we didn't look for it, but you can find the nickel. Now the wear on the nickel is essentially constant and it is disappearing into the soup at the rate of 10,000 parts of silicon to 1 part of nickel. That is a traceable, attributable state of affairs. We also measured another specimen using the treatment and we found one half of the amount of nickel. In 500 millimeters per minute we found 0.196, and that is what our claim to fame is, we extended the life of the saw by preserving the nickel matrix into which particular allotropic modification a diamond is embedded.